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Technological Advancements and the Changing Face of Crop Yield Stability in Asia

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Abstract: Recent technological advancements have revolutionized agriculture in Asia, leading to significant changes in crop yield stability. This study examines the changing face of crop yield stability in Asia resulting from the increasing adoption of innovative technologies in agriculture. Through a review of current research and case studies, the impact of technology-driven changes on yield levels, variability, and predictability is explored. The study applies a yield stability index (YSI) to evaluate the yield stability of six crops in seven Asian countries during two periods (1961–1994 and 1995–2020), comparing the countries, crops, and stability changes between the two segments. The novelty of the research is the application of YSI, which, contrary to usual stability metrics, can distinguish between rare large extreme yields and frequent minor fluctuations, and based on this feature, evaluates the suitability of the prevailing technologies to local environmental conditions. The YSI is used to evaluate the stability of technologies, indicating whether the technologies can respond well to the annual variations of environmental conditions. Positive YSI values indicate stable technologies that can respond well to the annual variations of environmental conditions, and the concept of a well-technologized crop is used for crops in countries with stable positive YSI values, indicating the suitability of the actual crop to the actual geographical environment. These results can guide production technology developments and the introduction or abandonment of certain crops in certain geographical zones, especially regarding the implications of climate change and global warming. This study highlights the transformative power of technology in improving crop yield stability and food security in Asia, while discussing the potential challenges associated with these changes and the need for continued research to address them.

Keywords: agriculture; Asia; crop; technological advancements; yield stability

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1. Introduction

Crop production is strongly influenced by varying environmental conditions (Chen et al. 2018; Hao et al. 2007; Jallouli et al. 2022; Li et al. 2021; Madalla et al. 2022; Powell et al. 2012; Rahman et al. 2001; Ravi et al. 2013; Swegarden et al. 2016; Temesgen et al. 2015; Wachira et al. 2002), and production technology (management practices, such as crop varieties, fertilization, and cropping system types) should be able to respond to environmental features typical for the geographical zone of production. High yields should be achieved with low annual fluctuations, regardless of actual weather patterns. If yield variations remain minor, the technology produces yields that are consistent with expectations. However, infrequent occurrences of extremely low or high yields can pose significant challenges for both producers and consumers. Thus, an important goal of production technology development is to deliver high yields with reasonably small fluctuations around the rising annual trend.

The literature on food security analyses focus mainly on agricultural output, while the assessment of the stability aspect of food security is very uncommon. It involves some dynamic measure of outcomes over a given time horizon, measuring the deviation of the time series from a given threshold (Nicholson et al. 2021). Climate change is an obvious risk factor that may lead to more uncertain yields; although the relationship of climate change and food supplies have been extensively studied in the literature, they have not been analyzed specifically from a yield stability viewpoint.

Statistical dispersion measures, such as the standard deviation or coefficient of variation, are frequently employed to quantify the degree of variation. However, these indicators are usually unable to separate frequent small fluctuations from rare large ones, although the two cases have completely different effects on farmers' welfare and food supplies. Farmers generally consider small yield fluctuations to be an acceptable aspect of crop production uncertainties. However, an extremely low or high yield could have disastrous consequences for them. Finding a crop variety that yields well and is stable enough in the intended setting is the goal of crop variety selection (Kamidi 2001). Although the trend of rising yields is encouraging, growers are at danger from the yearly swings. Variations in yields lead to variations in the supply of specific products as well as in farmers' sales revenues. As multiple empirical studies have highlighted, this pertains to both low yields and insufficient supply, as well as high yields and surpluses that cause low prices and consequently low profitability (Kovářová et al. 2017; Kovářová and Procházková 2017).

