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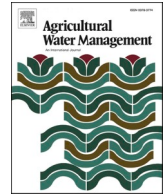
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Meta-analysis of water stress impact on rice quality in China

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ABSTRACT

Climate change will lead to an increase in the frequency of droughts and extreme rainfalls, with a potential negative impact on rice production. Many studies have been conducted to assess the impact of water stress on yields, but much less attention was paid to rice quality, leading to a poor understanding of the effect of water stress on rice grain quality traits, especially in China - a major rice producer. Although a number of individual experiments have been carried out on this topic, no quantitative synthesis has yet been produced. Therefore, to quantify the effect of water stress on rice quality in China, we present here the results of a meta-analysis based on 1341 experimental records collected for seven standard rice quality criteria extracted from 37 articles. We employed random effect models to estimate mean effect sizes measuring the extent of the impact of water stress on rice quality and identify the main driving factors. The results showed that water stress significantly increased grain chalky rate by 7.63 % and chalkiness by 17.7 % and significantly decreased the milling quality indexes (brown rice rate decreased by 0.8 %, milled rice rate decreased by 0.9 %, and head rice rate decreased by 2 %) compared to well-watered conditions, both effects leading to reduced rice quality. Water stress also caused a significant increase in protein content by 4.65 %. Soil water potential had a strong effect on the impact of water stress on rice milling quality, while protein content was mainly regulated by the growth stage at which water stress occurred. These results offer compelling evidence of the effect of water stress on rice quality in China, highlighting the significance of developing climate change adaptation strategies to ensure the maintenance of satisfactory rice quality in the future, thereby fostering the production of high-quality rice with high yield.

1. Introduction

Rice is one of the most important staple foods for more than half of the world's population (Khush, 2013; Seck et al., 2012; Zeng et al., 2017), and its yield has always been of great concern. Since the 1960s and 1970s, the world's major rice-producing countries have adopted new practices and new rice cultivars in order to increase grain yields and feed a rapidly growing population (van Ittersum et al., 2013). By 2030, it is anticipated that global rice production will need to surpass the 2017–2019 benchmarks by approximately 7 million metric tons annually (OECD/FAO, 2020), while climate change is expected to have negative impacts on rice yields in several major producing regions (Abramoff et al., 2023; Gerber et al., 2024). Meanwhile, with the improvement of the living standards of rice consumers, awareness of grain quality has gradually increased and become a source of concern. Given the key role of rice in China's food security, Chinese rice scientists and producers are paying increasing attention to rice quality in order to

meet consumer demand for high-quality rice.

Rice quality is a complex trait consisting of several evaluation indicators such as milling characteristics, appearance quality, eating and cooking quality and nutritional value, etc. These qualities reflect intrinsic and extrinsic attributes of rice, such as appearance, taste and flavor, which play a crucial role in determining market acceptance and commercial value. However, rice quality is the result of a complex interaction between genetic characteristics and environmental conditions, including climate (Gaballah et al., 2021; Krishnan et al., 2011; Xu et al., 2021). Climate change is one of the severe challenges facing China and global agriculture in the 21st century, leading to an increase in the frequency and intensity of hot and dry events in some regions, especially in the main rice-producing areas such as eastern China and the middle and lower reaches of the Yangtze River (Hao, 2022; Zhang et al., 2022), severely affecting the productivity of important crops and damaging the normal function of ecosystems (Gornall et al., 2010). Due to global warming, decreasing rainfall and increasing frequency of dry spells in

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some regions, water resources deficit has become one of the major limiting factors for high quality rice production in China (Qi et al., 2022; Zhao and Wang, 2020). Understanding the mechanistic effects of drought on rice will contribute to a better utilization of water resources in rice production (Yang et al., 2022).

Although irrigated rice represents a large share of total production (93 %) in China (Chen et al., 2016), water scarcity and uneven irrigation can also affect irrigated rice, as shown in rice trials under natural drought conditions and water-saving irrigation (Chi et al., 2001; Peng et al., 2000; Zhang et al., 2001). Several studies also indicate that drought has negative impacts on rice quality traits (Zheng et al., 2005, 2006), and that its impact depends on the level of water deficit and on the crop stage of drought occurrence. For example, during the tillering stage, mild water stress can enhance milling quality. However, severe water stress can impair soil moisture absorption, restrict nutrient reserves, and hinder meristem and cell division, ultimately resulting in detrimental effects (Ke, 2010; Panda et al., 2021; Zhou et al., 2005). Drought conditions during the mid-booting stage can cause a reduction in brown rice rate, milled rice rate and flavor, thereby degrading rice quality (Wang et al., 2006; Zhang et al., 2017). For the grain-filling stage, light water stress can significantly improve the filling rate, trigger key enzyme activities of the sucrose-starch metabolism pathway in the grains, and reduce endogenous ethylene content, thereby reducing chalkiness and improving milling quality (You et al., 2017). However, both moderate and heavy stress have opposite effects, and lead to reduced photosynthetic rate and shortened filling period, significantly decreasing rice quality by increasing chalkiness and chalky rate (Wang et al., 2007; Yang et al., 2019). All in all, existing studies on the effects of drought on rice quality have yielded divergent conclusions due to differences in ecological conditions, varieties, time of drought occurrence and water deficit degree (Chen and Yang, 2010; Duan et al., 2019; Xing et al., 2018). A synthesis of existing data is needed to better understand the effect of water stress on rice quality.

By integrating the findings of numerous experiments conducted under varying conditions, a meta-analysis would provide a comprehensive evaluation of the effects of water stress on rice quality (Ben Mariem et al., 2021). To this end, we synthesized 1341 experimental records from 37 related articles to conduct a China-wide meta-analysis quantifying water stress effects on rice quality. We focused on the response of seven standard rice quality traits, namely chalky rate, chalkiness, brown rice rate, milled rice rate, head rice rate, amylose content and protein content, to water stress (see definitions in Table S1). We aimed at (1) quantifying the extent to which each rice quality trait responded to water stress, (2) assessing how multiple factors moderated the response of rice quality to water stress, and (3) identifying these factors according to their relative importance in order to provide recommendations for improving rice quality in the future.

2. Materials and methods

2.1. Criteria for considering studies following the PICOL

The objective of our study was to answer the primary question: “How does water stress impact individual quality traits in rice, and to what extent does each trait respond to varying levels of water stress?” The research question components were structured based on the PICOL model (Table 1): population, intervention, comparator, outcome and location.

We established a database on rice quality based on data from peer-reviewed papers, incorporated randomized controlled trials (RCTs) comparing the effects of treatments related to drought or water stress with well-irrigated without water stress conditions on various rice quality indicators. The water stress level in the experiment (treatment) was quantified using soil water potential rather than soil water content. Soil water content does not reflect the effect of water stress on plants, while soil water potential is a function of soil texture and soil moisture, and is more suitable for characterizing the degree of water stress on

Table 1

Definition of components of the primary question.

Population	Intervention	Comparator	Outcome	Location
Rice	Water stress during rice growth	Absence of water stress	Changes in specific quality indicators	China
Type of rice: indica & japonica	The water stress level in the experiment	The value of soil water potential is 0	Chalky grain rate	Northeast China, North China, and the middle and lower reaches of the Yangtze River
Type of cultivation: field & pots	(treatment) was quantified using soil water potential		Brown rice rate	
			Milled rice rate	
			Head rice rate	
			Amylose content	
			Protein content	

plants (Masseroni et al., 2016; Zhao et al., 2011). We evaluated the milling, appearance, flavor, cooking, and nutritional quality traits of rice based on the indicators listed in Table S1.

2.2. Literature search and study identification

We first conducted an extensive literature survey through the Web of Science database (<https://webofscience.clarivate.cn/>), Google Scholar (<http://scholar.google.com>), and the China National Knowledge Infrastructure Database (<http://www.cnki.net/>) until November 2023, using Topic= ("drought * " OR "arid * " OR "dry * " OR "water stress" OR "extreme climate") and Topic= ("rice quality" OR "grain quality" OR "crop quality") as search terms. The initial search yielded 5497 articles written in English and 98 articles written in Chinese related to the study within the timeframe of 1946–2023. The total of 5491 articles with duplicates removed were further screened according to the following criteria: (1) The specific location, duration, rice variety and complete growth cycle of the experiments were clearly stated, and obtain information on soil type, soil fertility (N, P, and K content in the soil), etc.; (2) The experiments should include at least one treatment related to drought or water stress, with a well-irrigated control group without water stress such as flooding with 1–3 cm water layer. Other management measures, such as soil, fertilization, rice variety used and planting density, were kept identical between the drought treatment and the control; (3) The recorded rice quality indicators in the experiments included at least one of the parameters mentioned in Table S1; (4) The experiments employed a replicated design. Data from the same experiment but reported in more than one publication were not repeated. Based on these criteria, 37 studies were included in our analysis. The details of the literature search and selection process are presented in Supplementary Figure S1.

