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Is Wheat Yield Truly Low in Japan?: Examining Yield Formation Efficiency in Comparison With Northwest Europe

Shoko Ishikawa[1] | Takahiro Nakashima[2] | Martin C. Hare[3] | Peter S. Kettlewell[3]

[1]Central Region Agricultural Research Center, National Agriculture and Food Research Organization, Tsukuba, Japan | [2]Strategic Planning Headquarters, National Agriculture and Food Research Organization, Tsukuba, Japan | [3]Centre for Crop and Environmental Science, Harper Adams University, Newport, UK

Correspondence: Shoko Ishikawa (ishikawa.shoko192@naro.go.jp) | Takahiro Nakashima (nakashima.takahiro874@naro.go.jp)

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ABSTRACT

From a perspective of food security, the agricultural sector worldwide has a responsibility to improve crop yields. Wheat yield in Japan is about half that of high-yielding countries in Northwest Europe. Explanations offered so far—such as high temperatures and a rainy summer season shortening wheat's growth period, or comparatively underdeveloped breeding and cultivation techniques—remain speculative. This lack of clarity risks misdirecting research efforts on wheat cultivation in Japan and possibly other parts of the world. To address the issue, the present study focused on the efficiency of yield formation, rather than yield itself, across Japan and Northwest Europe. The efficiency of yield formation, derived from the division of actual yield by sunshine hours during the specific growth period from ear emergence to maturity, was compared between two geographical regions while factoring in climate variables. Despite the large yield difference, there was no significant difference in the efficiency of yield formation of wheat between the two regions. This indicates that Japan's low yield is largely due to climatic adversity for wheat, that is, high temperature, high precipitation and short sunshine hours during the critical growth phase for yield formation of the crop. The implication is that improvements in breeding and cultivation techniques alone are not likely to significantly increase wheat yield in Japan. A fruitful direction for future research endeavors in wheat production in monsoon Asia was discussed.

JEL Classification: C12, Q15, Q54

1 | Introduction

There was a time when sushi was the representative image of Japanese food. In recent years, it is possible to regard that ramen has taken over sushi's position if one listens to the voices of foreign visitors to Japan (Japan Tourism Agency 2023). Noodle dishes, including ramen, have long been eaten in Japan and are made from wheat (*Triticum aestivum* L.). Unlike rice that is almost self-sufficient in the country, a large part of wheat is imported from overseas, especially from the USA, Canada and Australia (Ministry of Agriculture, Forestry and Fisheries of Japan [MAFF] 2022). Attention has been drawn to the need for increasing domestic wheat production, partly due to the increase in the international wheat price influenced by the situation in Ukraine (MAFF 2023). According to the Food and Agriculture Organization of the United Nations [FAO] (2025), wheat yield in Japan was 4.69 $Mg\,ha^{-1}$ on average during 2019–2023, a lower value compared to those in Northwest Europe such as the United Kingdom (8.09 $Mg\,ha^{-1}$), Germany (7.51 $Mg\,ha^{-1}$), and the Netherlands (8.76 $Mg\,ha^{-1}$). Explanations offered so far from the Japanese side—such as high temperatures and a rainy summer season shortening wheat's growth period especially grain fill (Mizuochi 1988; Shiga 2003), or comparatively underdeveloped breeding and cultivation techniques (Sekine and Umemoto 2015)—remain speculative and lack robust scientific evidence. This is partly because these studies looked only at specific regions, mostly Hokkaido, the northernmost part of Japan. Viewing the issue on a broader scale, Ishikawa et al. (2024) found a climate-yield pattern across Japan and the UK that wheat yield was linearly decreasing in response to an increase in humidity expressed by the rainfall-evapotranspiration index, one of the indices that constitute a climate classification system called the Global Yield Gap Atlas-Climate Zonation Scheme (GYGA-CZS). Elucidating a cause of the large yield difference between the two countries remained unsolved, however. This may have something to do with the nature of the rainfall-evapotranspiration index, as it is derived from weather conditions on an annual basis rather than those related to wheat phenology (van Wart et al. 2013). The present study revisited the unsolved issue by focusing on weather conditions during a specific growth period of particular importance for the yield formation of wheat in humid environments.