In addition to obviously causing low incomes and economic losses in place of a healthy profit, excessively high yields may also have unfavorable effects on the economy. In spite of high yields, high outputs can cause the market supply to rise well above demand, which would eventually result in falling prices and low incomes if adequate storage facilities are not offered at a reasonable cost. As the example of sugarbeet production in the Czech Republic shows, (Kovářová et al. 2017; Kovářová and Procházková 2017) there is a correlation between high yields and lower producer prices. For milk yield and milk price fluctuations, as well as changes in milk turnover between 2006 and 2011, Kovářová and Procházková (2017) provided similar evidence. According to Tóth-Kaszás et al. (2017), producer risk aversion is a crucial trait of small-scale farmers. Finding a local market for their products is a critical issue for them. However, because there is a limited market, overproduction inevitably causes problems with sales and, ultimately, with turning a profit.

Agricultural support policies can help farmers reduce the risks associated with yield fluctuations, but they cannot guarantee safe supply levels in the event of low yields (Heinemann et al. 2014; Takács-György and Takács 2012).

Shifts in weather patterns due to climatic change require the development of varieties that have wider adaptability, showing high performance for yields, and other essential agronomic traits that are consistent (stable) over a wide range of environmental conditions (Becker and Leon 1988). Yield stability between varieties is due to the occurrence of interactions between genotypes and particular environmental conditions where they are grown. These interactions pose a continuous challenge among plant breeders and agronomists in making cultivar recommendations to farmers because of the associated consequences especially when selection is based on yield alone (Kang 1993; Kumar et al. 2020). This is due to lack of emphasis on both yield and stability in most breeding programs (Mekbib 2002; Kumar et al. 2020) as well as lack of appropriate policy in which variety are released without consideration of yield and stability simultaneously.

A production technology, including proper choice of variety that gives reasonably stable yields under all local weather and environmental conditions, might be the best defense against the risks caused by yield instability. As a result, there are no extreme highs or lows, and the producer can make future plans with confidence. Therefore, it is crucial to develop stable technologies that can adapt to shifting environmental conditions and provide high but steady yields.

The primary objective of technological advancement is to achieve greater crop yields, but this can result in yield fluctuations that generate revenue fluctuations for farmers, posing a significant risk for them. The negative correlation between crop yields and prices has been established by several studies (see for example Coble et al. 2000; Imai et al. 2011; Sherrick 2012; Kovářová et al. 2017). The definition of "reasonably stable" yield, i.e., of a measure of the deviation of the annual yield from an expected yield trend over time is an intriguing problem. A predicted trend of annual yields over time may guide farmers in planning for the coming years so they can estimate the expected costs and sales revenues, based on the expected yield. When actual yields deviate too much from the expected value, this creates a serious risk for the farmer. Therefore, such deviations should be rare and of a limited magnitude to facilitate viable farming. High yields are often related to higher yield variability (Khalili and Pour-Aboughadareh 2016; Nielsen and Vigil 2018), and producers may be more inclined to accept a high average yield with larger yield variance than lower yields and small yield variance. As a result, evaluations of yield stability should take into account both the average yield and the variability of the yield. Measuring the risk of a yield falling below a certain limit is more useful than measuring the general level of yield variances (Piepho 1998).

Different dispersion indicators are typically used to measure the time series fluctuation around the trend. Any introductory statistical text will describe the general usage of the following: the sum of squares of errors, the standard deviation, the coefficient of variation (the standard deviation divided by the mean value), and the sum of absolute errors (the absolute value of the difference between the actual value and the trend estimation) (see e.g., Kamidi 2001). There is a wealth of research on evaluating the stability of intertemporal crop yields, or more broadly, the variability of time series data.

Yield variability can be measured both at the individual crop variety level and at the national level—that is, the average yields of all the varieties of a particular crop grown in a particular area.

The standard deviation of the data, or the standard deviation of crop yields, is the most widely used technique to evaluate stability. However, other techniques are also employed, such as calculating the average percent deviation from a trend, whether it be linear or non-linear (Cuddy and Della Valle 1978; Piepho 1998).

According to Timsina et al. (1993), a cultivar is considered stable if it exhibits a high mean yield, a high regression coefficient for the regression line fitted to the yield time series, and as little deviation from regression as possible. Empirical studies have employed a range of metrics to assess yield stability, including the sum of the squared difference or percentage between actual and baseline yield over time for wheat yields in Australia (Bracho-Mujica et al. 2019) and rice yields in Nepal (Devkota et al. 2019); squared sums of differences between actual annual yields and average yields for oats in the UK (Howarth et al. 2021) and maize and legumes in South Africa (Madembo et al. 2020); and yield standard deviations for rice in Bangladesh (Assefa et al. 2021).

