A common climate–yield relationship for wheat and barley in Japan and the United Kingdom

by Ishikawa, S., Nakashima, T., Hare, M.C. and Kettlewell, P.S.

DOI link to the version of record on the publisher's site

Ishikawa, S., Nakashima, T., Hare, M.C. and Kettlewell, P.S. (2024) 'A common climate–yield relationship for wheat and barley in Japan and the United Kingdom', *Climate*, *12*(8) article number 125.

climate

Article

A Common Climate–Yield Relationship for Wheat and Barley in Japan and the United Kingdom

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

[1] Central Region Agricultural Research Center, National Agriculture and Food Research Organization, 2-1-18 Kannondai, Tsukuba 305-8666, Japan
[2] Strategic Planning Headquarters, National Agriculture and Food Research Organization, 3-1-3 Kannondai, Tsukuba 305-8604, Japan
[3] Centre for Crop and Environmental Science, Harper Adams University, Newport TF10 8NB, UK
* Correspondence: shokoish@affrc.go.jp (S.I.); tnakasim@affrc.go.jp (T.N.)

Abstract: Wheat and barley yields in Japan are considerably lower than those in the UK, even where similar Climate Zones (CZs) of relatively cold and humid nature are shared. In order to understand this difference, it is first necessary to find out if any common climate–yield relationship exists between the two countries. The Climate Zonation Scheme (CZS) developed in the Global Yield Gap Atlas (GYGA) was used to analyse actual yield (Ya) with three climatic factors of the GYGA-CZS, i.e., growing degree days (GDD), aridity index (AI) and temperature seasonality (TS). A significant relationship was found between AI scores and Ya values across the two countries. Ya values decreased with an increase in AI scores; in other words, lower yields are associated with higher AI scores. In addition, the degree of yield reduction with the rise in AI scores was greater in Japan than in the UK. The present study also proposed a novel method to link CZs of the GYGA-CZS to regional classification units, especially for countries where statistical crop yield data are available only at a coarse scale.

Keywords: climate classification; Global Yield Gap Atlas (GYGA); growing degree days; aridity index; temperature seasonality; spatial framework; municipality; upland; paddy; rice

Citation: Ishikawa, S.; Nakashima, T.; Hare, M.C.; Kettlewell, P.S. A Common Climate–Yield Relationship for Wheat and Barley in Japan and the United Kingdom. *Climate* **2024**, *12*, 125. https://doi.org/10.3390/cli12080125

Academic Editor: Nektarios Kourgialas

Received: 28 June 2024
Revised: 9 August 2024
Accepted: 12 August 2024
Published: 20 August 2024

1. Introduction

Despite being known as the Land of Rice Plants (*Mizuho no Kuni*), Japan has a long history of producing cereals other than rice. Wheat cultivation in the country dates back to B.C. [1]. Government statistics show substantial production of wheat and barleys in the 1880s [2]. The production of wheat increased steadily and stayed high until 1961. During this period, wheat was mostly produced in prefectures other than Hokkaido, the farthest north region of the country. In the following decade, wheat production fell by nearly 90%. This was partly caused by lower yield and lower yield stability of wheat, leading to poorer profitability compared to rice. After the mid-1970s, the Hokkaido region started to become a significant wheat producer [3,4]. In recent statistics, approximately 65% of domestic wheat production comes from the Hokkaido region: 677,700 tonnes (t) from 121,400 hectares (ha) as of 2020 [2]. The average yield of wheat in the Hokkaido region is 5.58 t ha^{-1}, which is 40% higher than the average yield of 3.98 t ha^{-1} in the rest of the wheat-growing regions [2].

Wheat yields in Japan, even in the Hokkaido region, are not as high as those in high-yielding countries, such as in many European countries. For example, in the UK, known as one of the high-yielding countries, wheat yield is approximately 1.6 times greater than that in Japan as of 2020 [5]. A question is raised if wheat yields in Japan, especially in the Hokkaido region, can reach the level of wheat yields achieved in the UK and other European countries [6]. By examining various aspects including climate, breeding and management of wheat production in Europe and Japan, a suggestion is made that high temperature and heavy rainfall in summer are major factors hindering high yields in

Japan [6]. This is convincing, considering that high temperature shortens grain filling period and hinders high yields [7,8] while heavy rainfall during grain filling period can have adverse effects on yield through infection of Fusarium head blight, lodging and pre-harvest sprouting [9–11]. The suggestion previously mentioned [6] is also consistent with the United States Department of Agriculture crop calendar [12] that shows a large difference in the harvest window of winter wheat between Europe and East Asia. While the harvest window of wheat in a large part of European countries falls in July and August, it mostly falls in June in East Asian countries.

According to the Köppen–Geiger climate classification system [13,14], the UK falls into climate group Cfb, meaning marine west coast climate, while Japan mostly falls into four groups, i.e., Dfa, Dfb and Dwb, meaning humid continental climate and Cfa, meaning humid subtropical climate [15]. Interestingly, a recent reappraisal study of the Köppen–Geiger system has revealed that some areas in the Hokkaido region and its southern neighbour (i.e., the Tohoku region) belong to Cfb, the same climate group observed in the UK [16]. Similar situations are observed with the climate classification system developed in the Global Yield Gap Atlas (GYGA) [17,18]. The climate classification system called the GYGA–Climate Zonation Scheme (GYGA-CZS) updates its predecessors, e.g., [19,20], enabling a finer categorization of climates in the world [18]. In the GYGA-CZS, world climate is theoretically classified into 300 Climate Zones (CZs), six CZs of which are shared by Japan and the UK. These clearly indicate that there are similarities in climate between the two countries. Perhaps related to this, the harvest window of wheat in some areas of northern Japan, particularly in the Hokkaido region, can be late July and early August [21]. Surprisingly, there are unignorable differences in wheat yields even in similar CZs between Japan and the UK [2,17]. Here, a question arises how we are to interpret this phenomenon. The point previously raised that the yield differences between Hokkaido and the UK are due to climatic factors [6] needs to be re-examined in a more detailed manner. As already mentioned, high temperature and heavy rainfall in summer are regarded as major factors hindering high yields in Japan [6]. If this speculation is correct, yields are supposed to be poor in regions of warm and humid climates. Would one then obtain the highest yields in cool and dry regions? If so, how do yields decrease in response to a change in climates as the location proceeds from north to south? The present study aims at finding if there is any climate–yield relationship valid for a whole country.

The GYGA project, led by van Ittersum et al. [22], estimates yield gaps of major staple crops at a regional and national scale in order to address global food issues. They report actual yields (Ya) of crops for CZs and estimate yield gaps based on the difference between potential yields and Ya values [17]. The yield gaps estimated for CZs are aggregated to a regional and country scale to explore room for increased production. Given the role of CZs as aggregating units, it is not surprising that many GYGA-related studies have a tendency to emphasise the GYGA-CZS as an aggregation tool [17,23,24]. One may, however, wonder why yield-related values such as yield gaps and Ya values are reported for CZs. Is it not because an assumption has been implicitly made that crop yields are affected by individual CZs in a systematic manner? There is little reference to the implicit assumption behind the use of the GYGA-CZS. Ishikawa et al. [25] is probably the first study that attempted to articulate and test the implicit assumption, using Ya values of irrigated paddy rice in Japan. They found that using climatic factors defined in the GYGA-CZS enabled them to identify favourable areas for high- and stable-yielding rice production. The present study is a sequel to the previous study [25] and attempts to re-examine the suggestion previously put forward [6], this time focusing on wheat and barleys. The main objective of the present study was to statistically analyse Ya values of wheat and barleys in Japan and the UK within the GYGA-CZS to find out if any common climate–yield relationship exists between the two countries. The principal results obtained here include the findings of a common climate–yield relationship between Ya value and humidity related to precipitation and evapotranspiration across the two countries, and of a greater effect of humidity on Ya value in Japan than in the UK. With further research, information on this relationship might help us understand why wheat and barley yields in Japan are considerably lower compared to those in the UK and other high-yielding countries.

2. Materials and Methods

2.1. GYGA–Climate Zonation Scheme

The GYGA-CZS is made of approximately 10 km × 10 km grid-cells of various CZs expressed as four- or five-digit integers. The size of the grid-cells is in accordance with the agricultural inventory datasets presented by Ramankutty et al. [26] at 5 min spatial resolution in latitude by longitude. A CZ consists of three elements, i.e., growing degree days (GDD: an index to address temperature), aridity index (AI: an index to address precipitation and evapotranspiration) and temperature seasonality (TS: an index to address annual temperature range). GDD and AI are scored on a 10-point scale from one to ten and from zero to nine, respectively. A smaller score of GDD corresponds to a colder climate, and a smaller score of AI corresponds to a drier climate. TS is scored on a 3-point scale from one to three, where a smaller score corresponds to a smaller annual temperature range. The combination of the three elements theoretically creates 300 different CZs. In a CZ identified as a four- or five-digit integer, GDD, AI and TS scores are placed in the thousands place, hundreds place and ones place, respectively, of the integer. For example, the CZ identified as 2903, hereafter referred to as CZ2903, has a GDD score of two, an AI score of nine and a TS score of three, indicating a cool and wet climate with a large variation in temperature over the course of the year. A more detailed explanation of the GYGA-CZS can be found elsewhere [17,18].

2.2. Linkage of Climatic Zones to Crop Yields

2.2.1. Japan

The key to achieving the objectives of the present study is to link CZs to available yield data as much as possible for statistical analysis. The standard protocol in the GYGA project to link CZs to yield data is to take a 100 km buffer zone around a selected reference weather station [17,24]. This protocol works well in countries where topography is relatively homogenous, in other words, where a given CZ covers a large area [24]. It can also be applied to countries where yield data are not readily available for administrative divisions [27]. It is, however, not necessarily suitable to countries like Japan which are mountainous and covered by a large number of CZs for their size [25]. In addition, yield data are available at a municipality scale in Japan [2]. In such a case, it is reported that the standard protocol of taking a 100 km buffer zone has a risk of losing a large quantify of yield data [28].