2.3. Data collection

Data were extracted from 37 selected papers and entered into a database. We recorded data on sample size, sample mean and sample standard deviation, author information, experimental location (including latitude and longitude), experimental year, stress type, rice type, rice variety name, treatment stage and duration, treatment measures, soil water potential, rice quality, soil conditions, fertilizer information, and meteorological conditions (precipitation, relative humidity). In addition to extracting the required data from text and tables, the digital software Plot Digitizer (<https://automeris.io/WebPlotDigitizer/>) was used to retrieve data presented graphically. If only standard errors (SE) were provided in the literature, they were converted to standard deviations (SD) using the following formula:

$$SD = SE \times \sqrt{n} \quad (1)$$

where n is the number of replications. In cases where neither SD nor SE were available but P-values, sample sizes, and mean differences were provided, the SD of the experimental and control groups were retrieved by calculating the mean SD of the groups using the "Data Conversion Tool" officially recommended by Cochrane (<https://training.cochrane.org/resource/revman-calculator>). As China is the largest rice-producing country in the world and as most studies screened on rice quality were conducted in this country, we eventually extracted 1341 records from 37 studies covering 12 major rice-producing provinces in China (Fig. 1) located in Northeast China, North China, and the middle and lower reaches of the Yangtze River.

2.4. Data analysis

We first pre-processed the collected data to harmonize the formats of year of experiment, soil type, processing stage, treatment measure, and rice variety. When an experiment was conducted over two years, the last year was retained (for example, 2014–2015, was changed to 2015). The growth period of rice was divided into four stages: (i) tillering stage, (ii) jointing and booting stage, (iii) heading and flowering stage, and (iv) grain-filling stage. Drought period could cover a single stage or a combination of different stages, depending on the experiment. Ranges of soil water potential values obtained through measurements using a soil tensiometer were replaced by their median values. Because the standard deviations were sometimes missing, we used three methods, namely, Approximate Bayesian Bootstrap, HotDeck, and Bracken1992, to estimate the missing standard deviations. The methods HotDeck et Bracken1992 were implemented with the function `impute_SD` of the R package "metagear" (Lajeunesse, 2016). Approximate Bayesian Calculation was implemented by resampling data points with replacement, where the weights for each observation are drawn from a Dirichlet distribution (Rubin, 1981). The results showed that the effect values and confidence intervals calculated after imputing the data by the three

methods were similar, which is all better than that non-imputing the missing data result (Figure S3).

For each quality trait, we used a log response ratio (lnRR) (Hedges et al., 1999) to determine the relative effect of drought or water stress on rice quality, as follows:

$$\ln RR = \ln \frac{X_t}{X_c} = \ln X_t - \ln X_c \quad (2)$$

where X_c and X_t are the mean values of the rice quality trait considered without water stress (control) and with water stress (treatment), respectively. The lnRR was chosen because it is simple to interpret, independent of the unit used to measure X , and is widely used in global meta-analysis (Chen et al., 2022; Noble et al., 2017). The variance (v) of each individual effect size was calculated as follows:

$$v = \frac{SD_t^2}{N_t X_t^2} + \frac{SD_c^2}{N_c X_c^2} \quad (3)$$

where N_t and N_c are the sample sizes of the treatment and control groups, respectively, and SD_t and SD_c are the standard deviations of the treatment and control groups, respectively (Hedges et al., 1999).

It should note that fixed-effects models consider only within-case variation in effect values, assuming no differences between research cases. However, in this study, the differences in the effects of water stress on rice quality may stem from several aspects such as experiment settings, measurement methods, and environmental factors. The random-effects model can well account for these differences, reflecting the independence of each study and allowing for more robust inferences about the results (Wallace et al., 2017). Therefore, the random-effects model was used to calculate the overall effect value of drought on rice quality as described below:

$$\ln \bar{R} = \frac{\sum_{i=1}^k \ln RR_i w_i}{\sum_{i=1}^k w_i} \quad (4)$$

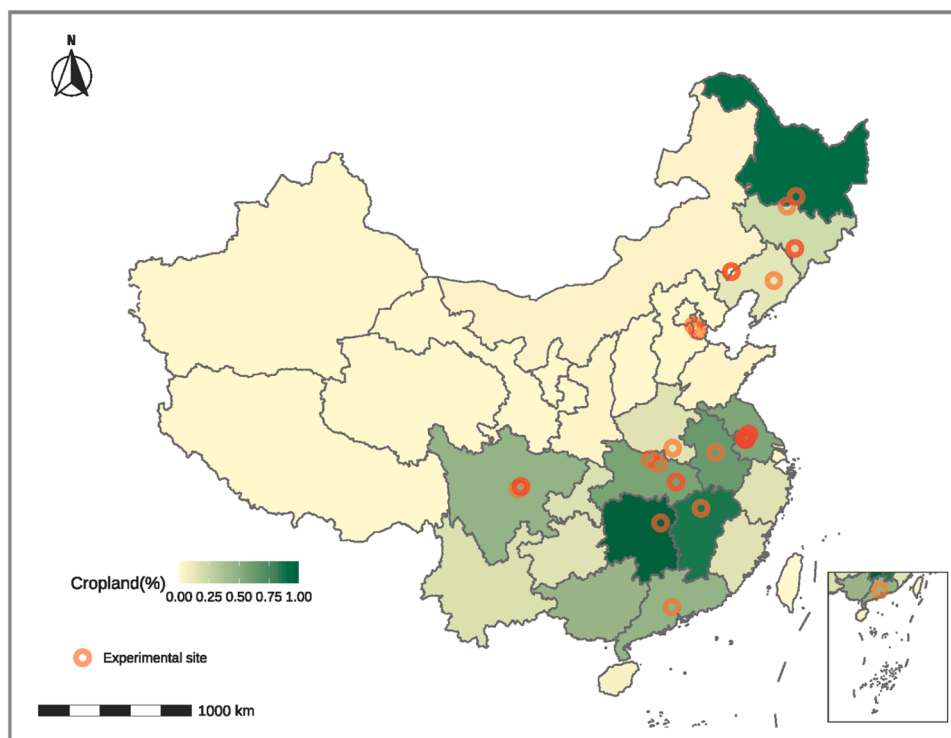


Fig. 1. Overview of all the study sites included in this meta-analysis. Note: The map is produced based on the standard map with review number GS (2018)2512 downloaded from the official website of the Ministry of Civil Affairs of China, with no modifications to the boundaries of the base map.

where $\ln RR_i$ and w_i are the i -th individual effect size and weight respectively, k is the total number of individual effect sizes. The value of w_i was calculated using Eq. (5):

$$w_i = \frac{1}{v_i + \tau^2} \quad (5)$$

where v_i is the variance of the i -th individual effect size (Eq. (3)), τ^2 is the between-study variance estimated by the restricted maximum likelihood (REML) method. Higher values of τ^2 indicate greater heterogeneity among studies, suggesting that the effects of water stress on rice quality may differ significantly across environments (such as soil conditions, rice varieties, or experimental types). Heterogeneity was also assessed using: (1) the Q-statistical test based on a χ^2 distribution (the heterogeneity was considered significant when the p-value of the Q test was lower than 0.05) (Hoaglin, 2016), (2) the I^2 statistics measuring the proportion of variability explained by differences between studies rather than by sampling error. Heterogeneity is usually considered not important if I^2 ranges from 0 % to 40 %, moderate from 30 % to 60 %, substantial from 50 % to 90 % and considerable from 75 % to 100 % (Langan et al., 2019) (Table S4).