Following a series of studies modelling photosynthesis of plant communities (Hirose 2005; Pearcy 1990), radiation use efficiency (RUE) has been studied intensively in a wide range of crops (Monteith 1977; Zhu et al. 2010). If grown in favourable environments, RUE across various C_3 species is known to fall within a relatively narrow range around $1.4\,g\,MJ^{-1}$ (Sinclair and Muchow 1999). Nevertheless, it is well known to those involved in crop breeding that an elite variety released from breeding programs is not necessarily grown in a favourable environment where its potential capacity can be exploited. It happens rather often that the released variety is hindered from achieving the expected range of RUE under adverse climatic events or sub-optimum growing conditions. RUE has therefore been used to compare the efficiency of crop cultivation among field experiments conducted in different parts of the world (Sinclair and Muchow 1999). Although leaf area index (LAI) is involved in the estimation of RUE, obviously it is not possible to obtain LAI from the crop grown in the past, an issue typically observed with historical yield records such as governmental statistical datasets. A question arises here if one is able to evaluate the efficiency of crop cultivation, or more specifically, the efficiency of yield formation in situations where RUE is not available. Murata (1964, 1975) introduced a variable derived from the division of actual yield (Ya) by solar radiation (SR) as an index to compare the efficiency of yield formation of rice in Japan. In short, Ya/SR was devised to standardise actual yield with the available resource that differs among 46 prefectures in the country stretching from north to south. Possibly because a crop canopy at an early growth period with a small LAI cannot intercept all of the available SR (Slafer et al. 2023), he adopted SR during the post-canopy closure of the crop. Unlike rice where 24%–27% of grain carbohydrate comes from the stored carbohydrate before anthesis (Cock and Yoshida 1972), the contribution during the pre-anthesis period has been recognised to be lower for wheat. Evans et al. (1975) argued that CO_2 assimilation after anthesis formed as much as 90%–95% of the carbohydrate in wheat grain. Bidinger et al. (1977) reported that the contribution to grain yield of pre-anthesis assimilate in wheat and barley was just 12% for watered crops. It is also notable that insufficient assimilate and nutrient supply can cause a significant reduction in floret number (Peltonen-Sainio and Peltonen 1995) therefore reducing yield. A steep reduction in competent florets per spikelet occurred in a short period of time from a few days before anthesis to anthesis (Fischer 2011; Fischer and Stockman 1980). This is a good reason why one needs to pay attention to the growth period around the heading stage for wheat (Fischer 2011). These observations suggest that one should focus on the SR intercepted by the crop canopy from heading onwards to address the efficiency of yield formation for wheat.

Using Ya/SR, Murata (1964, 1975) evaluated the efficiency of yield formation of rice in relation to mean temperature (MT) during the critical period for yield formation of the crop in Japan. Regression analysis showed that a convex-upward quadratic curve fitted well to the data with the maximum point at the MT of 21.5°C. Thus, Ya/SR decreased as MT departed from 21.5°C. He argued that Ya/SR went down when MT was below 21.5°C due to reduced carbohydrate translocation, and when MT was above 21.5°C it went down due to increased respiration, reduced leaf area and reduced photosynthetic activity accompanied by ageing. Hanyu et al. (1966) found that replacing SR with sunshine hours (SH) gave a similar result for the data of rice obtained from experimental stations distributed throughout the country. The quadratic curve obtained for Ya/SH reached the maximum point at the MT of 21.4°C, a very close value to Murata (1964, 1975). This suggests that the analysis can be performed using SH, which is readily accessible, implying a potential for its wider application. Applications of this approach have been found particularly with rice (Arai-Sanoh et al. 2022; Nagata et al. 2016); however, no application has been recognised with wheat. Given that wheat originates from a higher latitude than rice, the efficiency of yield formation of wheat is not likely to reach the upper limit in the range of temperatures observed in Japan. Also, considering the magnitude of adverse effects of rainfall on wheat yield in humid environments (Murakami et al. 2021; Shah et al. 2025; Song et al. 2019), it is a natural progression that the approach is extended to study an effect, if any, of mean rainfall (MR) during the growth period from heading to maturity of the crop. In the present study, we compared Ya/SH of wheat observed between two distant regions, that is, Japan and high-yielding countries in Northwest Europe, while examining if Ya/SH has a relationship with MT and with MR during the critical growth phase for yield formation of the crop. The principal results obtained here help us elucidate a cause of the large difference in wheat yields observed between Japan and Northwest Europe sharing humid climates, which is hoped to merit future research endeavour in wheat production in monsoon Asia.

2 | Materials and Methods

2.1 | Target Countries

Target countries were Japan and seven high-yielding countries selected from Northwest Europe where wheat yield exceeded greatly that of Japan during 2005–2020 (FAO 2025). The selected countries were Denmark, Ireland, the UK, Belgium, France, Germany and the Netherlands. There was no increasing or decreasing trend with wheat yield during the study period for each of the target countries, which is in accordance with the previous studies that observed stagnating wheat yield in Europe after the 1990s as well as in Japan after the early 2000s (Brisson et al. 2010; Calderini and Slafer 1998; Lin and Huybers 2012).

2.2 | Actual Yield

Ya (kg ha^{-1}) of wheat was collected from Global Yield Gap Atlas [GYGA] (2025) on a location basis for the high-yielding countries in Northwest Europe. Ya was averaged across years for each location, except for five locations in France (i.e., Marseille/Marignane, Melun, Montpellier, Perpignan, and Toulouse/Blagnac) as well as for three locations in Germany (i.e., Cottbus, Erfurt-Weimar, and Magdeburg). These eight locations are in relatively dry climates where the rainfall-evapotranspiration index (Aridity Index) in the GYGA-CZS is below six (GYGA 2025). As a result, these locations were excluded from analysis, as the present study focused on wheat grown in humid environments. For reference, Aridity Index is scored on a 10-point scale from zero to nine, where a smaller score corresponds to a drier climate (GYGA 2025; van Wart et al. 2013). It ranges from six to nine in the UK and from seven to nine in Japan (Ishikawa et al. 2024, 2020). The number of locations considered for Northwest Europe in the present study was 55 in total (see Figure S1 in Supporting Information for details).