In the present study, following our previous study [25], municipality-based Ya values were linked to grid-based CZs. The linkage was apparent when a municipality was covered by a single CZ. When a municipality was covered by multiple CZs and when one of the CZs was dominant, the dominant CZ was linked to the municipality. When it was difficult to recognise a dominant CZ, the municipality was not related to any CZ and was excluded from the analysis. Out of 1718 municipalities in Japan today [29], 1461 municipalities were allocated to CZs. By linking municipalities to CZs, GDD, AI and TS scores corresponding to the municipalities are determined as a natural progression. In the GYGA-CZS, there were 23 different CZs in Japan, 19 of which are presented in Figure 1a. The four CZs not shown in Figure 1a are those in southern islands, i.e., CZ7901, CZ7902, CZ8901 and CZ8902, and were excluded from the analysis due to less relevance to wheat and barley production [2]. Also excluded were CZ1803, CZ1902, CZ3802 and CZ4703 due to their small shares (<0.1%). In total, 15 CZs were employed for the analysis in the present study (Figure 1b).

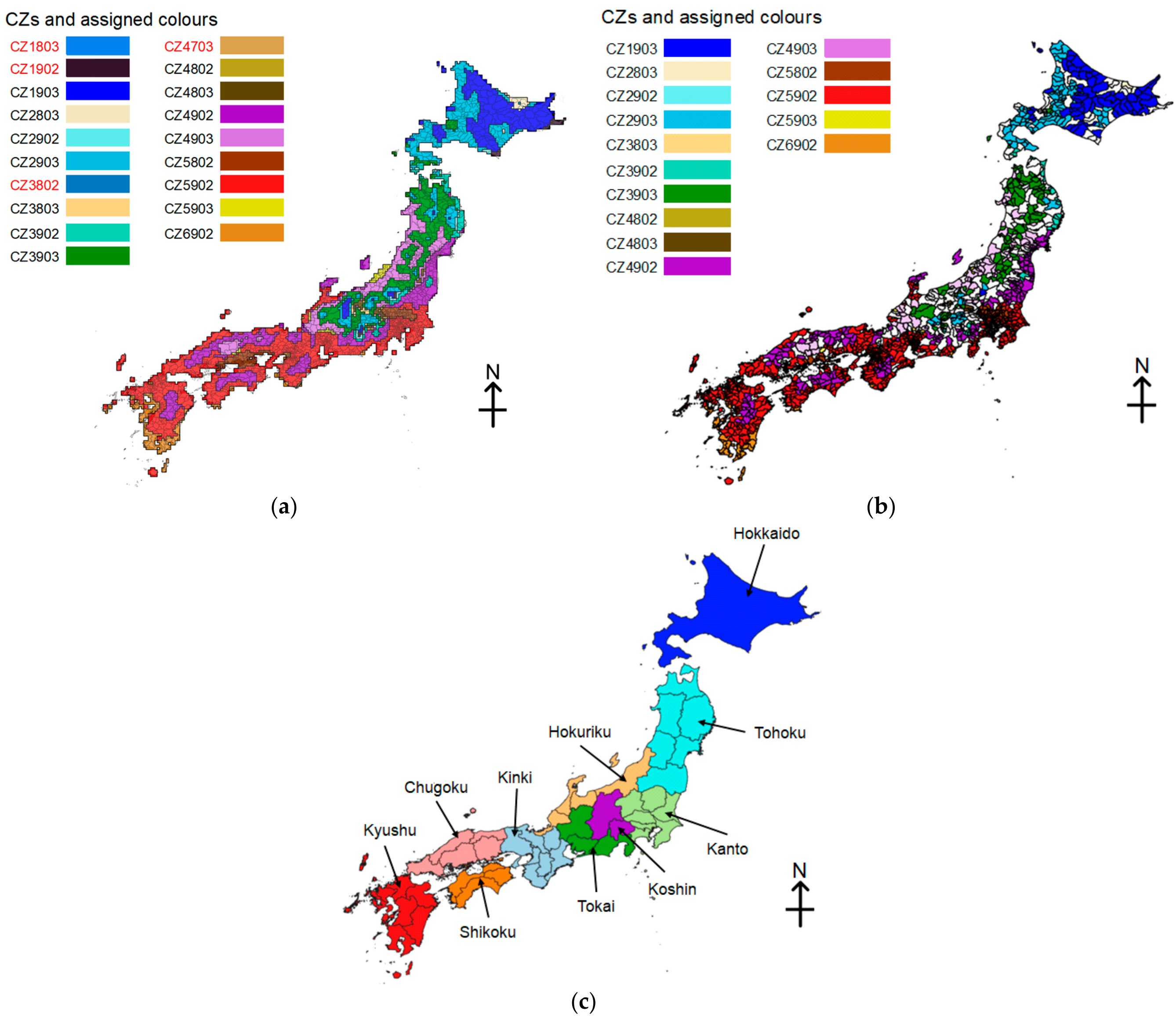
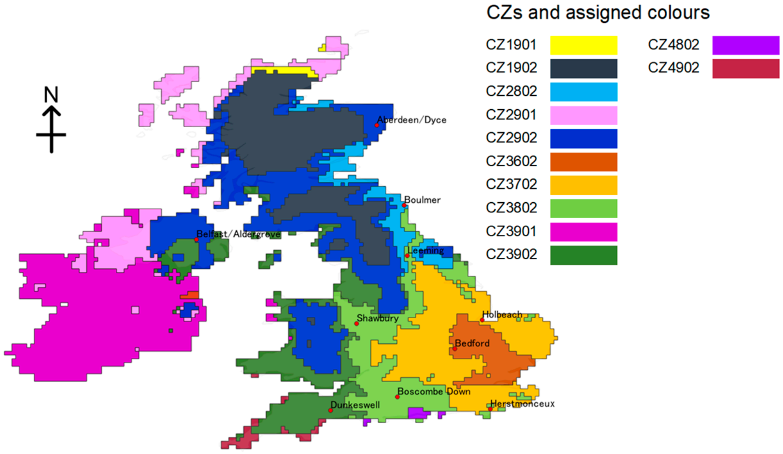


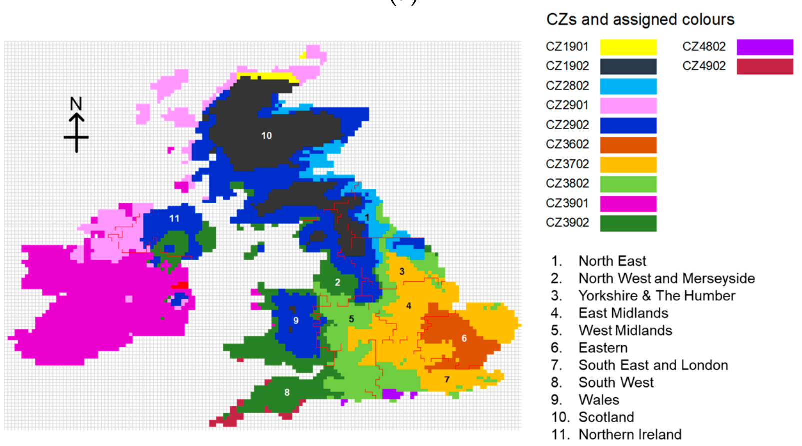
Figure 1. Original map of CZs in Japan expressed on a grid-cell basis of GYGA–Climate Zonation Scheme (**a**), map of CZs linked to municipalities (**b**) and regions of Japan (**c**). CZ, climate zone; CZs in red letters in the legend are excluded from analysis.

2.2.2. The United Kingdom

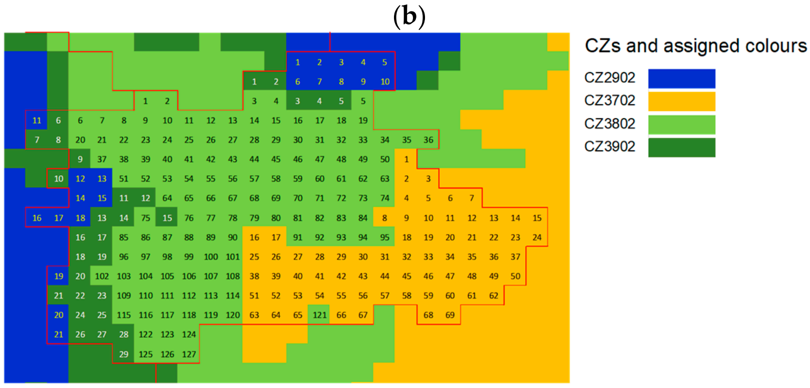
As shown in Figure 2a, the UK has 12 CZs on a land area roughly two-thirds the size of Japan. Unlike in Japan, yield data of wheat and barley are available only at a coarse scale of 11 geographical regions [30]. The average area of one region in the UK is approximately 100 times larger than that of one municipality in Japan. As speculated, all regions in the UK have multiple CZs and a dominant CZ was difficult to recognise in many regions. Excluding these regions from the analysis would lead to a serious loss of the coverage of yield data, which is against the key principle mentioned earlier. In the present study, an alternative protocol was proposed to link CZs to regions in the UK.



(**a**)



(**b**)



(**c**)

Figure 2. Original map of CZs in Great Britain and the island of Ireland expressed on a grid-cell basis of GYGA–Climate Zonation Scheme (**a**), map of CZs reproduced on a spreadsheet (**b**) and enlarged map of West Midlands (**c**). CZ, climate zone; different colours indicate different CZs. Red dots in the map indicate locations whose actual yield values were retrieved from Sylvester-Bradley et al. [31].