The 95% CI of $\ln \bar{R}$ was computed as:

$$95\%CI = \ln \bar{R} \pm 1.96 * S_{\ln \bar{R}} \quad (6)$$

where $S_{\ln \bar{R}}$ is the overall SE of $\ln \bar{R}$, which was computed as:

$$S_{\ln \bar{R}} = \sqrt{\frac{1}{\sum_{i=1}^k w_i}} \quad (7)$$

If the 95 % CI did not include zero, the rice quality trait was considered to be significantly increased (> 0) or decreased (< 0) in the treatment compared to the control group ($p < 0.05$). To facilitate interpretation, the estimated mean effect size (4) was converted back into a relative change (%) as follows:

$$\text{Percentage change}(\%) = (e^{\ln \bar{R}} - 1) \times 100 \quad (8)$$

All the computations were performed with the R package “metafor (v.4.4.0)” (Viechtbauer, 2010), using the function `rma`. The nested hierarchical structures in the random-effects model were used to address the non-independence of effect values.

In addition to mean effect size estimation, meta-regression models were fitted to explore the relationship between the individual effect sizes and several covariates including soil water potential in the treatments, rice type, experiment type, soil type and crop stages (Supplementary tables S3-S18). Each of these covariates was selected based on their theoretical and empirical relevance to the effects of water stress on rice quality. For instance, soil water potential, which reflects the degree of drought in the soil, directly affects the crop response to water stress, while different rice varieties will exhibit varying levels of tolerance. The experiment type, soil type, and nutrient content in the soil provide the context for environmental conditions, and crop growth stages are critical for understanding developmental sensitivities. We calculated the Variance Inflation Factor (VIF) of each variable included in the model and the correlation matrix between the variables to test for possible multicollinearity among the variables. We found that there was no strong multicollinearity problem among the included variables, as indicated by a VIF value less than 5 (Table S19) or a correlation greater than 0.7 (Figure S5).

The best-fitting model was selected using the Akaike Information Criterion (AIC), which was computed as per Eq. (9):

$$AIC = -2\log(L) + 2P \quad (9)$$

where L is the maximum likelihood estimate of the model and P is the number of parameters in the model. In order to better understand the relative support between multiple models, the AIC weights were

calculated to reflect the probability of the model being selected among all candidate models as follows:

$$w_{AIC_i} = \frac{e^{-\frac{1}{2}(AIC_i - AIC_{\min})}}{\sum_{j=1}^K e^{-\frac{1}{2}(AIC_j - AIC_{\min})}} \quad (10)$$

where w_{AIC_i} is the AIC weight of the i -th model, AIC_i is the AIC value of the i -th model, AIC_{\min} is the smallest AIC value among all models, and K is the total number of models. Models with similar AIC (differences lower than 2 points compared to the minimum AIC) were averaged based on AIC weights (Link and Barker, 2006). The importance scores were then computed to identify the most influential factors. Factors with importance higher than 0.8 were considered as factors with major influence on quality traits. The models were fitted with the `rma.mv` function of the R package “metafor (v.4.4.0)” (Viechtbauer, 2010).

On the basis of the optimal model, we calculated fail-safe numbers using the Rosenthal approach, and examined publication bias across the entire dataset using funnel plots, Egger regression, and the “trim and fill” approaches (Nakagawa and Santos, 2012) (see Table S2 and Figure S2). The “trim and fill” method involved trimming away any asymmetries in the funnel plot after initial estimation, estimating the center value of the funnel plot with the remaining symmetrical, and identifying missing studies that may contribute to publication bias. The trimmed portion as well as the missing portion was then filled in mirroring along both sides of the center and the overall effect size was recalculated to provide a more conservative estimate and more robust results on the effect of water stress on rice quality. In case of publication bias, this method can reveal changes in both the effect size and the associated confidence intervals, reflecting the influence of potential unpublished studies. All analyses were done in R (v.4.3.2) (R Core Team, 2023) with the packages “metafor” for meta-analyses and `ggplot2` (v.3.4.4) (Villanueva and Chen, 2019) for visualization.

3. Results

3.1. Responses of rice quality traits to water stress

The results showed that water stress had different effects on different rice quality traits. Specifically, brown rice rate, milled rice rate and head rice rate decreased significantly under water stress conditions, on average, by -0.80 % (mean effect, ln; 95 % confidence interval, CI: -1.12 % to -0.49 %; $p < 0.001$), -0.90 % (CI: -1.32 % to -0.47 %; $p < 0.001$) and -2.00 % (CI: -3.23 % to -0.76 %; $p = 0.0017$) (Fig. 2c-e and h), respectively, implying that water stress had a significant negative effect on the milling quality of rice which reduces the market value of rice. In addition, chalky rate, chalkiness and protein content increased by 7.63 % (CI: 2.28 % to $+13.27$ %; $p = 0.0047$), 17.7 % (CI: $+8.95$ % to $+27.15$ %; $p < 0.001$) and 4.65 % (CI: $+2.76$ % to $+6.57$ %; $p < 0.001$) (Fig. 2a, b, g and h), respectively. Increases in chalkiness and chalky rate indicated that water stress deteriorated appearance quality, which can affect consumer preferences and marketability. Although an elevated protein content enhanced its nutritional value, it generally made cooked rice harder in texture and poor palatability, which may affect consumer satisfaction. Water stress also increase amylose content (0.21 %; CI: -0.64 % to $+1.06$ %; $p = 0.633$) of rice, but the effect was not significant (Fig. 2f and h).

The sample sizes for investigations into milling and appearance quality traits were substantial (number of individual effect sizes $n > 180$), which explains why the confidence intervals were relatively narrow, indicating a high level of certainty in the effect of water stress on these traits, as evidenced by the significant range of effects observed. Conversely, the non-significant impact on amylose content may be due to a lower sample size (only 178 individual effect sizes available for this trait), which suggests a potentially high type II error (low statistical power), implying that the absence of statistically significant effect does