As the yield of wheat in Japan has not been reported at GYGA (2025) yet, it was collected from MAFF (2024) on a municipality basis during 2005–2020, and was averaged across years for each municipality. In the protocol of GYGA (2025), crop yield from a given climate zone is added to the database only when the climate zone contains more than 5% of total national harvest area for the crop, which indicates an exclusion of minor production areas from the GYGA database. Furthermore, the protocol makes the database of each country contain more than 50% of national crop area, implying that nearly half of the production areas may have been excluded from the database. This is a good contrast that municipality-based wheat yield in Japan comes from all municipalities regularly growing wheat, which ensures inclusion of minor production sites. At the same time, Boogaard et al. (2013) argued that many wheat growers in France, Germany, and the UK practice near-optimum crop management and that yields in these countries are approaching the biophysical limit under rainfed conditions. Presumably, the selected countries in the present study other than France, Germany and the UK are in a similar situation, considering the level of wheat yields observed there. Unlike the near-optimum management practised in Northwest Europe, the management practices applied to wheat in Japan are thought to differ considerably among municipalities. This is because wheat yields in Japan range greatly from <1 t ha^{-1} to those exceeding 7 t ha^{-1} (Ishikawa et al. 2024). Such a wide range of yields is not observed for unsubsidised paddy rice (MAFF 2024). As to wheat in Japan showing great yield variability, it is rational to regard that quite a considerable number of farms are under the influence of subsidies paid to this crop (Nakashima and Ishikawa 2023). This leads to a situation where wheat is often grown with inadequate management. Based on the differences in the datasets described so far, the top 30% of high-yielding municipalities in Japan were subjected to analysis. The number of municipalities considered for Japan totalled 96. The municipalities mainly came from the Hokkaido (31%), the Kanto (26%) and the Kyushu regions (21%), which are located in the northern, central and southern parts of the country, respectively. In other words, the selected municipalities are mostly coincident with major wheat production areas in the country.

2.3 | Dates of Heading and Maturity

Heading and maturity dates of major wheat cultivars in Japan are available at MAFF (2019) on a prefecture basis every few years. Average dates of heading and maturity were obtained across years and cultivars for each prefecture during the analysis period. As to the UK, sowing date and days to ripening of major cultivars are available at Agriculture and Horticulture Development Board [AHDB] (2024) for experimental sites. Maturity date was obtained by adding the days to ripening to the sowing date for these sites and was averaged across years and cultivars for each site. The average date of maturity was aggregated to a county level. As to counties where maturity date was not obtainable from the data source, the maturity date of a neighbouring county was used. Heading date was calculated for counties, assuming the period from heading to maturity to be 64 days (AHDB 2023) except for Belfast/Aldergrove for which heading date was assumed to be 54 days before maturity date (Teasgasc 2024). As to Germany, heading and maturity dates were determined, referring to Lobert et al. (2023), for locations where Ya was collected. As to France, dates of anthesis and maturity were retrieved from Le Roux et al. (2024) for locations where Ya was collected, while dates of anthesis and maturity for locations in Belgium, Denmark, Ireland and the Netherlands were retrieved from simulated dates for wheat based on Boogaard et al. (2013). The use of simulated dates was justified by their remark that the simulated dates of anthesis and maturity closely resembled the observed crop calendars that were used for simulation. As the dates provided by Boogaard et al. (2013) were given in a 2-week range, specific dates were established in the present study by referring to other literature (Berghuijs et al. 2023; Montesino-San Martín et al. 2014; Olesen et al. 2000; Yara 2024). In cases where the date of anthesis was provided, heading date was calculated by subtracting 3 days from the date of anthesis, for 3 days coincide approximately with 50-degree days of cumulative temperature required for the growth stage of wheat to proceed from heading to anthesis (AHDB 2023).

2.4 | Weather Data

SH (h), MT (°C) and MR (mm d^{-1}) during the growth stage from heading to maturity of wheat were obtained by using the climatological normals, defined as 30-year averages, currently available. As for Japan, monthly normal values of sunshine hours, average temperature, and rainfall are available at Japan Meteorological Agency [JMA] (2025a) for the selected municipalities. Equations (1–3) show the calculation procedures of SH, MT, and MR, respectively, for an example where heading occurs in June and grain matures in August.