First, grid-cells of the GYGA-CZS were reproduced using a spreadsheet software, Excel (Ver. 2402, Microsoft), by setting up the spreadsheet cells to have the same length and width (Figure 2a). Figure 2b shows the reproduced map of Great Britain and the island of Ireland, where the regional boundaries were drawn while referring to the UK map superimposed on the GYGA-CZS with a geographic information system, QGIS Desktop (QGIS Development Team). Then, the number of grid cells was counted for CZs in a given region. Based on the counting results, weighted average values of GDD and AI scores were calculated for each region. For example, Figure 2c shows the enlarged map of West Midlands, where the number of spreadsheet cells totalled 246. Counting the cells in different colours, 21, 69, 127 and 29 cells correspond to CZ2902, CZ3702, CZ3802 and CZ3902, respectively. Counting the spreadsheet cells gives the shares of GDD scores of two and three as well as those of AI scores of seven, eight and nine. The shares of the spreadsheet cells with the GDD score of two and those with the GDD score of three accounted for 21/246 and 225/246, while the shares of spreadsheet cells with the AI score of seven, those with the AI score of eight and those with the AI score of nine accounted for 69/246, 127/246 and 50/246, respectively. Weighted by these weights, the average value of GDD was calculated as $(21/246) \times 2 + (225/246) \times 3$, and the average value of AI was calculated as $(69/246) \times 7 + (127/246) \times 8 + (50/246) \times 9$ in West Midlands (see Figure S1 in Supplementary Materials for all regions). Being weighted average values, the calculated GDD and AI scores are not necessarily expressed as integers as provided by the GYGA-CZS. The weighted average values of GDD and AI scores are hereafter referred to as representative GDD and AI scores for simplicity. It should be noted that TS scores were excluded from the analysis related to the UK, as one of the two TS scores found there (i.e., the TS score of two) occupies most of the country (Figure 2a). The TS score of one was found mainly along coastal lines (e.g., the north and west coasts of Scotland) and in relatively small shares in the UK (Figure 2a). For comparison, representative GDD and AI scores were also calculated for the Hokkaido, Kanto and Kyushu regions of Japan (Figure S2 in Supplementary Materials).

2.3. Yield Data Collection

Yield data were collected following the actual yield protocol of GYGA, where the use of actual yield data over a period of 5–10 years is recommended [17]. In Japan, wheat and barleys are grown not only in upland fields but also in drained paddy fields. They are often grown in paddy fields as secondary crops for rice cultivation or as a part of agricultural policy for reducing rice acreage [32,33]. Ya values of wheat and three types of barley (i.e., two-row, six-row and naked) are available at a municipality scale, separately for upland and paddy fields, from 2010 onwards [2], and yield data during the period of 2010–2020 were used in the present study. The dataset that consists of the four crops with separate Ya values for upland and paddy fields is referred to the dataset JP (Table 1 and Table S1 in Supplementary Materials for more details). Another dataset, the dataset JP_{wheat} was extracted from the dataset JP so that it solely consisted of Ya values of wheat produced in upland fields (Table 1). Spring wheat is cultivated in a part of the Hokkaido region, accounting for 7.4% of the wheat producing area of the country [34]. Similarly, spring barley is cultivated in Hokkaido, the share of which is less than 3% of barley cultivated in the country [34]. Yield data of spring wheat and barley are inseparable from those of winter wheat and barley in the data source [2].

Table 1. Datasets of Ya [1] values prepared for the analyses in the present study.

Dataset	Crop				Field	Period	Unit Assigned to CZ [5]	*n*	Data Source
	Wheat	T-Barley [2]	S-Barley [3]	N-Barley [4]					
Dataset JP	✓ ✓	✓ ✓	✓ ✓	✓ ✓	Upland Paddy	2010–2020	Municipality	5245 8348	[2]
Dataset JP_{wheat}	✓				Upland	2010–2020	Municipality	3748	[2]
Dataset UK	✓	✓	✓		Upland	2005–2020	Region	352	[30]
Dataset UK_{wheat}	✓				Upland	2005–2015	Experimental station	143	[17]

[1] Ya, actual yield; [2] T-Barley, two-row barley; [3] S-Barley, six-row barley; [4] N-Barley, naked barley; [5] CZ, climate zone.

Ya values of wheat and barley in the UK are available for the period from 1999 until 2020 for 11 regions, i.e., North East, North West and Merseyside, Yorkshire & the Humber, East Midlands, West Midlands, Eastern, South East and London, South West, Wales, Scotland and Northern Ireland [30]. From this data source, yield data during the period of 2005–2020 were used in the present study to fully cover the period of the dataset JP and the dataset JP_{wheat}, as well as that of the other dataset of Ya values in the UK that is detailed later in this section. The dataset comprised of Ya values for wheat and barley from this data source [30] is hereafter referred to as the dataset UK (Table 1). Although yield data of spring and winter barleys are separately provided in the data source [30], averaged yields of spring and winter barleys were subjected to the analysis in accordance with the dataset JP. No separation was made between two-row and six-row barleys in the data source [30]. In addition to government statistics, research projects such as GYGA report Ya values of staple crops from various locations in the world [17]. For the UK, Ya values of wheat derived from field experiments are reported for 10 locations during the period of 2005–2015 [31] (Figure 2a). Unlike yield data provided at administrative divisions (e.g., region and municipality), the location-specific Ya values can be directly linked to CZs and their components (i.e., GDD and AI scores) in the GYGA-CZS. The dataset of the location-specific Ya values for wheat is hereafter referred to as the dataset UK_{wheat} and was used in the present study to compare the results obtained from the dataset UK (Table 1). Due to the differences in data availability, it was not possible to align all data periods. In the present study, datasets of Ya values were, however, prepared in such a way that both the overlapping period between the dataset JP and the dataset UK, as well as that between the dataset UK and the dataset UK_{wheat}, ensure a certain length of time (i.e., 11 years).

2.4. Statistical Analysis and Two Hypotheses

The yield data collected in the above procedures were statistically analysed using climatic factors as explanatory variables. Its major goal was to test two hypotheses formulated following the ideas mentioned in the Introduction. The first hypothesis is that Ya values decrease with an increase in GDD or representative GDD scores; in other words, lower yields result from warmer areas characterised by higher GDD or higher representative GDD scores. The second hypothesis is that Ya values decrease with an increase in AI or representative AI scores; in other words, lower yields are associated with humid areas characterised by higher AI or higher representative AI scores. To test the hypotheses, Ya values in the dataset JP, the dataset JP_{wheat} and the dataset UK_{wheat} were individually subjected to an analysis of variance (ANOVA), setting the climatic components of the GYGA-CZS (i.e., GDD, AI and TS scores) as fixed factors. This was followed by Scheffé's multiple comparisons. As for the dataset JP, the ANOVA was separately carried out for upland and paddy fields. For the reason mentioned earlier, TS scores were excluded from the fixed factors in the analysis of the dataset UK_{wheat}. As for the dataset UK, simple regression analyses were performed to explain Ya values by representative GDD scores and by representative AI scores determined for all regions in the UK. The regression was conducted separately for barley and wheat.

Also determined was the Pearson's correlation coefficient between Ya values obtained from upland fields and those from paddy fields in Japan. Ya values of wheat and barleys were extracted from the dataset JP by selecting municipalities where wheat and/or barleys were grown both in upland and paddy fields in same year. In addition, an ANOVA was performed on the coefficient of variance (CV) of Ya values over time in the dataset JP_{wheat}, followed by Scheffé's multiple comparisons. The sample size of Ya values for the dataset UK_{wheat} was not sufficient to perform an ANOVA of CV, and therefore an average value of CV was numerically calculated for reference. The use of CV of Ya enables comparison of yield stability of wheat with that of rice reported in the previous work [25]. All statistical analyses were performed using SPSS Advanced Statistics (Ver. 28, IBM). The results were considered statistically significant at $p < 0.05$.

3. Results

3.1. Climate Zones and Field Types for Wheat and Barley Cultivation in Japan

Figure 1a presents the original map of CZs in Japan expressed on a grid-cell basis of the GYGA-CZS, while the map of CZs linked to municipalities is shown in Figure 1b. Figure 1c displays the regions of Japan to facilitate reading. The linkage of CZs to municipalities went well in more than 80% of municipalities that cultivate wheat (see Table S2 in Supplementary Materials for the coverages of barleys). In the Hokkaido region, CZ1903 and CZ2903 prevailed, while the Tohoku region was characterised by CZ3903, CZ4902 and CZ4903

(Figure 1b). The Kanto and the Tokai regions as well as the west part of the country (i.e., the Kinki, the Chugoku, the Shikoku and the Kyushu regions) had large areas of CZ4902 and CZ5902. CZ6902 was common in the south part of the Kyushu region and was sometimes observed along the coast in other regions. Summarizing the above, CZs in Japan are comprised of six types of GDD scores from one to six, two types of AI scores, eight and nine, and two types of TS scores, two and three.

Figure 3 shows field types in which wheat is grown during the period of analysis. Municipalities in dark green indicate that wheat is grown only in upland fields, while those in blue indicate that it is grown only in paddy fields. Municipalities in light green indicate that the crop is grown in both types of fields. As indicated, wheat is grown mainly in upland fields alone in the east part of the Hokkaido region and parts of the Tohoku and Kanto regions, while many municipalities grow wheat both in upland and paddy fields. Barleys had higher proportions of municipalities growing them in both upland and paddy fields or in paddy fields alone (Figure S3 in Supplementary Materials). Figure 4 presents the scatter diagram of Ya values obtained from paddy fields against those from upland fields in municipalities where wheat and/or barleys are grown in both types of fields in same year. Very large yield differences in Ya values were observed across the municipalities, irrespective of field types. The Pearson's correlation coefficient was as high as 0.89, and the positive correlation was highly significant ($p < 0.001$). These indicate that despite a marked difference in soil groups between upland and paddy fields [35], there was a clear tendency that municipalities with high Ya values in upland fields have high Ya values in paddy fields.

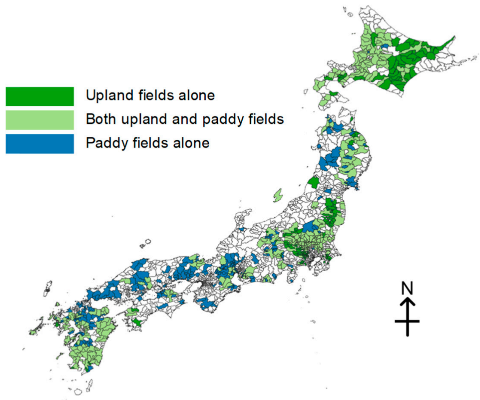


Figure 3. Map of municipalities in Japan showing field types used for growing wheat during period of analysis.