Regression-fitted yield series are commonly employed in yield stability measures; instability is quantified as the mean square deviation from the regression model. Khalili and Pour-Aboughadareh (2016), for instance, compare different barley cultivars and evaluate how well-adapted each is to particular natural conditions. High mean yields across environments with minimal variability or deviation from the mean yield are necessary for high adaptability, as these authors state. As measures of variability, they employ the coefficient of variation and the sum of squares of deviations surrounding a regression line.

Wang et al. (2012) evaluated yield variability for paddy rice, maize, wheat, and rapeseed in Yunnan province, China, using data from experiments on maize. They calculated the ratio of the residual values to the estimated trend values after determining the trend of each crop yield series. Positive residuals are not problematic in any way according to their assessment, but they view negative residual values as different degrees of disaster. Studies based on similar trends were conducted for Western Europe and the United States (Gollin 2006; Grover et al. 2009; Heinemann et al. 2014; Nielsen and Vigil 2018).

To measure the income stability that results from yield stability, the following indicators are generally applied: the absolute deviation of the series from the five-year moving average, or from the all-year average, or from its relative counterpart, which is calculated by dividing the absolute measure by the five-year moving average as can the corresponding standard deviations. In more intricate models, a regression equation is fitted, and the residual series' size, standard deviation, and standard error are evaluated (Harkness et al. 2021). Statistical dispersion indicators, such as the average percentage deviation from a linear or non-linear trend (Cuddy and Della Valle 1978), the coefficient of variation, the standard deviation or related indicators, the sum of the absolute errors (the absolute difference between actual values and trend estimations), and similar techniques (Vandewalle et al. 1997), are used to measure income time series fluctuations around a linear or non-linear trend.

Singular spectrum analysis (SSA) is another tool for analyzing fluctuations. It breaks down a time series into a set of components like trend, periodicities, and noise. Data series are deemed more stable if their periodicities span longer time intervals. Although SSA was successfully used in a South Korean study, Lee et al. (2016) noted that this technique does not provide much information regarding the actual size of the fluctuations, and because it is based on a fairly complex statistical model, it is challenging to interpret the computational results in a useful manner.

An AMMI (additive main effects and multiplicative interaction)-based selection index was created by Rao and Prabhakaran (2005) to integrate yield and stability when choosing genotypes tested in various environments. The univariate (ANOVA) and multivariate (principal component analysis) approaches are combined in this complex model, and the yield deviations from the mean values' sum squares are used to evaluate the stability of the various varieties.

There is one common trait in the above assessments of yield fluctuations: they use all fluctuations in a similar way, adding up small and large fluctuations alike, arriving at an overall measure of variance. However, as it was stated before, rare, but extreme fluctuations, especially extremely low values, pose a more severe situation for farmers than many minor ones (Bacsi et al. 2022), and it is more beneficial to measure the risk of a yield falling below a specific limit rather than the overall level of yield variance (Piepho 1998).

The term "weakly technologized crop" refers to crops with large yield variability (i.e., unstable yield time series) in a given time period (Bacsi and Vizvári 2002; Bacsi and Hollósy 2019b). This means that the farming technology—including choice of variety, sowing time, application of nutrients and pesticides, timing of harvest, etc.—are not well fitted to the environmental conditions of the growing region. To compare the yield stability levels of the same crop in the same region for different time periods can show how successful the farming technology improvements are in adapting the farming methods to the changing environment, including climate.

Bacsi and Vizvári (2002) developed a yield risk index to measure the occurrence of extremely high or low yields in a time series, while its 'inverse', the yield stability index (Vizvári and Bacsi 2002) quantifies the proportion of annual yields being reasonably close to the yield trend within a given time period. This index was adjusted and improved by (Bacsi and Hollósy 2019a, 2019b) and applied by the same authors for European countries and crops to evaluate the stability of coffee production worldwide (Bacsi et al. 2022).