$$\mathrm{SH} = \alpha_{\mathrm{Jun.}} \frac{x}{30} + \alpha_{\mathrm{Jul.}} \frac{y}{31} + \alpha_{\mathrm{Aug.}} \frac{z}{31} \tag{1}$$

$$\text{MT} = \frac{\beta_{\text{Jun.}}x + \beta_{\text{Jul.}}y + \beta_{\text{Aug.}}z}{x + y + z} \quad (2)$$

$$\text{MR} = \frac{\gamma_{\text{Jun.}}\frac{x}{30} + \gamma_{\text{Jul.}}\frac{y}{31} + \gamma_{\text{Aug.}}\frac{z}{31}}{x + y + z} \quad (3)$$

where $\alpha_{\text{Jun.}}$, $\alpha_{\text{Jul.}}$, and $\alpha_{\text{Aug.}}$ are sunshine hours (h), $\beta_{\text{Jun.}}$, $\beta_{\text{Jul.}}$, and $\beta_{\text{Aug.}}$ are average temperature (°C), and $\gamma_{\text{Jun.}}$, $\gamma_{\text{Jul.}}$, and $\gamma_{\text{Aug.}}$ are rainfall (mm) in June, July, and August, respectively, and where x, y, and z are number of days (d) overlapped with the period from heading to maturity in June, July, and August, respectively (July is fully overlapped and therefore y is equal to 31 in this example). As to the UK, monthly normal values of sunshine hours, maximum temperature, minimum temperature, and rainfall are available at Met Office (2025) to fully cover the locations where Ya values were collected. Monthly normal value of average temperature was calculated from maximum and minimum temperatures prior to the calculation of MT in Equation (2). As to the other countries in Northwest Europe, monthly normal values of sunshine hours, average temperature, and rainfall were obtained at Climate-Data.org (2025).

2.5 | Statistical Analysis

Ya/SH was calculated in kg $\text{ha}^{-1}\,\text{h}^{-1}$ for each municipality in Japan and for each location in Northwest Europe and was analysed as follows. At first, Ya/SH was subjected to an analysis of variance (ANOVA) setting geographical regions (i.e., Japan and Northwest Europe) as a fixed factor. As the next step, Ya/SH was subjected to an analysis of covariance (ANCOVA) setting the geographical regions as a fixed factor and placing MT as a covariate. Similarly, another ANCOVA was performed placing MR as a covariate. These analyses aimed at testing whether there is a difference in Ya/SH between two geographical regions with or without considering the effects of climatic factors, MT and MR. Also performed were two-tailed independent t-tests to examine the difference in Ya, SH, MT, and MR between two regions. All statistical analyses were performed using SPSS Advanced Statistics (Ver. 28, IBM). The results were considered statistically significant at $p < 0.05$ unless specified otherwise.

3 | Results

Table 1 summarises the estimated mean and standard deviation of variables, that is, Ya, SH, MT, and MR, presented for Japan and Northwest Europe. As expected, Ya was significantly higher in Northwest Europe than that in Japan ($p < 0.001$) with Ya in the former being approximately twice that in the latter. SH was smaller by 41% in Japan than that in Northwest Europe ($p < 0.001$). MT was higher by 1.3°C in Japan than that in Northwest Europe ($p < 0.001$), and MR was greater by 64% in Japan than that in Northwest Europe ($p < 0.001$). Figure 1a shows the growth period from heading to maturity of wheat presented for countries in Northwest Europe and for regions in Japan. In Northwest Europe, the growth period from heading to maturity occurred mainly in June and July. As for Japan, a similar calendar was observed only in Hokkaido, the northernmost part of the country (Figure 1b). In the rest of the country, May was the major month forming the period between heading and maturity. The occurrence of heading was observed mostly in April, especially in the western part. It was also observed that the growth period of wheat from heading to maturity overlaps with the rainy season, when looking at the climatological normal (JMA 2025b), for four out of nine regions. Considering annual fluctuations in starting points of rainy seasons, it appears difficult even for the rest of the regions to be entirely free from the influence of rainy seasons.

Table 2 presents the results of ANOVA and ANCOVA on Ya/SH. For ANOVA, there was a significant effect of geographical region on Ya/SH ($p < 0.001$), indicating a higher efficiency of yield formation in Northwest Europe than in Japan. On the other hand, the effect of geographical region was insignificant ($p = 0.321$) when Ya/SH was adjusted by MT as a covariate in ANCOVA. There, MT had a significant effect on Ya/SH ($p < 0.001$). Similarly, adjustment of Ya/SH by MR made the effect of geographical region on Ya/SH insignificant ($p = 0.703$), with a significant effect of MR on Ya/SH ($p < 0.001$). As shown in Table 3, the unadjusted mean of Ya/SH in Northwest Europe was higher by 2.92 kg $\text{ha}^{-1}\,\text{h}^{-1}$ or 21% than that in Japan. The 21% advantage of Ya/SH in Northwest Europe, however, disappeared when the effect of MT was taken into consideration. Placing MR in the place of MT led to the same observation, that is, the disappearance of the advantage. These indicate that the difference in Ya between Japan and Northwest Europe is explainable by the differences in SH, MT and MR between the two geographical regions. As displayed in Figure 2a, regression analysis revealed a significant linear relationship between MT and Ya/SH across Japan and Northwest Europe ($p < 0.001$) with the linear coefficient and the constant term being −1.82 ($p < 0.001$) and 46.87 ($p < 0.001$) respectively. Similarly, a significant linear relationship was found between MR and Ya/SH ($p < 0.001$) with the linear coefficient and the constant term being −1.78 ($p < 0.001$)

TABLE 1 | Estimated mean and standard deviation (SD) of actual yield (Ya) of wheat and sunshine hours (SH), mean temperature (MT) and mean rainfall (MR) during the period from heading to maturity, presented for Japan, and Northwest Europe.