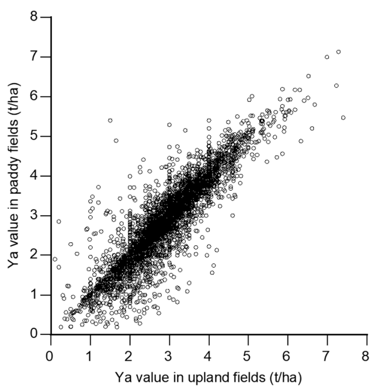


Figure 4. Scatter diagram of Ya values obtained from paddy fields against those from upland fields in municipalities of Japan. Ya, actual yield; Ya values of wheat and barleys are extracted from the dataset JP, targeting municipalities where wheat and/or barleys are grown both in upland and paddy fields in the same year.

3.2. Climate Zones in the United Kingdom and Comparison with Japan

Figure 2a presents the original map of CZs in Great Britain and the island of Ireland expressed on a grid-cell basis of the GYGA-CZS. The map of CZs reproduced on a spreadsheet in the present study is shown in Figure 2b (see Figure S1 in Supplementary Materials for more details). Starting from the north, CZ1902 and CZ2902 prevailed in Scotland and North West and Merseyside. North West and Merseyside had a large area of CZ3902 as well. North East had large areas of CZ1902 and CZ2802. In Northern Ireland, CZ2902 and CZ3902 prevailed with an area of CZ2901 in the west. Yorkshire & the Humber had a large variation of CZs, i.e., CZ1902, CZ2802, CZ2902, CZ3702, CZ3802 and CZ3902. Looking at the east part of the country, East Midlands, Eastern, and South East and London were characterised by large areas of CZ3702. CZ3602 was mostly observed in Eastern. Turning to the west, West Midlands had large areas of CZ3702 and CZ3802, while Wales and South West had large areas of CZ3902. Wales and South West are different in that the former had a large area of CZ2902 and the latter had some areas of CZ3802 and CZ4902. One reason for the prevalence of CZs with low GDD scores (i.e., CZ1902 and CZ2902) in Scotland, North West and Merseyside and Wales may be related to the mountainous terrain. The range of GDD scores in the UK was from one to four, which was relatable to that observed in the Hokkaido and the Tohoku regions of Japan, if limited to plains (Figure 1a,b). AI score ranged from six to nine in the UK, while it ranged from eight to nine in Japan (Figure 1a,b).

Figure 5 presents the scatter diagram of representative GDD and AI scores calculated for all regions of the UK and those for the Hokkaido, Kanto and Kyushu regions of Japan. The representative GDD scores in the UK ranged from 1.56 to 3.12, which falls between those in the Hokkaido and the Kanto regions of Japan, showing a climatic similarity in terms of temperature between the UK and the eastern part of Japan. Compared to the Hokkaido, Kanto and Kyushu regions of Japan, representative AI scores of regions in the UK are, however, at best the same or below, ranging from 6.52 to 9.00. In addition, representative AI scores appear to be decreasing with an increase in representative GDD score in the UK, indicating that a temperature rise is likely to cause or is associated with dryness. Such a trend was not observed among the three regions in Japan, where representative AI scores remained high irrespective of GDD scores. This implies that a greater evapotranspiration caused by temperature rise is well supplemented by precipitation in warm regions with high GDD scores in Japan. When limited to GDD and AI scores, climate conditions in the Hokkaido region are comparable with those in the UK, while those in the Kanto and the Kyushu regions were very different from those in the UK.

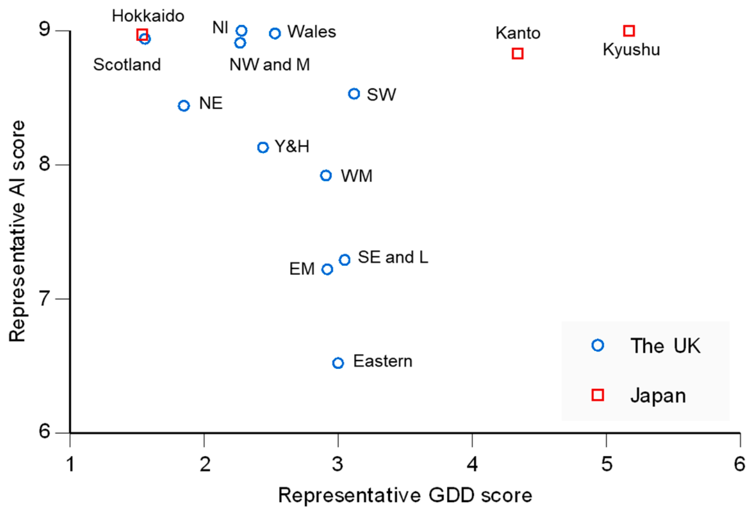


Figure 5. Scatter diagram of representative GDD and AI scores calculated for all regions of the UK (NE, North East; NW and M, North West and Merseyside; Y&H, Yorkshire & the Humber; EM, East Midlands; WM, West Midlands; SE and L, South East and London; SW, South West; NI, Northern Ireland) and those for the Hokkaido, the Kanto and the Kyushu regions of Japan.

3.3. Relationships between Climatic Factors and Yields

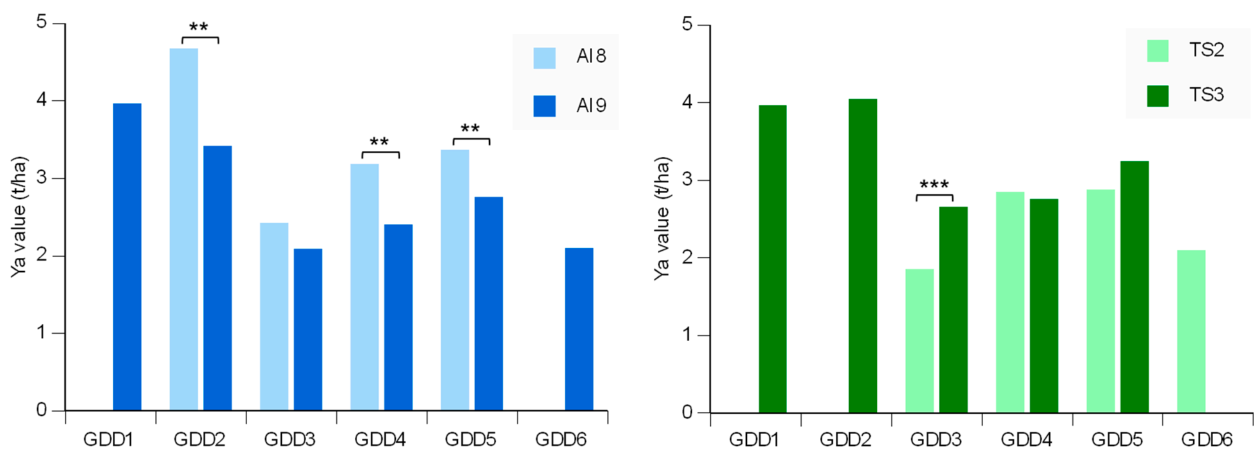
3.3.1. Japan

Table 2 shows the ANOVA results of Ya values for field types (i.e., upland and paddy) in the dataset JP. There were significant interactions between GDD and AI scores ($p < 0.01$) and between GDD and TS scores ($p < 0.001$) for upland fields. Ya values were significantly greater at the AI score of eight than at that of nine when GDD score was two, four and five (Figure 6a). There was no significant difference between the two AI scores when GDD score was three. As to TS scores, Ya values were greater at the TS score of three than at that of two when GDD score was three (Figure 6b). There was no significant difference between the two TS scores when GDD score was four and five. For paddy fields, significant interactions were observed between GDD and AI scores ($p < 0.001$) and between GDD and TS scores ($p < 0.05$) (Table 2). Ya values were greater at the AI score of eight than at that of nine when GDD score was four and five, whereas there was no significant difference by the two AI scores when GDD score was three (Figure 7a). Ya values were greater at the TS score of two than at that of three when GDD score was four (Figure 7b). No significant difference was observed between the two TS scores when GDD score was three and five. Looking at the GDD score alone, Ya values were among the highest at the GDD scores of one and two, especially when grown in upland fields, whereas Ya values were the lowest at the GDD score of three in both types of the fields (Figures 6 and 7). As to AI scores, Ya values tended to be higher at the AI score of eight than at that of nine, indicating a declining trend with an increase in AI score (Figures 6a and 7a).

Table 2. ANOVA results of Ya [1] values for field types in the dataset JP.

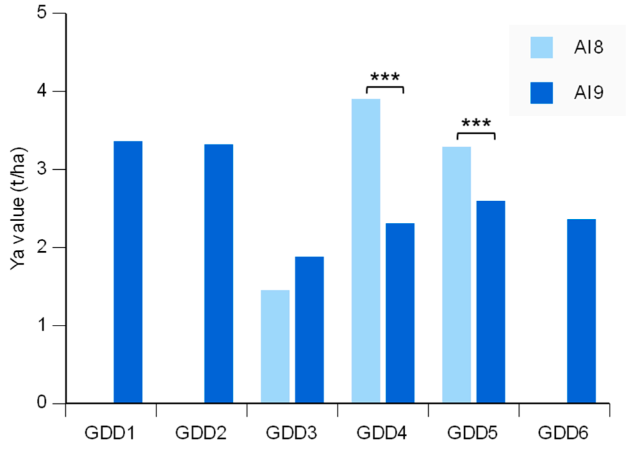
Factor	Upland	Paddy
GDD [2]	***	***
AI [3]	***	***
TS [4]	***	ns
GDD × AI	**	***
GDD × TS	***	*
crop	***	***
year	***	***

[1] Ya, actual yield; [2] GDD, growing degree days; [3] AI, aridity index; [4] TS, temperature seasonality; ***, $p < 0.001$; **, $p < 0.01$; *, $p < 0.05$; ns, non-significant.