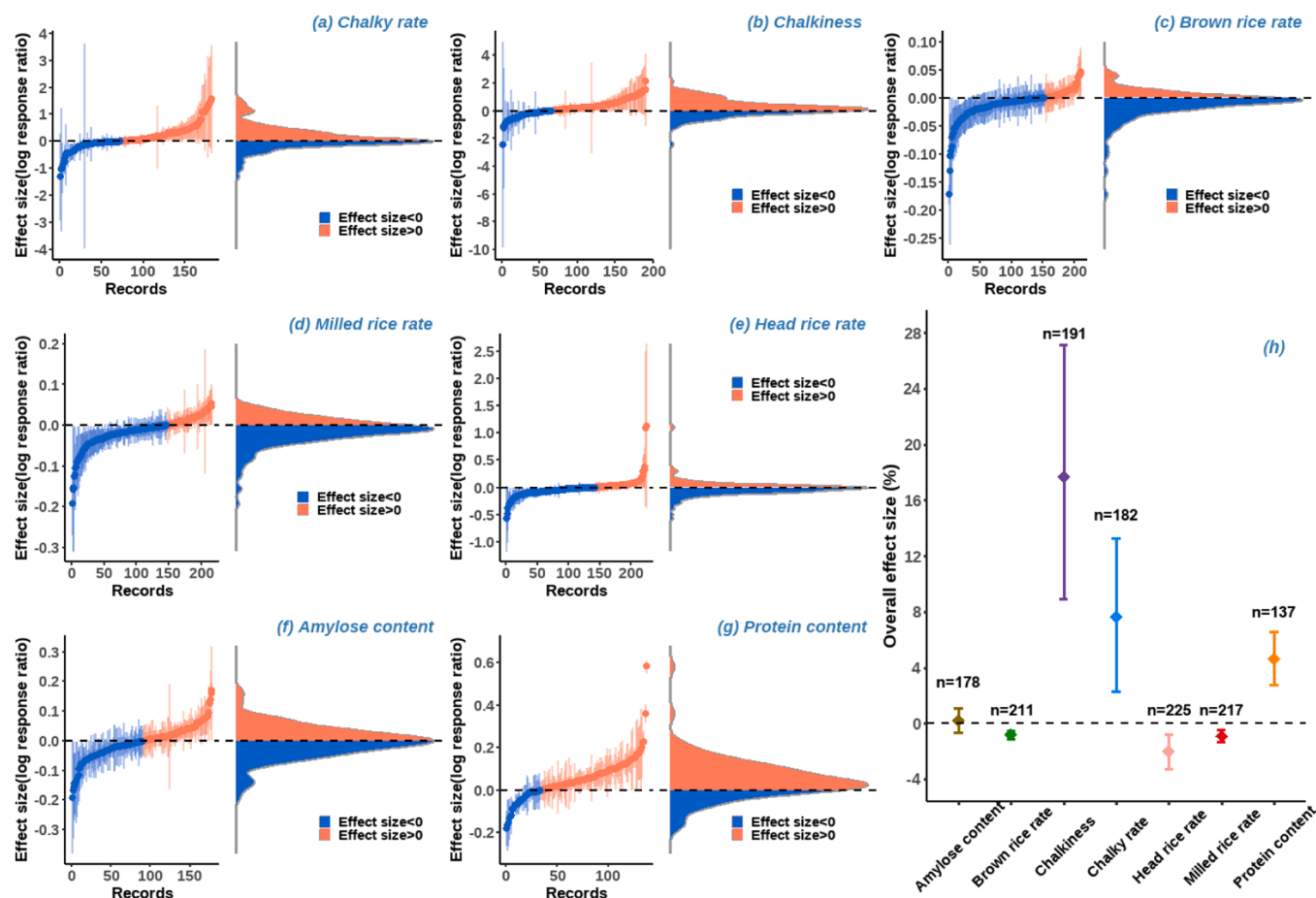


Fig. 2. Individual effect sizes (log response ratios, LnRR) frequency distributions (a-g) and estimated mean response ratios (h) to water stress for several quality traits, namely Chalky rate, Chalkiness, Brown rice rate, Milling rice rate, Head rice rate, Amylose content and Protein content. In figures a-g, red color indicates LnRR > 0, i.e., positive effect, and blue color indicates LnRR < 0, i.e., negative effect. The dots represent the mean values and vertical bars reflect their 95 % confidence intervals. In figure h, diamonds represent the estimated mean effect size for each quality trait (and 95 % CI), n is the number of experimental record entries. The horizontal dashed line is the zero line indicating absence of drought effect. Heterogeneity of effect sizes (between-study variability) was significant ($p < 0.001$).

not conclusively rule out the existence of a water stress effect on this trait. Additionally, the possibility of a type I error should be acknowledged for protein content because the sample size for assessing the effect of water stress on this trait was relatively modest ($n = 137$), and the significant outcome might have emerged by chance for this trait (Fig. 2). To ascertain the robustness of our findings, we conducted leave-one-out analyses by sequentially excluding each group of experimental records sharing the same control condition within the same study and then recalculating the effect sizes. Overall, the aggregate effect size exhibited a notable degree of reliability and was largely independent from the individual studies (Figure S4).

The effect sizes derived for chalky rate and chalkiness were significantly and positively correlated with soil water potential. The more negative the value of soil water potential, the larger the positive effect of water stress on chalky rate and chalkiness (Fig. 3a and b). This result indicates that the effect on these two quality traits was stronger in case of high negative values of the soil water potential, i.e. high level of water stress. The positive effect of soil water potential on protein content was not significant (Fig. 3g). On the other hand, the effect sizes for brown rice rate, milled rice rate, head rice rate and amylose content were negatively correlated with soil water potential (Fig. 3c-f). When soil water potential was greater than -10 kPa (light water stress conditions), LnRR of the two appearance quality traits were less than 0, while the LnRR of the three milling quality traits and the content of amylose content were all greater than 0, although they were no or marginally significantly different from zero. For stronger water stress levels, the

effect sizes became significantly positive for the appearance quality traits and significantly negative for milling quality traits, revealing an increasing deterioration of grain quality in case of high water stress.

3.2. Response of rice quality at different growth stages of water stress occurrence

In the experimental treatments of the experiments included in our dataset, drought occurrence was reported at four single-stage phases: tillering stage, jointing and booting stage, heading and flowering stage and grain-filling stage, as well as three multi-stage phases: tillering to grain-filling stage, heading to grain-filling stage, and the whole growth period. When comparing different growth periods (Fig. 4), we found that at the tillering stage of rice, water stress significantly increased the amylose content by 2.2 % and decreased the protein content by 5.13 %. These effects at the tillering stage were opposite to the overall effect and significantly different compared to other growing stages. Interestingly, at this growth stage, the effects on the other quality traits were minor at this stage. Significant reductions in brown rice rate, milled rice rate and head rice rate were found for water stress occurring at later stages, such as jointing and booting stage, heading and flowering stage and grain-filling stage. At these stages, the protein content was also found to increase significantly. One-way ANOVA revealed that the water stress effects were not significantly different across growth stages for appearance quality, but the effects on brown rice rate and milled rice rate were significantly different at the jointing and booting stages compared to

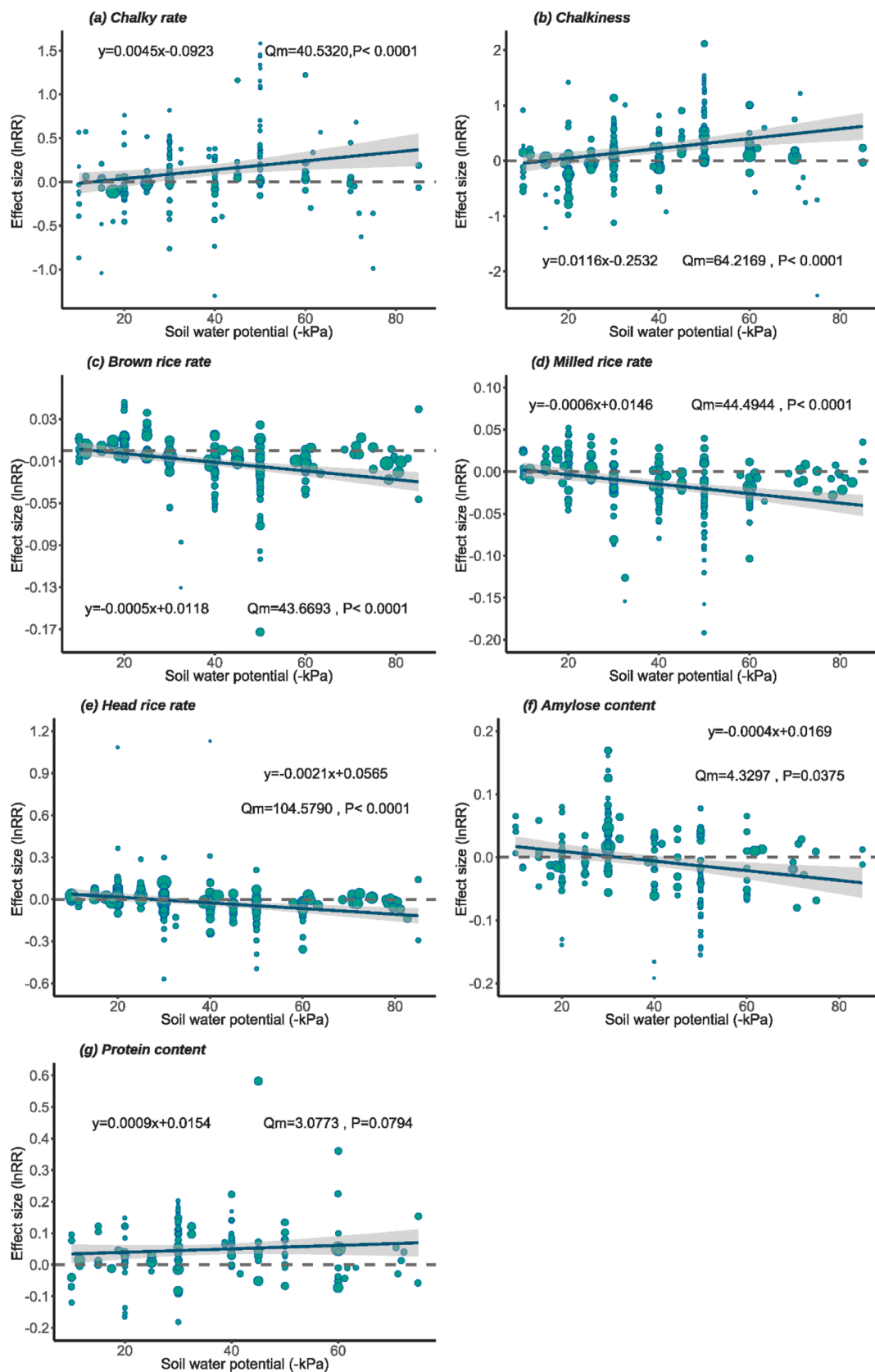


Fig. 3. Relationships between the effect size (LnRR) of each rice quality trait and soil water potential (SWP, measuring the drought intensity in the treated groups) using linear regression. Each symbol represents one observation, point sizes stand for weightings of corresponding observations. Shaded areas represent the 95 % confidence intervals of the linear regressions. The horizontal dashed line is the zero line. Qm measures the proportion of heterogeneity (between-study variability) explained by the explanatory variable (SWP), and the larger its value, the greater the influence of SWP on the effect size. $P < 0.05$ indicates significant effect.