	Ya (t ha^{-1})		SH (h)		MT (°C)		MR (mm d^{-1})	
Region	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Northwest Europe	7.68	0.92	475	111	16.5	1.4	2.5	0.5
Japan	3.88	0.40	280	40	17.8	0.8	4.1	1.0
	***		***		***		***	

Note: ***, $p < 0.001$ (t-test between Japan and Northwest Europe).

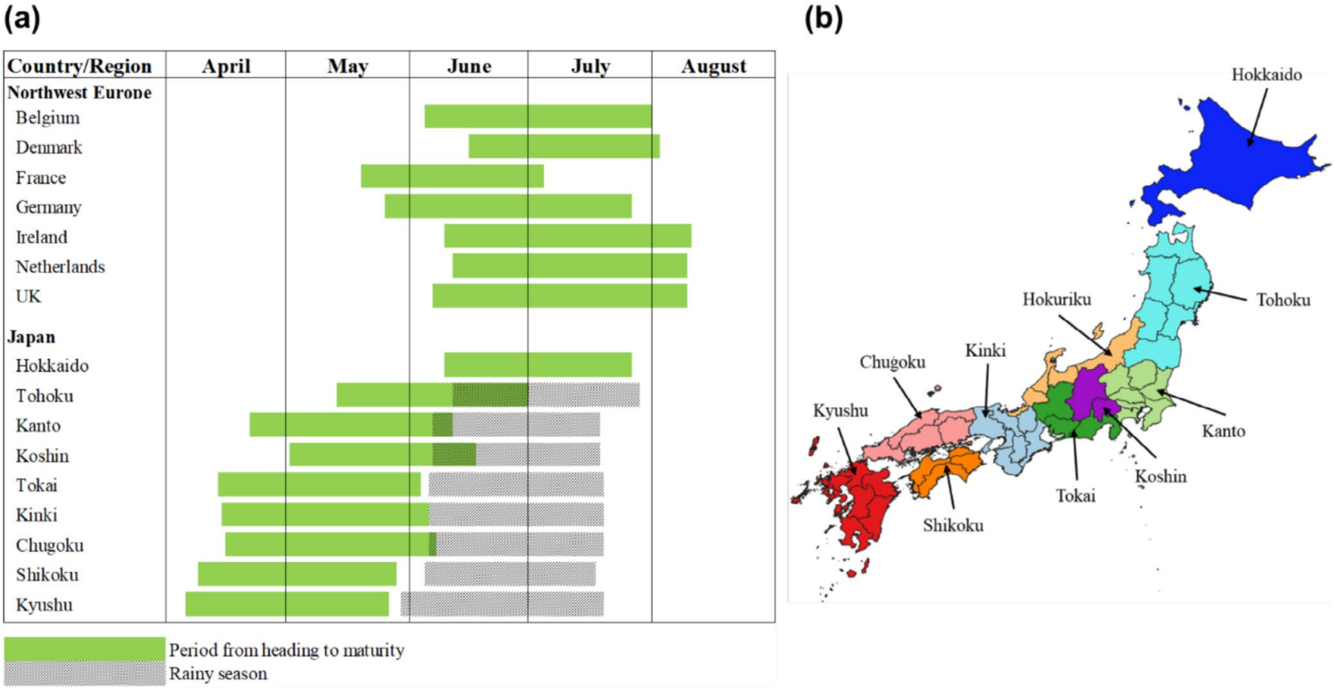

FIGURE 1 | Growth period from heading to maturity of wheat presented for countries in Northwest Europe and for regions in Japan (a) and map of regions in Japan (b).

TABLE 2 | Results of analysis of variance (ANOVA) on Ya/SH (kg ha^{-1} h^{-1}) and analysis of covariance (ANCOVA) with MT (°C) and with MR (mm d^{-1}).

Analysis	Source	SS	df	MS	*F*	*p*
ANOVA	Region	298.91	1	298.91	19.4	<0.001
	Error	2301.44	149	15.45		
ANCOVA	Region	12.35	1	12.35	0.99	0.321
	MT as covariate	459.14	1	459.14	36.89	<0.001
	Error	1842.30	148	12.45		
ANCOVA	Region	1.98	1	1.98	0.15	0.703
	MR as covariate	292.49	1	292.49	21.55	<0.001
	Error	2008.96	148	13.57		

Note: Ya, actual yield; SH, MT, and MR indicate sunshine hours, mean temperature, and mean rainfall, respectively, during the growth period from heading to maturity.
Abbreviations: df, degrees of freedom; MS, mean squares; Region, geographical region (Japan and Northwest Europe); SS, sum of squares.

TABLE 3 | Estimated means and standard error (SE) of Ya/SH (kg ha^{-1} h^{-1}) where unadjusted and adjusted values by covariates are presented for Japan and Northwest Europe.