The purpose of the present research is to assess yield stability for major crops in Asia and compare yield stability changes between the 1961–1994 and the 1995–2020 time periods. The analysis applies the yield stability index (YSI), originally developed in 2002 (Bacsi and Vizvári 2002; Vizvári and Bacsi 2002) and further improved and tested in 2019 (Bacsi and Hollósy 2019a, 2019b; Bacsi et al. 2022), to assess the extent of yield fluctuations. As it was explained before, yield fluctuations are usually assessed by the dispersion of the yield values around a yield trend, thus making no distinction between frequent small fluctuations and rare large fluctuations. The YSI index applied here was designed to distinguish between these two types of fluctuations, considering only the large fluctuations harmful. According to our best knowledge, no other indicators of stability are capable of doing this. The objective of the present research is, therefore, to compare major producers in Asia to see where the main crops are grown with stable technology under rising temperatures. Another objective is to demonstrate the advantage of YSI over traditional stability measurements to give guidance for policy formulation and managerial decisions. For this purpose, YSI results are compared to the coefficient of variation (CV%), which is a basic measure of the traditional fluctuation measurements, to show that YSI can give a different, and more relevant, assessment of stability by its underlying concept of distinguishing between small and large fluctuations.

The analysis deals with six major crops in Asia—i.e., bananas, coffee beans, palm oil, paddy rice, cotton seed, and tea—for seven countries who are important producers and exporters of these crops. The YSI values are computed for these crops and countries—first, for the 1961–1994 period, and second, for 1995–2020—to evaluate yield stability change between two time periods and identify stable, so-called "well-technologized" countries and crops. This kind of analysis has never been conducted for Asia, except for some coffee-producing countries (Bacsi et al. 2022); therefore, its findings may serve as a guideline for farmers and for agricultural policymakers in their future decisions.

The structure of the paper is as follows: Section 2 presents the methodology, starting with the explanation of data sources and the choice of crops and countries. Then, the explanation of splitting the time period of the analysis (1961–2020) to two sub-periods based on climate change trends to facilitate the comparison of yield stability values between an earlier, cooler, and a later, warmer time period. After that, the computation method of YSI is introduced, and its meaning and interpretation is explained. Section 3 presents the results, comparing YSI values between 1961–1994 and 1995–2020, comparing the YSI values to the CV% values of the same crops and time periods, and presenting well-technologized crops in the seven countries. Section 4 presents the discussion of the results, Section 5 draws the conclusions, and the paper ends with Appendix A of mathematical formulas to compute YSI.

2. Methodology

2.1. Choice of Crops and Countries to Analyse

Yield time series of crops and trade indicators were retrieved from the FAOSTAT da abase (FAO-QV 2022; FAO-QC 2022) for 1961–2020 to identify major crops in the Asian continent and the major producers of these crops. FAO-QC (2022) contains secondary data on the production quantities, areas harvested, and yields for all the countries of the world for crop and livestock products for the time period of 1961 to 2021. From this database, we collected yield time series and production quantity time series for the countries of Asia and the world total. The FAO-QV (2022) page was used to collect the production value of the crops of Asian countries and of the continent as a whole.