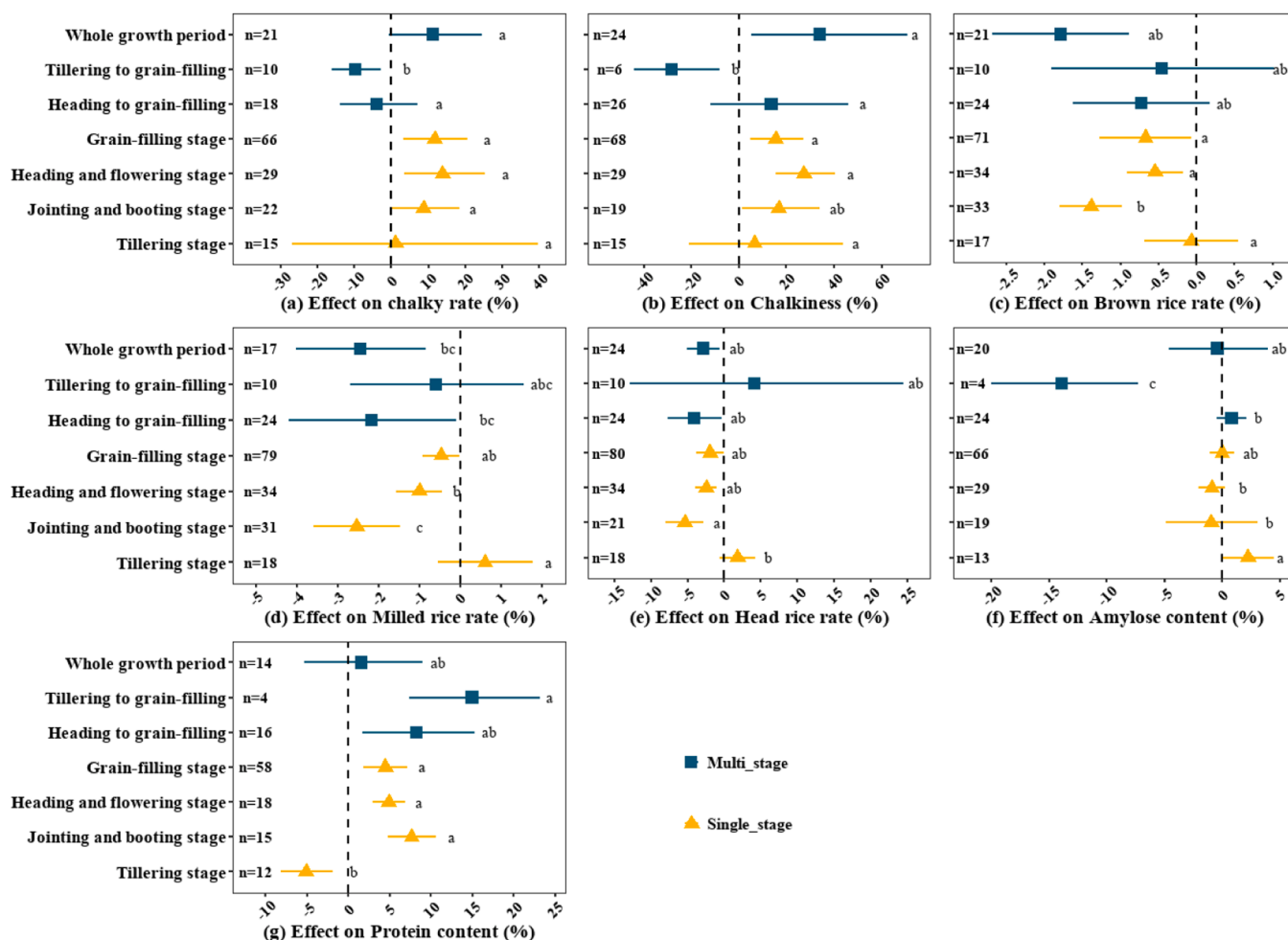


Fig. 4. Estimated mean effect sizes for data grouped by different growth stages of rice at which water stress occurred. Squares or triangles represent estimated effect sizes, error bars represent 95 % confidence intervals (95 % CI), and n represents the number of data in each group. The vertical dashed line is the zero line indicating absence of drought effect. In a-g, one-way ANOVA was conducted to determine significant differences among different growth stages. Different lowercase letters behind the error bars indicate significant differences ($p < 0.05$).

other growth stages.

For water stress occurring at several crop stages, protein content significantly increased by 8.23 % and 14.99 % at heading to grain-filling stage and tillering to grain-filling stage, respectively. However, significant negative effects on amylose content, chalky rate and chalkiness were estimated when water stress occurred from tillering to grain filling, thus contrasting with results obtained at other growth stages. When drought occurred throughout the whole growing period, the chalky rate and chalkiness increased prominently by 11.17 % and 34.06 %, while the brown rice rate, milled rice rate and head rice rate all decreased remarkably.

3.3. Effect of rice type and experiment type

Responses to water stress were similar for both rice types (Japonica and Indica) and not significantly different (Fig. 5). Results obtained in field experiments and pot experiments were partly different. We found that the impact of water stress on the various remaining rice quality traits were often smaller under the field experiments, except for amylose content. In contrast, in pot experiments, the two appearance qualities of chalky rate and chalkiness increased by 7.7 % and 21.47 % (Fig. 5a and b), respectively, the protein content significantly increased by 6.52 % (Fig. 5g), and all three milling characteristics decreased substantially (Fig. 5c-e).

3.4. Effect of soil type and fertility

The soils of the experimental sites can be categorized into clay, clay loam, and sandy loam based on the size of soil particles (i.e., soil texture), and into paddy soil, brown soil, and yellow-brown soil based on the process of soil formation. For both appearance quality indicators, only rice grown in sandy loam soil showed a remarkable increase of 8.98 % in chalkiness due to drought, whereas rice chalky rate and chalkiness in other soil types did not respond significantly to drought (Fig. 5a and b). Water stress occurrence significantly reduced brown rice rate of rice grown in sandy soil and milled rice rate of rice grown in paddy soil (Fig. 5c-e), and largely increased the protein content of rice grown in clay soil and sandy loam soil (Fig. 5g). However, the differences of effect for milled rice quality among soil types were not significant. Amylose content increased by 5.11 % and 1.42 % under water stress conditions in arid clay loam and sandy loam soils, respectively, but decreased by 3.58 % in arid brown soil, which is one reason why the overall effect value of water stress on amylose content was not statistically significant (Fig. 5f).

We also explored the relationship between the response of rice quality to water stress and the nitrogen (N), phosphorus (P), and potassium (K) soil contents. The results of regression analysis showed that K content had almost no effect, whereas the contents of both N and P was significantly negatively correlated with the effect value of amylose content under water stress conditions (Fig. 6f), and somewhat positively