	Unadjusted		Adjusted by MT		Adjusted by MR	
Region	Mean	SE	Mean	SE	Mean	SE
Northwest Europe	17.18 a	0.53	15.77	0.53	15.53	0.61
Japan	14.26 b	0.40	15.07	0.38	15.21	0.43

Note: Ya, actual yield; SH, MT, and MR indicate sunshine hours, mean temperature, and mean rainfall, respectively, during the period from heading to maturity. Region, geographical region (Japan and Northwest Europe); Different letters indicate statistically significant differences.

and 21.53 ($p < 0.001$), respectively (Figure 2b). These results tell us that the efficiency of yield formation of wheat can be plotted against MT and MR on the common straight lines across two geographical regions located far apart.

4 | Discussion

In the present study, we compared the efficiency of yield formation of wheat between Japan and Northwest Europe, inspired by Murata (1964, 1975) and Hanyu et al. (1966) where a convex-upward quadratic curve was observed between MT and the efficiency in rice. The challenging part of the present study lies in the consideration of MR in relation to Ya/SH of wheat. This was made possible by specifying the critical phase for

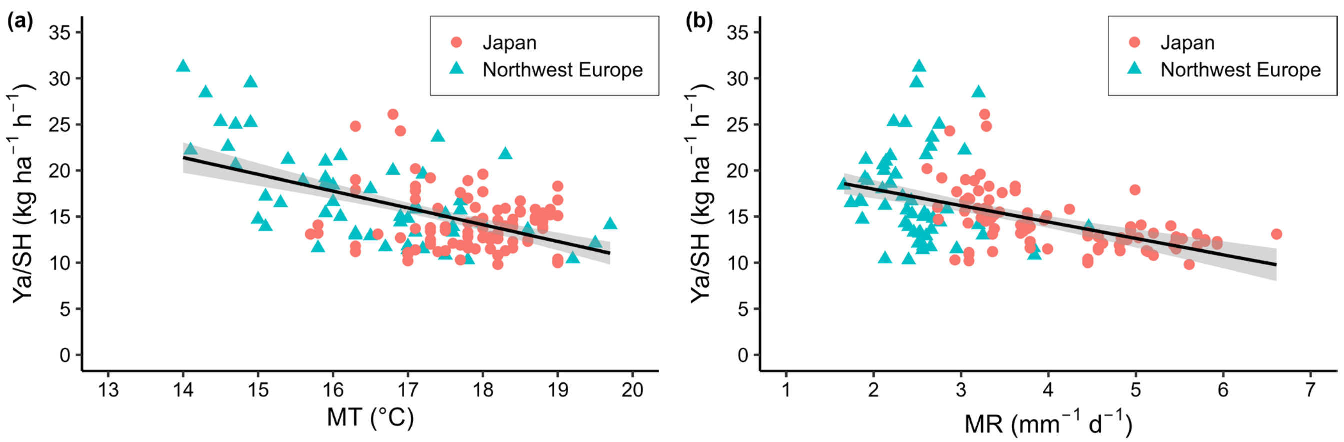

FIGURE 2 | Scatter diagrams with fitted regression line and 95% confidence interval band, depicting a negative linear relationship between MT and Ya/SH (a) and between MR and Ya/SH (b) across Japan and Northwest Europe. Ya, actual yield; SH, MT and MR indicate sunshine hours, mean temperature and mean rainfall, respectively, during the growth period from heading to maturity.

yield formation of wheat based on the published work (Bidinger et al. 1977; Evans et al. 1975; Fischer 2011). It has been shown in the results that while Ya of wheat in Northwest Europe was approximately twice that in Japan, Ya/SH was higher just by 21% in the former than in the latter. Thus, the apparent superiority with Northwest Europe has shrunk considerably when it comes to the efficiency of yield formation (see also Figure S2). This is obviously due to the shorter sunshine hours in Japan; however, it was not possible to overcome the geographical yield difference by considering the amount of available resource (i.e., sunshine hours) alone. Overcoming the yield difference was finally possible when the effect of the climate factors MT and MR was taken into consideration. This tells us that Japan's low yield is largely due to high temperature, high precipitation and short sunshine hours during the critical growth phase from ear emergence to maturity. It is rather fascinating to know that what we have been recognizing as a large yield difference between the two geographical regions is actually a manifestation of climatic adversity for wheat, which is a piece of knowledge possibly extendable to monsoon Asia where a hot and humid summer prevails.