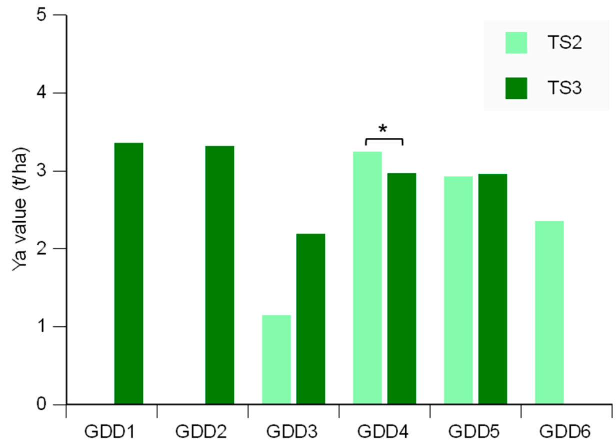


(**a**) (**b**)

Figure 6. Ya values of wheat and barleys in upland fields presented for the combinations of GDD and AI scores (**a**) and for those of GDD and TS scores (**b**). Ya, actual yield; GDD, growing degree days; AI, aridity index; TS, temperature seasonality. Data were analysed by two-way ANOVA followed by Scheffé's test. ***, $p < 0.001$; **, $p < 0.01$.



(**a**)



(**b**)

Figure 7. Ya values of wheat and barleys in paddy fields presented for the combinations of GDD and AI scores (**a**) and for those of GDD and TS scores (**b**). Ya, actual yield; GDD, growing degree days; AI, aridity index; TS, temperature seasonality. Data were analysed by two-way ANOVA followed by Scheffé's test. ***, $p < 0.001$; *, $p < 0.05$.

3.3.2. The United Kingdom

Figure 8 presents the scatter diagram of Ya values against representative AI scores for barley and against those for wheat in the UK. A linear equation fitted well the relationship between representative AI scores and Ya values of barley ($p < 0.001$) with the linear coefficient and the constant term being −0.29 ($p < 0.001$) and 8.21 ($p < 0.001$), respectively. Similarly for wheat, a linear equation fitted well ($p < 0.001$) with the linear coefficient and the constant term being −0.43 ($p < 0.001$) and 11.11 ($p < 0.001$), respectively (Figure 8). As to the negative linear relationship observed between representative AI scores and Ya values, the slope was steeper for wheat than for barley, suggesting that wheat yields are more sensitive to representative AI scores than barley yields. On the other hand, no significant linear relationship between representative GDD scores and Ya values was detected for either wheat ($p = 0.589$) or barley ($p = 0.547$). Ya values for both crops appeared to drop slightly from the representative GDD score of 1.56 to some point between 2 and 2.5, but then increased up to the representative GDD score of 3.12.

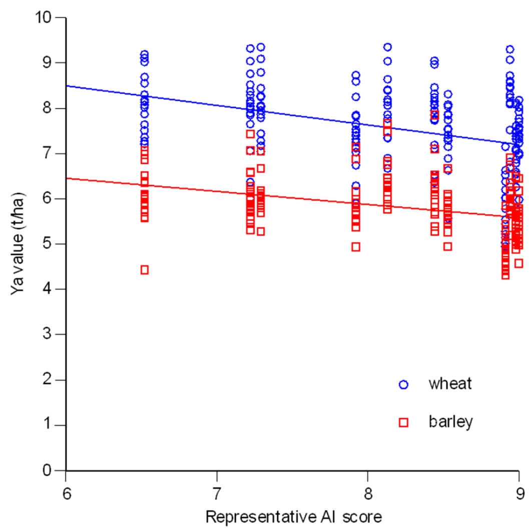


Figure 8. Scatter diagram of Ya values of barley and wheat against representative AI scores in the dataset UK. Ya, actual yield; AI, aridity index. Representative AI scores were calculated following the procedure described in Materials and Methods.

3.4. Comparison of the Analyses

Table 3 shows the ANOVA result of Ya values in the dataset UK_{wheat} and the ANOVA results of Ya values and their CV in the dataset JP_{wheat}. There was no interaction between GDD and AI scores in the dataset UK_{wheat} ($p = 0.061$). Ya values were significantly greater at the GDD score of two than at that of three ($p < 0.001$) with the difference being 0.11 t ha^{-1} (Figure 9a). Ya values were significantly greater at the AI scores of six and seven than at those of eight and nine ($p < 0.001$) with the difference between the AI scores of six and nine being 0.48 t ha^{-1} (Figure 9b). This indicates that Ya values decrease with an increase in AI score, which is in line with the decreasing trend of Ya values observed with the dataset UK (Figure 8).

Table 3. ANOVA result of Ya [1] values in the dataset UK_{wheat} and ANOVA results of Ya values and their CV [2] in the dataset JP_{wheat}.

Factor	Dataset UK_{wheat}	Dataset JP_{wheat}	
	Ya Values (t ha^{-1})	Ya Values (t ha^{-1})	CV of Ya Values (%)
GDD [3]	***	***	ns
AI [4]	***	***	**
TS [5]	—	*	ns
GDD × AI	ns	***	ns
GDD × TS	—	**	*
year	***	***	—

[1] Ya, actual yield; [2] CV, coefficient of variation; [3] GDD, growing degree days; [4] AI, aridity index; [5] TS, temperature seasonality; ***, $p < 0.001$; **, $p < 0.01$; *, $p < 0.05$; ns, non-significant.

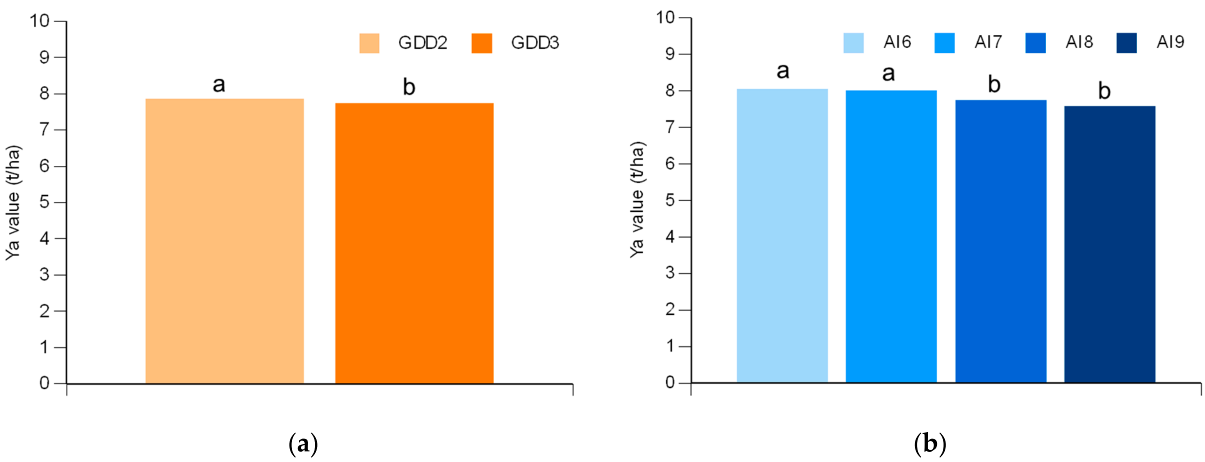


Figure 9. Ya values of wheat presented for GDD scores (**a**) and AI scores (**b**) in the dataset UK_{wheat}. Ya, actual yield; GDD, growing degree days; AI, aridity index. Different letters indicate statistically significant differences between GDD scores (**a**) and among AI scores (**b**) analysed using two-way ANOVA followed by Scheffé's test ($p < 0.05$).

In the dataset JP_{wheat}, interactions were observed between GDD and AI scores ($p < 0.001$) as well as between GDD and TS scores ($p < 0.01$) (Table 3). Ya values were significantly greater at the AI scores of eight than at that of nine when GDD score was two and four (Figure 10a). The difference in Ya values between the AI scores was pronounced (2.32 t ha^{-1}) when GDD score was two. When GDD score was three and five, no significant difference in Ya values by AI score was detected. Ya values were always greater, at least numerically, at the AI score of eight than at that of nine, which was in accordance with the results obtained from the dataset JP for upland fields (Figure 6a). The observations here appeared to be relatable to those in the UK in that there was a declining trend of Ya values towards a greater AI score (Figure 8). The effect of AI score on Ya values of wheat was, however, much greater in Japan than in the UK, as far as we learned from the difference in Ya values between the AI scores of eight and nine (Figures 8, 9b and 10a). Here, we need to recall a large difference in wheat yields between Japan and the UK [6]. This was actually observed with the datasets we prepared for the two countries. Ya value of wheat in Japan was the highest (5.93 t ha^{-1}) at the AI score of eight when GDD score was two (Figure 10a), while in the UK, it was the lowest (7.59 t ha^{-1}) at the AI score of nine (Figure 9b). Thus, even the lowest Ya value in the UK was greater by 1.66 t ha^{-1} than the highest Ya value in Japan.