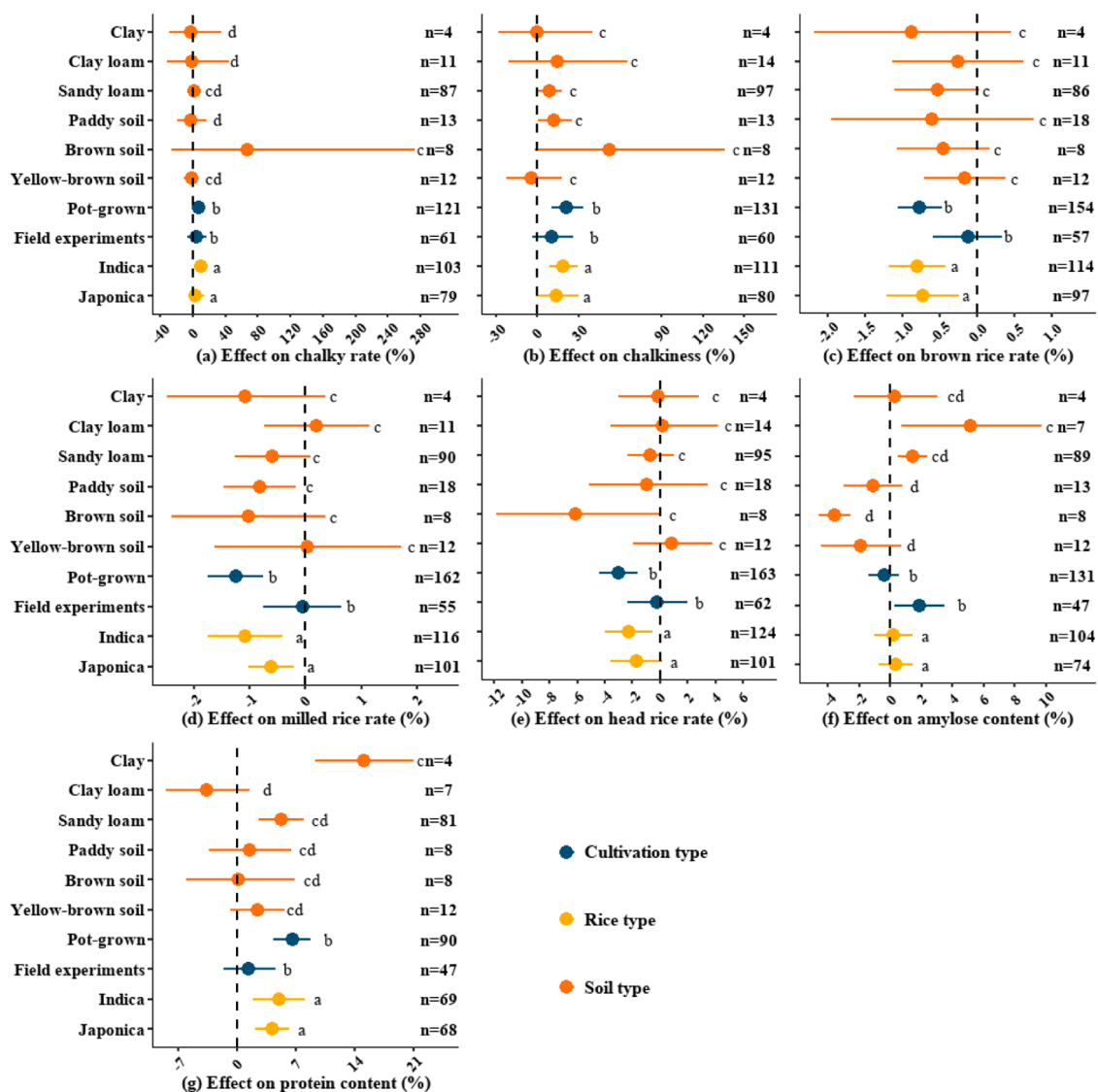


Fig. 5. Estimated mean effect sizes for data grouped by different soil types, types of experiments, and types of rice. The dots represent the estimated effect sizes, the error bars represent their 95 % confidence interval (95 %CI), and n is the number of individual effect sizes in each subgroup. The vertical dashed line is the zero line. In a-g, one-way ANOVA was conducted to determine significant differences between groups. Different lowercase letters behind the error bars indicate significant differences ($p < 0.05$).

correlated with the effect value of all three milling characteristics, although the trend was not significant (Fig. 6c-e). Importantly, the effect of water stress on the two appearance qualities tended to decrease when N content increased, while the trend was opposite for P (Fig. 6a and b). These results indicate that soil nitrogen can moderate the effect of drought on rice quality.

3.5. Combined impact and importance of moderators

A model selection and weighting procedure was implemented to identify the most influential factors regulating the effect of drought on rice quality. Considering the completeness of the original data and the relevance of various factors, six factors were considered for inclusion in the regression model (soil water potential (SWP_treat), rice type, growth stage at which water stress occurred, soil type, experiment type and soil nitrogen content), leading to 64 possible combinations of factors (2^6).

For each quality trait, we listed the top ten factor combinations leading to the lowest AIC (Table S10-S17). For chalky rate and chalkiness, the main influencing factors were Growth_stage, soil type, SWP, soil N, while the three milling quality traits were mainly moderated by

SWP and, for milled rice rate, by growth stage (Fig. 7). The most influential factors for protein content were crop growing stage and the type of experiment (field vs. pot), but only the growing stage was dominant with an importance (AIC weight) higher than 0.8. No dominant factor was found for amylose content (Fig. 7).

4. Discussion

This synthesis shows that water stress had contrasting effects on the different rice quality traits (Fig. 2). It causes an increase in chalkiness and chalky rate of rice, which resulted in poorer appearance quality, as manifested by the visual characteristics of darkened color and partial white opacity (Graham, 2002; Tomlins et al., 2007). In addition, water stress significantly reduces rice milling qualities (brown rice rate, milled rice rate, and head rice rate), making it fragile or difficult to process, affecting the preparation and quality of rice products (Neerja and Renu, 2019). Interestingly, drought generally increases the protein content of rice grains and thus improves its nutritional value. Additionally, our study found that rice variety characteristics, environmental factors such as soil, as well as cultivation stage and fertilization, influence the extent