Related to the decreasing trend of Ya/SH with a rise in MT, negative impacts of high temperatures during anthesis and preceding the period of ear formation on wheat growth and yield have been well documented (Asseng et al. 2015; Barlow et al. 2015; Semenov et al. 2014). It was reported that pollen sterility was induced by temperatures above 31°C immediately before anthesis (Porter and Gawith 1999) and that exposure to a temperature of 27°C during anthesis led to high proportions of sterile grains, resulting in yield losses (Wheeler et al. 1996). In addition, acceleration of grain development by high temperatures has also been documented where grain mass often gets to be reduced as a consequence of phenomena such as a shortened duration of grain fill and increased respiration (Nicolas et al. 1984; Posch et al. 2019). The cultivation of wheat is usually designed to avoid encountering such high temperatures around anthesis. For example, in Kyushu, the southern part of Japan, anthesis occurs in April (Figure 1), when the maximum temperature is around 20°C (JMA 2025a). If anthesis occurred in June there, as in Hokkaido, the northernmost part of Japan, the crop would encounter a temperature exceeding 27°C. In fact, it is not rare that even in April, the maximum temperature exceeds 27°C in the Kyushu region (JMA 2025a), which implies a difficulty in avoiding the occurrence of sterility entirely. In such an environment, it is desirable that wheat varieties are equipped with tolerance to high temperatures. It may not be surprising that this has already been achieved to some extent through wheat breeding programmes in Japan. As illustrated in Figure 2a, there were municipalities in Japan whose Ya/SH was comparable to or even greater than that observed with some of the locations in Northwest Europe, although MT in these municipalities was in a higher range compared to that observed with the mentioned locations in Northwest Europe (see also Figure S3). A similar advantage may exist in breeding programmes of Japan, considering that some sorts of tolerances to excess rainfall are likely to be developed under wet climates.

Adverse effects associated with excess rainfall during the period from heading to maturity of cereals make a list including reduced interception of solar radiation by the crop canopy, damage caused by soil anoxia, fungal diseases especially Fusarium head blight (Nóia Júnior et al. 2023), lodging (Easson et al. 1993; Shah et al. 2025), and pre-harvest sprouting (Song et al. 2019; Zeeshan et al. 2018). Song et al. (2019) reported that the grain yield of winter wheat in some of the wetter parts of China was mainly influenced by excess precipitation in May, which coincides with the grain fill period there. Located in the same geographical area, that is, monsoon Asia, similar problems have been witnessed in wheat cultivating areas in Japan (Nishio et al. 2024). Except for Hokkaido, the last phase of the wheat ripening period tends to overlap with the rainy season in June (Figure 1), despite managemental efforts to avoid the rainy season, for example, earlier harvest than planned. Apart from Murakami et al. (2021) who documented a negative linear relationship between wheat yield and rainfall from April to July in the Hokkaido region of Japan, the work by Shimoda et al. (2022) needs to be mentioned here. They pointed out a particular vulnerability of wheat florets to high humidity during anthesis in Hokkaido, which occurred possibly through fungal infection especially of Fusarium head blight, although they found it difficult to determine whether the decline in the number of fertile florets was due to humidity itself or to the promoted fungal growth by humidity. It is well known that abiotic stresses such as drought and extreme temperatures reduce the grain number of cereals such as wheat and rice (Dolferus et al. 2011); however, it is not very often that humidity itself is counted as a possible stress factor. Considering that humidity is also an abiotic factor that cannot be controlled, management measures such as the use of fungicides (Ishikawa et al. 2012) and breeding adaptive varieties (Mirdita et al. 2015) are of particular importance for yield formation of wheat to take place properly. It is noted that wheat yield has been stagnant in many parts of the world over the last couple of decades (Brisson et al. 2010; Hawkesford et al. 2013; Lin and Huybers 2012). Even high-yielding countries in Northwest Europe have been plagued by fungal diseases, as rainfall can adversely affect wheat yield through these diseases. Septoria diseases have been counted as the primary pathogenic constraint on wheat production such as in England and Wales (Polley and Thomas 1991) and in the Nordic-Baltic region (Jalli et al. 2020). Rainfall is closely related to these diseases, as inocula of pathogens present on the basal leaves of a crop canopy spread vertically by splashy rainfall (Lovell et al. 1997; Robert et al. 2018). For the time being, synthetic fungicide application is likely to remain the major method of disease control in intensive cereal cultivation, although alternative methods have been explored (Deliopoulos et al. 2010; Singh et al. 2016). Otherwise, breeding resistant varieties to lodging (Acreche and Slafer 2011) and pre-harvest sprouting (Mares and Mrva 2014) helps deal with the issue of high humidity.