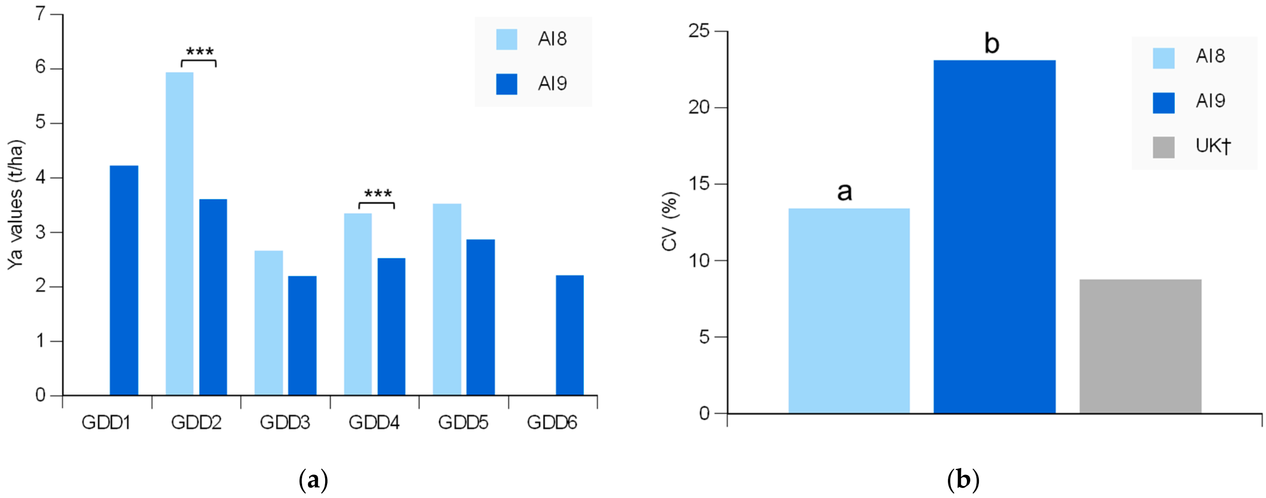


Figure 10. Ya values of wheat presented for the combination of GDD and AI scores (**a**) and CV of Ya values presented for AI scores (**b**) in the dataset JP_{wheat}. Ya, actual yield; CV, coefficient of variation. ***, $p < 0.001$. Different letters indicate statistically significant differences between AI scores analysed using two-way ANOVA followed by Scheffé's test ($p < 0.05$); †, average value of CV calculated for Ya values in the dataset UK_{wheat} for reference.

As to the CV of Ya values in the dataset JP_{wheat}, a significant interaction was observed between GDD and TS scores ($p < 0.05$) (Table 3). The TS score of three showed a smaller CV than the TS score of two when GDD score was three, but not when GDD score was four. Looking at AI scores, CV was significantly smaller at the AI score of eight than at that of nine ($p < 0.01$) (Table 3 and Figure 10b). The CV of wheat yields was 13.4% at the AI score of eight and 23.1% at that of nine with the difference being 9.7 percentage points (Figure 10b). This means that wheat yields are more stable in the CZs with the AI score of eight than in the CZs with the AI score of nine. For reference, in paddy fields, CV value of wheat yields was 22.3%, irrespective of the AI scores. In comparison, the numerical average of CV among the 10 locations in the dataset UK_{wheat} was 8.8% (Figure 10b).

4. Discussion

What motivated the present study was a simple question by a Japanese researcher [6] who asked if wheat yields in Japan could reach the level of wheat yields achieved in the UK and other European countries. He considered yield-restricting factors in Japan to be of climatic nature, specifically, high temperature and heavy rainfall in summer. In the present study, we employed the GYGA-CZS as a tool to elucidate the effects of climatic factors on wheat and barley yields in Japan and the UK. Following our previous study [25], municipality-based yield data in Japan were linked to CZs, and thus to the climatic factors GDD, AI and TS. An ANOVA was conducted to understand the effects of the climatic factors on wheat and barley yields (Table 2). At the same time, we proposed an alternative method for linking regional-based yield data of wheat and barley in the UK to the climatic factors GDD and AI. A regression analysis was then conducted to examine if there is a relationship between the weight-averaged climatic factors (i.e., representative GDD and AI) and yields of barley and wheat (Figure 8). To validate the proposed method and to make comparisons with ANOVA results in Japan, yield data of wheat obtained from multiple locations of the UK and their CZs as reported as a part of the GYGA project were subjected to an ANOVA (Table 3). It was also confirmed that consistent results can be obtained even if the periods of the dataset UK are changed to match the dataset JP and the dataset UK_{wheat} (see Table S3 in Supplementary Materials).

Using these methods, two hypotheses were tested. The first hypothesis that Ya values decrease with an increase in GDD or representative GDD scores did not appear to be compatible with the results obtained here. Among the GDD scores ranging from one to six in Japan, yields of wheat and barleys were the lowest at the GDD score of three for both upland and paddy fields (Figures 6 and 7), and in the UK, there was no significant negative relationship between representative GDD scores and Ya values on a whole-country scale. As to the dataset UK_{wheat}, Ya value at the GDD score of two was greater than that at the GDD score of three by 0.11 t ha^{-1}, showing a small decrease in response to an increase in GDD score (Figure 9a). It should, however, be noted that the dataset UK_{wheat} only includes yield data at the locations with the GDD scores of two and three (Figure 9a). Contrary to this, the relationship between AI score and yield was overall in accordance with the second hypothesis that Ya values decrease with an increase in AI or representative AI scores. Lower yields of upland wheat were always observed at the AI score of nine than at that of eight, irrespective of GDD scores, in Japan, where a significant yield difference by AI score was detected when GDD score was two and four (Figure 10a). A similar trend was observed as well when barleys were included in the analysis (Figures 6a and 7a). A negative linear relationship was also observed between representative AI scores and yields of barley and wheat in the UK (Figure 8). Taking these together, wheat and barley yields appear to be negatively affected by high precipitation. In addition, it was found that the rise in AI score caused a greater yield reduction in Japan than in the UK (Figures 8, 9b and 10a). Interestingly, there was a relationship to be noted between AI score and the CV of wheat yields in Japan. The CV value was lower, i.e., wheat yield was more stable, at the AI score of eight than at that of nine (Figure 10b). In other words, not only wheat yield but also its stability was compromised, as AI score increased. The present study found a common relationship between AI score and Ya value across two countries located far apart.

While much of the research places a focus on wheat and barley cultivation under dry conditions [36–38], there is no shortage of reports showing that excess rainfall adversely affects yield performance during grain filling stage of wheat and barleys [10,39]. The negative impacts of excess rainfall include Fusarium head blight, lodging, pre-harvest sprouting and flooding [9–11,40,41]. However, it is pointed out that historical analyses looking at extreme rainfall are insufficient, even though it is a major risk to food production [42]. As to wheat, it is reported that yield failure in 2016 in France was caused by cloud cover and heavy rainfall which consequently leads to the reduced availability of solar radiation for use by the crop canopy as well as damage to the crop due to soil anoxia, fungal foliar diseases and head blight [43]. Our finding as to the relationship between AI score and cereal yield observed in both the UK and Japan appears to be in accordance with these previous reports concerning the adverse effects of rainfall. Now that we have found the difference in the degree of yield reduction with an increase in AI score between the two countries, elaborating this part appears to be a key to understand the differences in wheat and barley yields between them. Furthermore, the Discussion so far illustrates that the GYGA-CZS is capable of extracting a common climate–yield relationship across countries. The present study showed that the implicit assumption made in a series of GYGA-related studies appears to be valid. The implicit assumption is, as pointed out in the Introduction, that individual CZs have impacts on crop yields in a systematic manner.

From this point on, the Discussion will be developed with more attention to detail. The first issue is the treatment of paddy fields. As already mentioned, wheat and barleys are grown not only in upland fields but also in drained paddy fields in Japan [32,33]. In general, upland and paddy soils belong to different soil groups: the former to andosols, brown forest soils and red-yellow soils and the latter to gley lowland soils and gray lowland soils [35]. It is, therefore, no wonder that one would question the impact of field types on cereal yields; however, we found evidence that the yields of wheat and barleys in upland fields were highly correlated with those in paddy fields (Figure 4). In addition, the ANOVA of wheat and barley yields for upland and paddy fields derived similar results as characterised by significant interactions between GDD and AI scores and between GDD and TS scores (Table 2). These results suggest that soil factors do not have much impact on yields of wheat and barleys, implying that there are dominant factors influencing wheat and barley yields other than field types in Japan. Rationally thinking, these dominant factors should be of climatic, genetic and managemental origins. Given that growers select the best cultivars for locations and that they pursue the optimum management, one could focus on looking into climatic factors. Nevertheless, the present study found a negative impact on wheat yields when grown in paddy fields. The CV of wheat yields was 13.4% at the AI score of eight and 23.1% at that of nine (Figure 10b), indicating that AI score has a large impact on yield stability of wheat in upland fields. Interestingly in paddy fields, CV value of wheat yields was calculated to be 22.3% irrespective of the AI scores in Japan. Learning from this, the stability of wheat yield is not likely to improve even when grown in a relatively dry climate, as far as it is grown in paddy fields. These observations remind us of the CV values of rice yields observed in paddy fields that range from 4% to 10% [25]. It goes without saying that stable crop cultivation is possible in paddy fields if the crop is rice. In the present study, the CV value of wheat yields in the UK was calculated to be 8.8% (Figure 10b) and comparable to that of paddy rice in Japan, which is constantly irrigated. It is interesting from an East Asian perspective to note this comparison and in particular the low CV value for wheat in the UK which indicates that a high stability of yield can be achieved with a crop grown in upland fields.