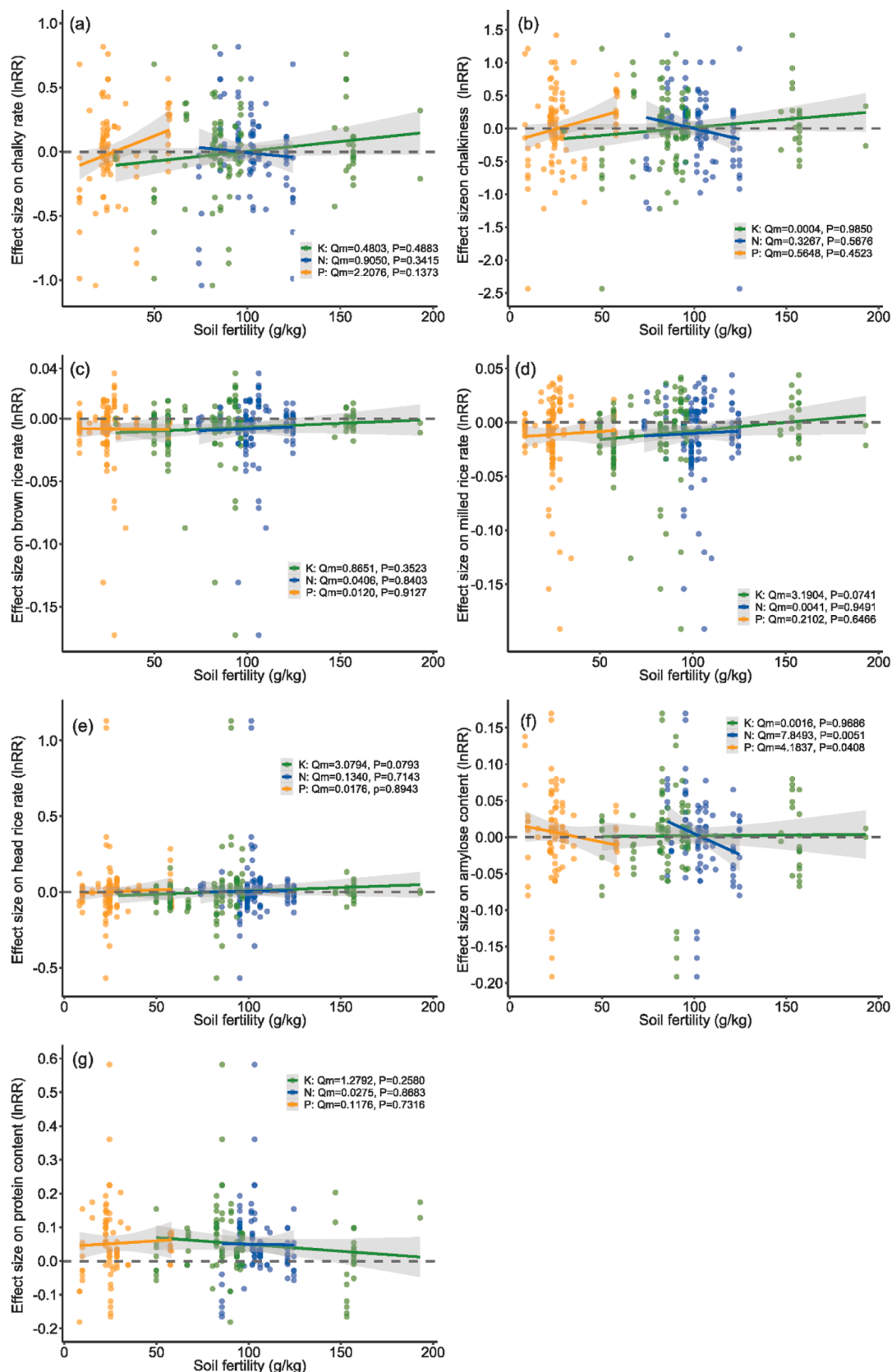


Fig. 6. Variation in the effect size (LnRR) of each rice quality trait with soil nitrogen (N, g/kg), phosphorus (P, g/kg) and potassium (K, g/kg) content. Solid lines were fitted with linear regressions. Each symbol represents one observation, point sizes stand for weightings of corresponding observations. The grey shaded zone is the 95 % confidence interval. The horizontal dashed line is the zero line. Q_m is the part of heterogeneity (between-study variability explained soil fertility), and the larger its value, the greater the influence of soil fertility on the effect size. $P < 0.05$ indicates significant effect.

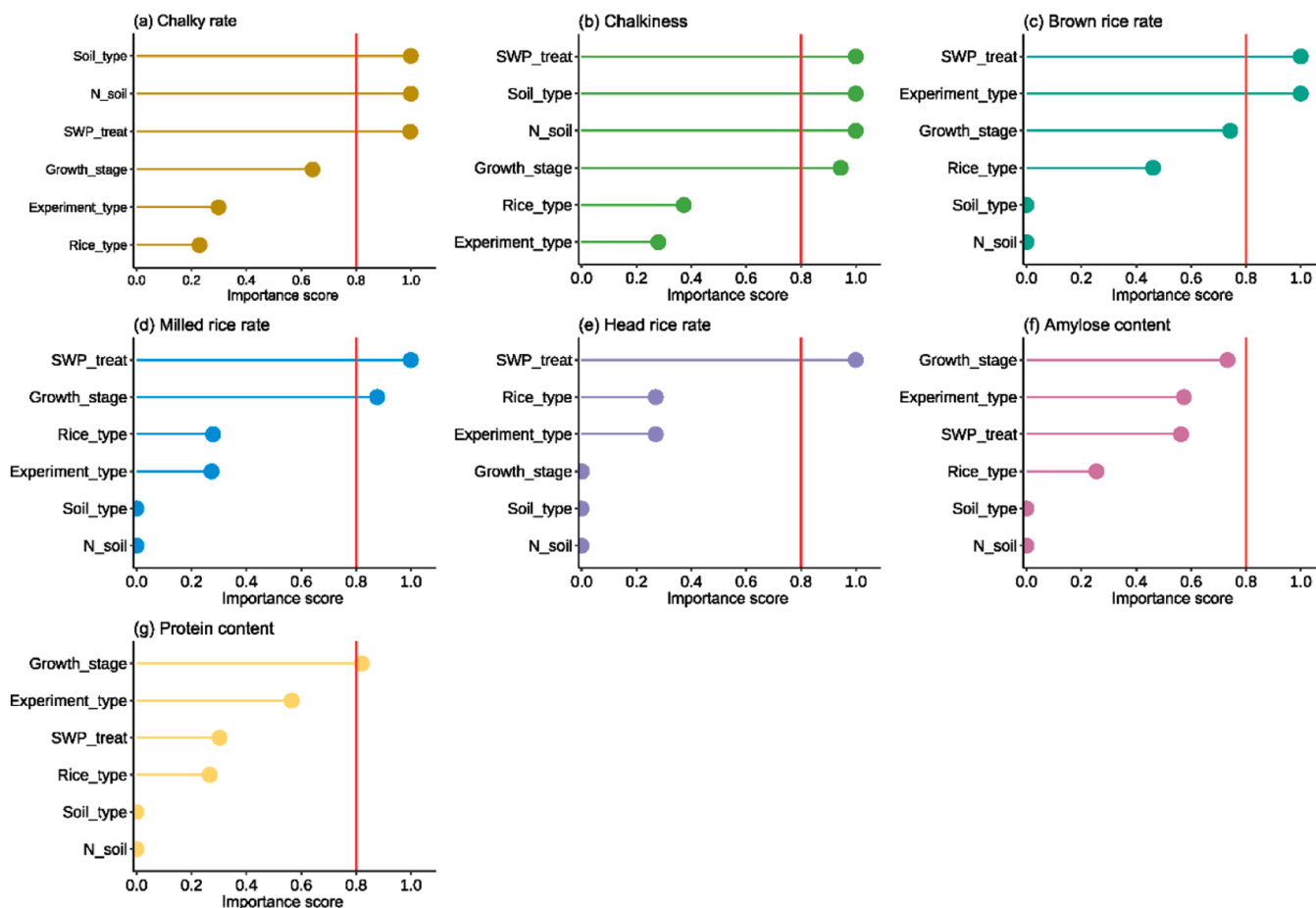


Fig. 7. Importance scores (AIC weights) of the most important regulatory factors for each quality trait. N_soil represents nitrogen content in soil. Soil_type represents soil types including clay, clay loam, sandy loam, paddy soil, brown soil, and yellow-brown soil. SWP_treat represents treatment soil water potential. Rice_type represents rice types including Indica rice and Japonica rice. Experiment_type represents cultivation types including Field experiments and Pot-grown. Growth_stage represents rice growth stages in water stress treatments. The importance of a factor greater than 0.8 indicates that the factor strongly contributes to explaining the variability of the quality trait under consideration.

of water stress effect of rice quality.

4.1. Impact on quality depends on rice growth stages of drought occurrence

Impact of water stress on rice quality was affected by different levels of water stress and by the period of drought occurrence (Chen et al., 2019). Ke (2010) reported that light water stress at tillering stage could improve milling quality to a certain extent. Light and medium stress at spikelet differentiation stage increases chalky rate, while medium and heavy stress at heading maturity stage significantly increases chalky rate. The present study showed similar results. Drought at tillering stage improved processing quality to some extent, even if not significant. The chalky rate increased significantly and the appearance quality deteriorated substantially when drought occurred at jointing and booting stage, heading and flowering and grain-filling stage (Fig. 4a). At the same time, the brown rice percentage, milled rice percentage and head rice percentage showed a decreasing trend, especially at the stage of jointing and booting (Fig. 4c-e).

Drought occurring in the middle stage of booting resulted in lower brown rice rate and flavor quality, while drought at the milk ripening and grouting stages led to a reduction in the head rice, and chalking rate and chalkiness increased significantly during the grouting stage (Wang et al., 2007). Water stress during rice flowering induced a decrease in head rice rate, an increase in chalkiness and chalky rate, an increase in protein content, and a decrease in amylose content, especially head rice

was most affected by water stress (Zheng and Li, 2017). Lv et al. (Lv et al., 2016) concluded that alternating wet and dry conditions during the whole growth period of rice improved milling quality, and that brown, milled and head rice rates were significantly higher than those of normal irrigation. On the contrary, our results showed that water stress during the whole growth stage significantly reduced the milling quality and appearance quality (Fig. 4a-e). However, the appearance quality was significantly improved from tillering stage to grain-filling stage.

Drought during the tillering stage occurs due to reduced uptake of soil moisture, resulting in limited nutrient reserve and decreased cell division in meristem tissues (Panda et al., 2021; Zubaer et al., 2007). During grain-filling stages, plants suffer from a reduction in photosynthesis rates and a decrease in assimilate transportation from source to sink (Cattivelli et al., 2008; Panda et al., 2021). Previous studies acknowledged that the grain-filling stage is a critical period for rice quality (You et al., 2017). Therefore, a light water stress at the tillering stage and adequate irrigation at the jointing and booting stage, heading and flowering stage, and grain-filling stage were beneficial to rice quality.