As to the speculation that breeding and cultivation techniques of wheat in Japan lag behind those in West Europe (Sekine and Umemoto 2015), this is not necessarily the case. As already shown in the present study, Japan's low yield is largely due to climatic adversity for the crop. Furthermore, given that Norin 10, the semi-dwarf wheat cultivar bred in Japan, contributed significantly to the yield improvement of wheat varieties in the Green Revolution (Borojevic and Borojevic 2005; Waines and Ehdaie 2007), it is not very sensible to assume that the breeding environment in Japan has been less favourable than that in other countries. Yet, it is noted that there have been reported cases where some varieties of cereals adopted from other countries outperformed local cereal varieties (de Lima et al. 2021; Yoshihira et al. 2000). As to wheat breeding in Japan that is undertaken by public institutions, the technical standards of breeding are considered to reach a comparable level regardless of geographical locations. Still, with wheat's place of origin being in a relatively cool and dry climate, wheat breeding in hot and humid southwestern regions may present a greater challenge compared to that in northeastern regions of the country. In Japan, wheat breeders have long been pursuing the trait of earliness to avoid the hot and humid summer (Hoshino and Seko 1996; Shimoda et al. 2022). The need to pursue earliness in wheat breeding is, however, not confined to monsoon Asia where a hot and humid summer prevails. Earliness of wheat is also required in places like Mediterranean countries where heat and dryness in summer must be avoided (Araus et al. 2002; Mondal et al. 2013; Tewolde et al. 2006). It is noteworthy that the trait of earliness in wheat has been utilised to avoid contrasting climatic risks, that is, dryness and humidity. The Transnational Nordic-Baltic collaboration is a network that has put cooperation in the field of wheat breeding at the forefront to promote sustainable cultivation of wheat in the Baltic region (Chawade et al. 2018). Such a collaboration may benefit regions requiring the trait of earliness in wheat including the ones where there is a future need to avoid high temperature and drought due to climate change (Mphande et al. 2020; Rezaei et al. 2018). When it comes to collaboration, one might also need to consider how soil differences would affect wheat yields. As to wheat production in Japan, we consider that soil factors have a relatively small influence on wheat yield compared to climate factors. This is based on our observation made in our previous work (Ishikawa et al. 2024), where wheat yield in upland fields highly correlates with that in paddy fields located in the same municipality. Considering that soil types differ greatly between upland and paddy fields in Japan (Obara et al. 2015), it was thought to be a natural consequence that we placed emphasis on climatic factors in the present study.

Finally, we would like to mention the functional form fitted in the present study to explain the relationship between MT and Ya/SH for wheat. As shown in Figure 2a, the efficiency of yield formation is monotonically decreasing in the range of mean temperature observed in Northwest Europe and Japan. Even the range of mean temperature between 14°C and 15°C was not low enough to reduce the efficiency of yield formation of wheat. This is in contrast with the observation for rice where the efficiency was reduced by the temperature below 21°C (Hanyu et al. 1966; Murata 1964, 1975). It is not surprising that the temperatures favoured by wheat and rice differ greatly, considering the climatic difference in the places of origin for these crops. As shown in the results, Ya/SH of wheat was decreasing at a constant rate of 1.82 $kg\,ha^{-1}\,h^{-1}$ with a temperature increase of 1°C, and the rate of decrease in Ya/SH of wheat caused by rainfall was also constant, 1.78 $kg\,ha^{-1}\,h^{-1}$ per 1 mm of mean rainfall. The common straight line established across Japan and Northwest Europe in the present study is potentially usable as a reference to diagnose the efficiency of yield formation of wheat at various locations in humid environments. If Ya/SH at a given location is plotted far below the line, there is likely to be room to increase the efficiency of yield formation through improved breeding and/or agronomic practices. In other words, an observation of low yield alone may not justify intensive investment in breeding and cultivation techniques for high yields. Such an investment is likely to be more fruitful to a region that is characterised by low efficiency of yield formation as well as low yield. The idea of diagnosing a production site based on efficiency of yield formation as described so far may offer a hint as to the potential direction of future research endeavour in the field of crop science. Given concerns about global warming and the consequent impacts on crops in many parts of the world, it is tempting to extend the consideration of efficiency of yield formation to drier regions in the future.

5 | Conclusion

In the present study, the efficiency of yield formation was compared for wheat between Japan and high-yielding countries in Northwest Europe, two geographical regions in humid environments. There was no significant difference in the efficiency of yield formation between the two geographical regions when the effect of temperature and rainfall during the growth period from heading to maturity was taken into consideration. This suggests that the inferior wheat yield in Japan is largely attributable to climate adversity, that is, high temperature and severe rainfall as well as less availability of solar radiation during the critical growth phase for yield formation of wheat. In other words, wheat yield in Japan is not low and is even comparable with that in Northwest Europe when considering the climatic factors. The piece of this knowledge obtained in the present study helps us allocate research resources efficiently to strengthen food security in monsoon Asia.

Author Contributions

Shoko Ishikawa: writing – review and editing, writing – original draft, validation, methodology, formal analysis, conceptualization. **Takahiro Nakashima:** writing – review and editing, writing – original draft, supervision, project administration, methodology, funding acquisition, conceptualization. **Martin C. Hare:** writing – review and editing, conceptualization. **Peter S. Kettlewell:** writing – review and editing, conceptualization.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are publicly available, and the references are properly given.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Locations of target countries in Northwest Europe whose Ya was subjected to analysis in the present study. Ya, actual yield. **Figure S2:** Scatter diagrams of Ya of wheat against MT (a) and against MR (b) across Japan and Northwest Europe. Ya, actual yield; MT and MR indicate mean temperature and mean rainfall, respectively, during the growth period from heading to maturity. **Figure S3:** Duplicate figure from Figure 2 that illustrates municipalities in Japan achieving comparable levels of Ya/SH to Northwest Europe in a higher range of MT (a) and MR (b). For example, Ya/SH of the blue-circled municipalities reaches approximately 25 $kg\,ha^{-1}\,h^{-1}$ at the MT range between 16.3°C and 16.9°C, while the comparative level of Ya/SH is achieved in Northwest Europe between 14.5°C and 14.9°C.