Ishikawa et at. [25] report that rice yields are higher in areas with the TS score of three than with that of two in Japan. Following the GYGA-CZS, TS scores are the indicators of annual temperature range that are defined as the standard deviation of the mean temperature of 12 months [17]. According to Scheitlin [44], an area with a large annual temperature range tends to have a large diurnal temperature range. Based on the report, it is speculated that rice yields better in areas where the diurnal temperature range is relatively large; in other words, the TS score is three. There are a number of reports showing importance of cool nighttime temperature to rice yields as well as those reporting negative impacts of an increase in nighttime temperatures on rice yields [45,46]. Statistically proven in our previous study [25] is the importance of areas with the TS score of three for rice cultivation which had been known among rice growers. It should be noted that rice is not the only crop that favours cool nighttime temperatures [47,48]. It is natural to assume that TS scores might also have an impact on wheat and barley yields. In the present study, an interaction between GDD and TS scores was observed for wheat and barley yields in both upland and paddy fields in Japan (Table 2). Nevertheless, a clear advantage of a TS score of three over that of two was not observed for wheat and barley yields in Japan (Figures 6b and 7b). This suggests that wheat and barley yields are less affected by TS scores than paddy rice yields. It appears more sensible, therefore, to be concerned with the AI score rather than with the TS score if considering production of high-yielding wheat and barleys. Although it was mentioned earlier in the Discussion that high AI scores tend to give lower yields, wheat and barley yields in Japan were high at the AI score of nine especially in upland fields when the GDD score was one (Figure 6a). The direct comparison between the AI scores of eight and nine is not possible, as the CZ combining the GDD score of one and the AI score of eight (i.e., CZ1803) exists only in a small share of the country and was excluded from the analysis in the present study. In areas with the GDD score of one, namely CZ1903 (Figure 1b), there seems little negative effect of precipitation on wheat and barley yields. This is understandable, however, if one recognises that a significant part of the precipitation in these areas is snow. Winter wheat in the Hokkaido region overwinters under snow during winter months [49], as snow in Hokkaido stays on the ground for as long as 100 to 150 days a year [50]. Admitting that snow has an excellent function in protecting crops from frost damage, it does restrict sunlight, weakening wheat plants to the extent that they may become affected by snow blight [50]. However, snow cover is not limited to CZ1903. CZ2903 widely distributes in the west part of Hokkaido (Figure 1b) which is known for its snow cover. Taking these factors into consideration, snow does not seem to be the factor making the combination of the GDD score of one with the AI score of nine exceptional. It might be reasonable to suppose the negative impacts of excessive rainfall are cancelled by low temperatures at the GDD score of one. Another possible counterexample of the results obtained in the present study is given by Cammarano et al. [51]. They found a strong positive correlation between spring barley yield and rainfall during the growing season (i.e., from April to August) in the east of Scotland, leading to their argument that spring drought has negative impacts on crop canopy development and consequently on grain yield. It is imaginable that spring barley and winter barley have different rooting depths during spring, and therefore it is understandable that spring barley is more susceptible to drought in early growth. Nonetheless, it is not clear how best to relate this finding to the present study, which found a trend of lower wheat and barley yields in areas of high AI scores, admitting that the AI score is not a measure of precipitation that can be related to a specific stage of crop development. To understand how drought is causing yield losses in areas with high AI scores, it may be necessary to analyse cereal yields with a focus on precipitation during specific growth periods such as booting. Following a simulation-based analysis, Boogaard et al. [52] showed that water-limited yields of winter wheat are as high as 7–9 t ha^{-1} in many countries of the European Union. Also shown was that Ireland, western England, Scotland and western France are unlikely to experience water-limited situations, achieving water-limited yields of as high as 8–11 t ha^{-1}. In the present study, we added a new view that wheat yield in some parts of the UK is hampered by excess humidity.

The discussion is concluded with reference to methodological aspects. The present study proposed a method for linking CZs of the GYGA-CZS to regional classification units for which statistical crop yield data are provided. The linking method was combined with regression analyses to examine the relationship between representative GDD and AI scores and yields of wheat and barley in the UK. An advantage of this method is that it can be applied to countries where crop yield data are available only at a coarse scale. Indeed, the regression results obtained from this method were agreeable with the ANOVA results derived from the GYGA dataset in the UK, especially in terms of the relationship between AI score and yield. However, the proposed linking method is bound to a shortcoming of counting for areas where a target crop is not much grown. Obviously, this has relevance to yield data available only at a coarse scale, such as a regional scale. In such situations, opinions can vary as to which CZs should be employed or removed in calculating representative GDD and AI scores. In the present study, we included all CZs except for minor CZs mentioned in Materials and Methods to avoid arguments over the appropriateness of the calculated representative GDD and AI scores. A series of analyses in other countries and crops may be needed to deepen the understanding of the effectiveness of the proposed method. In the present study, the use of the proposed linking method as well as the previously suggested method [25] helped to reveal a common relationship between AI score and yield of wheat and barleys in the UK and Japan. The task, however, of explaining the large yield differences that exist between the two countries remains. Fortunately, it seems we have obtained a key to solve this problem through the observation that there is a difference in the degree of yield reduction in response to an increase in AI score between Japan and the UK. Recalling here the simple question repeatedly mentioned [6], high temperature and heavy rainfall in summer are major factors hindering high yields in Japan, it would seem appropriate to analyse cereal yields with a focus on precipitation during specific growth periods such as booting and grain filling. In doing so, it is worthwhile remembering that GDD, AI and TS scores reflect weather conditions on an annual basis, not specific weather conditions when crops are actually grown.

5. Conclusions

Motivated by a simple question raised some time ago as to large yield differences of wheat and barley between Japan and the UK, the present study analysed Ya values of these crops in the two countries using climatic factors in the GYGA-CZS. The results showed a significant negative relationship between AI scores and Ya values across two countries and that the degree of yield reduction was much greater in Japan than in the UK. The present study also proposed a novel method to link CZs of the GYGA-CZS to regional classification units to enable regression analyses to examine the relationship between representative GDD and AI scores and yields of wheat and barley in the UK. The proposed method might be applicable to other countries where statistical crop yield data are provided only at a coarse scale.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/cli12080125/s1, Figure S1: Map of CZs reproduced on a spreadsheet from the original grid-cell basis map of GYGA–Climate Zonation Scheme for North East (a), North West and Merseyside (b), Yorkshire & the Humber (c), West Midlands (d), East Midlands (e), Eastern (f), South East and London (g), South West (h), Wales (i), Scotland (j) and Northern Ireland (k) in the UK.; Figure S2: Map of CZs reproduced on a spreadsheet from the original grid-cell basis map of GYGA–Climate Zonation Scheme for Hokkaido (a), Kanto (b) and Kyushu (c) in Japan.; Figure S3: Map of municipalities in Japan showing field types used for growing two-row barley (a), six-row barley (b) and naked barley (c) during period of analysis.; Table S1: Number of Ya value observations for GDD, AI and TS scores and for crops in the dataset JP; Table S2: Coverage of Ya value observations in the dataset JP to all observations sourced from MAFF (%); Table S3: Results of preliminary linear regression analysis of the relationship between representative AI scores and Ya values when the period of the dataset UK is changed.

Author Contributions: Conceptualization, S.I.; methodology, S.I.; software, S.I.; validation, S.I. and T.N.; formal analysis, S.I.; investigation, S.I.; data curation, S.I.; writing—original draft preparation, S.I. and T.N.; writing—review and editing, S.I., T.N., M.C.H. and P.S.K.; visualization, S.I. and T.N.; project administration, T.N.; funding acquisition, S.I. and T.N. All authors have read and agreed to the published version of the manuscript.

Funding: The present study was supported by the Japan Society for the Promotion of Science (Grant-in-Aid for Scientific Research C, 20K06267 and 23K05419).

Data Availability Statement: The original data presented in the study are openly available and the references are properly given.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Endo, E.; Leipe, C. The onset, dispersal and crop preferences of early agriculture in the Japanese archipelago as derived from seed impressions in pottery. *Quatern Int.* **2022**, *623*, 35–49. [CrossRef]
2. Ministry of Agriculture Forestry and Fisheries (MAFF). Statistical Survey on Crops. Available online: https://www.maff.go.jp/j/tokei/kouhyou/sakumotu/sakkyou_kome/index.html#c (accessed on 11 January 2024).
3. Iwama, K.; Ohara, M.; Araki, H.; Yamada, T.; Nakatsuji, H.; Kataoka, T.; Yamamoto, Y. *Agriculture in Hokkaido*; Hokkaido University: Sapporo, Japan, 2009.
4. Nihei, T. Development of wheat production in Hokkaido. *Geogr. Stud.* **2013**, *87*, 1–13. [CrossRef]
5. Food and Agriculture Organization (FAO). FAOSTAT. Available online: https://www.fao.org/faostat/en/#data (accessed on 11 January 2024).
6. Mizuochi, T. Prospects for development of high-yielding techniques of winter wheat in Hokkaido. *Nogyo Gijyutsu* **1988**, *43*, 337–342.
7. Mirosavljevic, M.; Mikic, S.; Zupunski, V.; Spika, A.K.; Trkulja, D.; Ottosen, C.O.; Zhou, R.; Abdelhakim, L. Effects of high temperature during anthesis and grain filling on physiological characteristics of winter wheat cultivars. *J. Agron. Crop Sci.* **2021**, *207*, 823–832. [CrossRef]
8. Shiga, H. Evaluation and estimation of yield variability in winter wheat using crop model. *Jpn. J. Soil. Sci. Plant Nutr.* **2003**, *74*, 835–838. [CrossRef]
9. Berry, P.M.; Sterling, M.; Spink, J.H.; Baker, C.J.; Sylvester-Bradley, R.; Mooney, S.J.; Tams, A.R.; Ennos, A.R. Understanding and reducing lodging in cereals. *Adv. Agron.* **2004**, *84*, 217–271. [CrossRef]
10. Song, Y.L.; Linderholm, H.W.; Wang, C.Y.; Tian, J.F.; Huo, Z.G.; Gao, P.; Song, Y.B.; Guo, A.H. The influence of excess precipitation on winter wheat under climate change in China from 1961 to 2017. *Sci. Total Environ.* **2019**, *690*, 189–196. [CrossRef]
11. Zeeshan, M.; Arshad, W.; Khan, M.I.; Ali, S.; Nawaz, A.; Batool, A.; Tariq, M.; Akram, M.I.; Ali, M.A. Breeding for pre-harvest sprouting resistance in bread wheat under rainfed conditions. *Front. Agric. Sci. Eng.* **2018**, *5*, 253–261. [CrossRef]
12. United States Department of Agriculture (USDA). Crop Calendar Charts. Available online: https://ipad.fas.usda.gov/ogamaps/cropcalendar.aspx (accessed on 11 January 2024).
13. Köppen, W. Das geographische System der Klimate. In *Handbuch der Klimatologie*; Köppen, W., Geiger, R., Eds.; Gebrüder Borntraeger: Berlin, Germany, 1936; pp. 1–44.