4.2. Effects of experiment types and soil conditions

We found that drought in field experiments did not have a large effect on rice quality. This may be due to the complexity of environmental factors and more uncontrollable factors in field trials. On the opposite, drought in pot experiments caused significant deterioration in

processing quality and appearance quality, and simultaneously increased protein content (Fig. 5a-e and g). The rice root system removed from the potting soil was cylindrical around the soil, whereas the one removed from the field was umbrella-shaped and dispersed. The pot experiments were subject to relatively fewer environmental influences and better reflected the effect of water stress on rice quality. The limited space of the potting soil hindered the divergent growth of the rice root system, which did not allow it to better absorb nutrients from the soil (Zhang et al., 2016). Different types of soils have different physicochemical properties, which have different impacts on soil water, fertilizer, air, heat and changes in soil nutrient content, and also have different effects on the growth and development of planted rice (Wang et al., 2012). Drought treatment in sandy loam soil significantly increased rice chalkiness, amylose content and protein content (Fig. 5b, f and g). In addition, we also found that the quality traits of rice grown in sandy loam soil were less responsive to drought, probably because sandy loam soil is permeable, easy to till, and quick to warm up, but also has high organic matter content and good fertilizer retention.

Nutrients for rice growth and development come from soil supply and artificial application, and the nutrients needed by rice are still mainly nitrogen, phosphorus and potassium, among which nitrogen promotes the effect is greater than phosphorus and potassium, but organic fertilizers on the growth of rice also have a greater role, which has been proved by numerous studies (Ding et al., 2009; Liang et al., 2009; Yang et al., 2023; Zhang et al., 2005). We found that an increase in N content decreased the effect of drought on chalky rate and chalkiness, while improving milled rice quality (Fig. 6a-e).

Soil water potential is the negative head pressure required to extract unit water from soil under isothermal conditions, which can reflect the degree of soil aridity; the drier the soil, the more negative is the water potential value. Based on the regression analysis of LnRR with soil water potential (Fig. 3), we found that light drought could improve the appearance quality and milling quality of rice to some extent, and increase the amylose content which could make rice softer and more sticky, while heavy drought had opposite effects. These findings were consistent with previous studies conducted at different scales. Liu et al. (Liu et al., 2012) applied alternating wet and dry treatments to rice at the fruiting stage and showed that mild wet and dry alternation reduced chalky traits and improved the appearance quality of rice, while heavy wet and dry alternation significantly increased chalky traits. Moderate drought at the fruiting stage reduced the chalkiness and extinction values and improved the quality of the rice, whereas the opposite was true for severe drought (Liu et al., 2008). Reasonable fertilization and suitable soil conditions can effectively improve the drought resistance of rice, and the combination of cultivation and irrigation control measures can increase the water-saving capacity of rice itself.

Soil water potential had a major influence on the effect of drought on rice milling quality, because soil water potential was directly related to the degree of drought (Fig. 7c-e). On the other hand, the protein content was mainly regulated by the rice growth stage (Fig. 7g). It has been shown that the translocation of photosynthetic products and nitrogen from plant to grain is the main reason for the increase in rice protein content (Desai and Bhatia, 1978). Adding to that, the increased grain protein concentration under drought could be explained by the shortened maturation time due to water stress, which tends to favor protein over starch accumulation in cereal grains (Wang and Frei, 2011).

4.3. Consequences of a reduced rice quality on practical use and marketability

Major factors determining the market value of rice are recognizable traits to consumers, including appearance and milling characteristics such as grain size, chalkiness, and color (Graham, 2002; Tomlins et al., 2007). Water stress significantly increased the chalkiness and chalky rate of rice grain, resulting in poor appearance quality. In the chalky parts of the grains, starch particles are separated by air spaces, making

grains more fragile during milling and starch less compact than in the large and tightly packed particles in the translucent areas (Fitzgerald et al., 2009; Lisle et al., 2000). By impacting aesthetic value of rice and the heading rice rate, water stress can reduce the market value of rice and consumer recognition. The economic value of broken rice is only 50–60 % of that of head rice (Neerja and Renu, 2019), which supports the huge impact that drought may have on the market by reducing the quality of milled rice. Changes in protein and amylose content caused by water stress will further affect the taste and cooking quality of rice, which mainly depends on consumer taste preferences. Therefore, it is important to develop drought-resistant rice varieties and formulate sustainable water management strategies to reduce the economic losses caused by rice quality deterioration.

4.4. Limitations and implications

Our publication bias analysis revealed that the risk of bias was small. Indeed, except for brown rice rate, the p-values of the funnel plots of the rice quality indicators were greater than 0.05 and did not reveal any significant publication bias (Figure S2). The calculation of the fail-safe coefficient values showed similar results. There are several limitations in our study. First, the dataset regarding the effect of water stress on rice quality is limited, and the sample sizes are too small for some variables or influencing factors to assess their effects accurately. For example, the effect of artificial fertilizer application was not considered in this study due to the small amount of data collected and the difficulty of standardization. Climatic factors such as relative air humidity and CO₂ concentration are not often described in enough details to allow for an in-depth statistical analysis. Second, rice varieties with different genotypes may have different sensitivity to water stress, but we were not able to assess the differences between genotypes due to data limitation. Third, most of the studies relied on pot experiments (n > 950) and the number of studies with field (n < 400) trials is limited. Consequently, essential factors such as spatial heterogeneity in growth and natural environmental variability may have been overlooked, potentially undermining the generalizability of the findings of the study. Nevertheless, the potted plant trials allowed for better control of the effect of water stress compared to field trials, which means that our results are unlikely to have been influenced by confounding effects. Although the results of the subgroup analyses conducted on the field experiment did not reach statistical significance, they exhibited similar trends for most quality indicators as those observed in the pot experiment.

There is thus a need for more field experiments relying on more uniform designs and protocols, over a wider geographic area to facilitate further research and to improve our comprehension of how drought affects rice quality on a larger scale. This will enable us to construct a comprehensive large-scale dataset reflecting the long-term effects of water stress on rice quality. Moreover, drought is often associated with high temperature, and the compound of drought and high temperature promotes the transport of amino acids and soluble proteins from the plant to the seed, thereby promoting seed protein synthesis (Gao et al., 2012; Jin et al., 2005). The deterioration of rice quality under both high temperature and drought was found to be greater than that under single stress (Duan et al., 2015, 2012). Thus, forthcoming studies should prioritize the impact of compound extreme weather events on rice quality.

5. Concluding remarks

In summary, we conducted a meta-analysis to evaluate the effects of water stress on seven rice quality traits under a variety of environmental conditions and management practices. We found that drought generally deteriorated the appearance and milling quality of rice, inducing an increase in chalky rate and chalkiness, and a decrease in brown, milled and head rice percentage, as well as leading to a significant increase in protein content. This analysis also emphasized the moderating role of soil conditions, with a strong influence of soil water potential revealing

that low water stress may improve appearance quality and milled rice quality, while strong water stress has negative effect on quality. Soil N content improved rice appearance quality to some extent and soil type was also an important factor. Appropriately reducing water inputs in the later stages of growth and selecting suitable soil conditions and fertilization measures for rice cultivation can not only save agricultural water, but also contribute to the improvement of rice quality.

Our findings make a substantial contribution to the understanding of how water stress impacts rice quality, particularly in the context of climate change and drought-exposed regions like China. Compared with existing studies, this study offers a more comprehensive analysis of several rice quality traits under water stress conditions. It further elucidates the mechanisms underlying changes in rice quality through the regulatory effects of factors including rice growth stage, rice type, experimental setup, and soil conditions. Our findings also underscore the urgent need for developing adaptive strategies to mitigate the detrimental effects of extreme weather events on rice quality, which is essential for sustaining high-quality agricultural production and ensuring global food security.

Author contributions

Xianfeng Liu designed the research. Shuhui Han carried out the literature search and extracted the data. Shuhui Han performed the meta-analysis with input from Xianfeng Liu and David Makowski. Xianfeng Liu, Philippe Ciais, and David Makowski contributed to the interpretation of the results and discussions, and Shuhui Han, Xianfeng Liu and David Makowski wrote the paper with the inputs from all co-authors.

CRedit authorship contribution statement

David Makowski: Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Philippe Ciais:** Writing – review & editing, Methodology, Conceptualization. **Shuhui Han:** Writing – original draft, Visualization, Software, Formal analysis, Data curation. **Xianfeng Liu:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agwat.2024.109230](https://doi.org/10.1016/j.agwat.2024.109230).

Data availability

Data will be made available on request.

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