14. Kottek, M.; Grieser, J.; Beck, C.; Rudolf, B.; Rubel, F. World map of the Koppen-Geiger climate classification updated. *Meteorol. Z.* **2006**, *15*, 259–263. [CrossRef]
15. Britannica. Köppen Climate Classification. Available online: https://www.britannica.com/science/Koppen-climate-classification/World-distribution-of-major-climatic-types (accessed on 11 January 2024).
16. Miyamoto, M. A reexamination on Koeppen climate classification in northern Tohoku and Hokkaido. *Geogr. Stud.* **2009**, *84*, 111–117. [CrossRef]
17. GYGA. Global Yield Gap Atlas. Available online: https://www.yieldgap.org/ (accessed on 11 January 2024).
18. van Wart, J.; van Bussel, L.G.J.; Wolf, J.; Licker, R.; Grassini, P.; Nelson, A.; Boogaard, H.; Gerber, J.; Mueller, N.D.; Claessens, L.; et al. Use of agro-climatic zones to upscale simulated crop yield potential. *Field Crops Res.* **2013**, *143*, 44–55. [CrossRef]
19. Food and Agriculture Organization (FAO). *Report on the Agro-Ecological Zones Project*; FAO: Rome, Italy, 1978.
20. Licker, R.; Johnston, M.; Foley, J.A.; Barford, C.; Kucharik, C.J.; Monfreda, C.; Ramankutty, N. Mind the gap: How do climate and agricultural management explain the 'yield gap' of croplands around the world? *Glob. Ecol. Biogeogr.* **2010**, *19*, 769–782. [CrossRef]
21. Department of Agriculture Hokkaido Government. *Technological Protocols for Agricultural Production in Hokkaido*, 5th ed.; Department of Agriculture Hokkaido Government: Sapporo, Japan, 2019.
22. van Ittersum, M.K.; Cassman, K.G.; Grassini, P.; Wolf, J.; Tittonell, P.; Hochman, Z. Yield gap analysis with local to global relevance—A review. *Field Crops Res.* **2013**, *143*, 4–17. [CrossRef]
23. Edreira, J.I.R.; Andrade, J.F.; Cassman, K.G.; van Ittersum, M.K.; van Loon, M.P.; Grassini, P. Spatial frameworks for robust estimation of yield gaps. *Nat. Food* **2021**, *2*, 773–779. [CrossRef] [PubMed]
24. van Bussel, L.G.J.; Grassini, P.; Van Wart, J.; Wolf, J.; Claessens, L.; Yang, H.S.; Boogaard, H.; de Groot, H.; Saito, K.; Cassman, K.G.; et al. From field to atlas: Upscaling of location-specific yield gap estimates. *Field Crops Res.* **2015**, *177*, 98–108. [CrossRef]
25. Ishikawa, S.; Nakashima, T.; Iizumi, T.; Hare, M.C. Evaluating irrigated rice yields in Japan within the Climate Zonation Scheme of the Global Yield Gap Atlas. *J. Agric. Sci.-Camb.* **2020**, *158*, 718–729. [CrossRef]
26. Ramankutty, N.; Evan, A.T.; Monfreda, C.; Foley, J.A. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Glob. Biogeochem. Cycles* **2008**, *22*, GB1003. [CrossRef]
27. Saito, K.; van Oort, P.; Dieng, I.; Johnson, J.M.; Niang, A.; Ahouanton, K.; Alognon, A.D.; Tanaka, A.; Senthilkumar, K.; Vandamme, E.; et al. Yield gap analysis towards meeting future rice demand. In *Achieving Sustainable Cultivation of Rice*; Sasaki, T., Ed.; Burleigh Dodds Science Publishing: London, UK, 2017; Volume 2, pp. 157–182.
28. Hochman, Z.; Gobbett, D.; Horan, H.; Garcia, J.N. Data rich yield gap analysis of wheat in Australia. *Field Crops Res.* **2016**, *197*, 97–106. [CrossRef]
29. Ministry of Internal Affairs and Communications (MIC). Regional Administration and Municipal Mergers. Available online: https://www.soumu.go.jp/kouiki/kouiki.html (accessed on 11 January 2024).
30. GOV.UK. Static Assets. Available online: https://docs.publishing.service.gov.uk/manual/assets.html (accessed on 11 January 2024).
31. Sylvester-Bradley, R.; Bingham, I.; Kindred, D.; Topp, K.; Watson, C. GYGA Data United Kingdom. Available online: https://www.yieldgap.org/United-Kingdom (accessed on 11 January 2024).
32. Fukuda, H.; Dyck, J.H.; Stout, J. *Rice Sector Policies in Japan*; US Department of Agriculture, Economic Research Service: Washington, DC, USA, 2003.
33. Nakashima, T.; Ishikawa, S. Exploring farmers' expectation toward farm-gate price of rice in Japan by positive mathematical programming. *Sustainability* **2023**, *15*, 621. [CrossRef]
34. Ministry of Agriculture Forestry and Fisheries (MAFF). Characteristic Tables of Recommended Cultivars of Irrigated and Upland Rice, Wheat, Barley and Soybean 2019. Available online: https://www.library-archive.maff.go.jp/index/200508430_0001?p=1 (accessed on 11 January 2024).
35. Obara, H.; Maejima, Y.; Kohyama, K.; Ohkura, T.; Takata, Y. Outline of the comprehensive soil classification system of Japan—First approximation. *Jarq.-Jpn. Agr. Res. Q.* **2015**, *49*, 217–226. [CrossRef]
36. Araus, J.L.; Slafer, G.A.; Reynolds, M.P.; Royo, C. Plant breeding and drought in C3 cereals: What should we breed for? *Ann. Bot.* **2002**, *89*, 925–940. [CrossRef] [PubMed]
37. Mphande, W.; Farrell, A.D.; Kettlewell, P.S. Commercial uses of antitranspirants in crop production: A review. *Outlook Agr.* **2023**, *52*, 3–10. [CrossRef]
38. Wasson, A.P.; Richards, R.A.; Chatrath, R.; Misra, S.C.; Prasad, S.V.S.; Rebetzke, G.J.; Kirkegaard, J.A.; Christopher, J.; Watt, M. Traits and selection strategies to improve root systems and water uptake in water-limited wheat crops. *J. Exp. Bot.* **2012**, *63*, 3485–3498. [CrossRef] [PubMed]
39. Hamachi, Y.; Yoshida, T. Multiple-regression analysis of malting barley yield and climatic conditions in Kyushu region. *Jpn. J. Crop Sci.* **1989**, *58*, 1–6. [CrossRef]
40. Byrne, T.; Grant, J.; Kock-Appelgren, P.; Förster, L.; Michel, T.; Miricescu, A.; Thomas, W.T.B.; Graciet, E.; Spink, J.; Ng, C.K.Y.; et al. Improving phenotyping in winter barley cultivars towards waterlogging tolerance by combining field trials under natural conditions with controlled growth condition experiments. *Eur. J. Agron.* **2022**, *133*, 126432. [CrossRef]
41. Nakazono, K.; Ohno, H.; Yoshida, H.; Nakagawa, H. Effects of meteorological factors during grain development on pre-harvest sprouting in wheat. *Jpn. J. Crop Sci.* **2013**, *82*, 183–191. [CrossRef]

42. Fu, J.; Jian, Y.W.; Wang, X.H.; Li, L.; Ciais, P.; Zscheischler, J.; Wang, Y.; Tang, Y.H.; Müller, C.; Webber, H.; et al. Extreme rainfall reduces one-twelfth of China's rice yield over the last two decades. *Nat. Food* **2023**, *4*, 416–426. [CrossRef]
43. Nóia Júnior, R.D.; Deswarte, J.C.; Cohan, J.P.; Martre, P.; van der Velde, M.; Lecerf, R.; Webber, H.; Ewert, F.; Ruane, A.C.; Slafer, G.A.; et al. The extreme 2016 wheat yield failure in France. *Glob. Change Biol.* **2023**, *29*, 3130–3146. [CrossRef] [PubMed]
44. Scheitlin, K. The maritime influence on diurnal temperature range in the Chesapeake Bay area. *Earth Interact.* **2013**, *17*, 1–21. [CrossRef]
45. Espe, M.B.; Cassman, K.G.; Yang, H.S.; Guilpart, N.; Grassini, P.; van Wart, J.; Anders, M.; Beighley, D.; Harrell, D.; Linscombe, S.; et al. Yield gap analysis of US rice production systems shows opportunities for improvement. *Field Crops Res.* **2016**, *196*, 276–283. [CrossRef]
46. Morita, S.; Shiratsuchi, H.; Takanashi, J.; Fujita, K. Effect of high temperature on ripening in rice plants—Comparison of the effects of high night temperatures and high day temperatures. *Jpn. J. Crop Sci.* **2002**, *71*, 102–109. [CrossRef]
47. García, G.A.; Dreccer, M.F.; Miralles, D.J.; Serrago, R.A. High night temperatures during grain number determination reduce wheat and barley grain yield: A field study. *Glob. Change Biol.* **2015**, *21*, 4153–4164. [CrossRef]
48. Russell, K.; Van Sanford, D.A. Breeding wheat for resilience to increasing nighttime temperatures. *Agronomy* **2020**, *10*, 531. [CrossRef]
49. Araki, H. Studies on the tillering of winter wheat in Hokkaido IV. Varietal difference in the effect of tillering time on ear formation and yield. *Jpn. J. Crop Sci.* **2016**, *85*, 218–222. [CrossRef]
50. Iriki, N. Wintering potential and quality of wheat in the cold and snowy region of Hokkaido. *Kagaku Seibutsu* **2001**, *39*, 97–101. [CrossRef]
51. Cammarano, D.; Hawes, C.; Squire, G.; Holland, J.; Rivington, M.; Murgia, T.; Roggero, P.P.; Fontana, F.; Casa, R.; Ronga, D. Rainfall and temperature impacts on barley (*Hordeum vulgare* L.) yield and malting quality in Scotland. *Field Crops Res.* **2019**, *241*, 107559. [CrossRef]
52. Boogaard, H.; Wolf, J.; Supit, I.; Niemeyer, S.; van Ittersum, M. A regional implementation of WOFOST for calculating yield gaps of autumn-sown wheat across the European Union. *Field Crops Res.* **2013**, *143*, 130–142. [CrossRef]