Crops were chosen, for which Asia produces at least 30% of the global value. The chosen crops are bananas, rice, palm oil, tea, coffee, and cotton seed (Table 1). As the last column of Table 1 shows, these crops are important in the total agricultural output of Asia, with their total output value representing around one-fifth of the continent's total output value (27.3% in 1990: and 19.3% in 2020). These crops over long time periods have been analyzed by many studies (Xu et al. 2020). Bananas are among the 10 most important food crops worldwide and are now considered a crucial but often underestimated food crop, providing a staple source of sustenance for millions around the globe because of their year-round production and high demand (Madalla et al. 2022; Ravi et al. 2013). Rice, being the second largest cereal crop, is considered as one of the most significant food crops worldwide (Zewdu et al. 2020). It serves as a staple food for almost half of the global population (Haryanto et al. 2008; Zhang et al. 2021). Palm oil is an economically important tropical crop which produces vegetable oil widely used in the production of food and detergents and as a feedstock for biofuel (Tao et al. 2017). Tea is a crucial commercial crop that has a significant impact on improving farmers' earnings and ensuring a good standard of living. Its popularity and broad acceptance by people worldwide have led to it becoming a highly profitable and sought-after crop (Islam et al. 2021; Zhao et al. 2022). Coffee is somewhat less significant in production than the rest of the selected crops, but it was included in the analysis. In a similar manner to tea, its production area is rather limited to Latin America, Africa, and Asia; therefore, Asia's contribution is not negligible. Also, as Bacsi et al. (202) show, 3 of the 12 largest producers are located on the Asian continent. Cotton, which is a major fiber crop, has a significant impact on a country's economy through industrial development (Shahzad et al. 2019).

Table 1. Asian production as % of total world output in value (International dollars at 2014–2016 value).

	Bananas	Coffee, Green	Tea	Rice, Paddy	Oil Palm Fruit	Seed Cotton	Total Agricultural Output of Asia	Selected Crops, % of Total Agricultural Output in Asia
			as % of Total World Output Value					
1990	38.8%	14.2%	78.9%	92.1%	72.3%	49.4%	38.5%	27.3%
1995	45.4%	20.3%	84.3%	91.2%	76.5%	64.5%	45.6%	23.8%
2000	49.6%	26.0%	83.4%	91.1%	80.6%	62.2%	47.1%	22.1%
2005	51.1%	27.6%	83.1%	90.5%	84.9%	62.3%	48.6%	21.2%
2010	55.2%	28.1%	83.4%	90.3%	87.7%	72.5%	50.5%	20.7%
2015	53.6%	31.8%	86.5%	90.2%	87.5%	68.8%	50.8%	19.2%
2020	54.0%	30.6%	83.1%	89.4%	88.6%	69.9%	51.1%	19.3%

Source: (FAO-QV 2022; FAO-QC 2022 data). The selected countries play important roles in some, or most, of the selected products, although their sizes differ; each of them has a larger share in production than their share in land area (see Table 2).

Table 2. Production value by country, as % of total production in Asia.

		China	India	Indonesia	Japan	Malaysia	Thailand	Vietnam	Asia	Selected Countries Total
Bananas	2015	17.7%	47.4%	15.4%	0.0%	0.5%	1.7%	3.2%	100.0%	85.9%
	2017	18.6%	49.2%	11.6%	0.0%	0.6%	1.8%	3.3%	100.0%	85.1%
	2020	18.3%	48.7%	12.6%	0.0%	0.5%	2.1%	3.4%	100.0%	85.6%
Coffee green	2015	4.1%	11.6%	22.7%	0.0%	0.2%	0.9%	51.7%	100.0%	91.3%
	2017	3.8%	10.5%	24.2%	0.0%	0.3%	0.9%	51.9%	100.0%	91.6%
	2020	3.5%	9.1%	23.7%	0.0%	0.1%	0.7%	54.0%	100.0%	91.0%
Oil palm fruit	2015	0.2%	0.0%	62.4%	0.0%	33.4%	3.8%	0.0%	100.0%	99.8%
	2017	0.2%	0.0%	67.4%	0.0%	28.2%	4.0%	0.0%	100.0%	99.8%
	2020	0.2%	0.0%	69.2%	0.0%	26.2%	4.2%	0.0%	100.0%	99.8%
Rice paddy	2015	32.4%	23.7%	9.2%	1.7%	0.4%	4.2%	6.8%	100.0%	78.5%
	2017	31.9%	25.0%	8.2%	1.6%	0.4%	4.9%	6.4%	100.0%	78.3%
	2020	31.6%	26.4%	8.1%	1.4%	0.3%	4.5%	6.3%	100.0%	78.6%
Seed cotton	2015	37.1%	35.1%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	72.2%
	2017	35.5%	36.1%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	71.7%
	2020	50.8%	30.5%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	81.3%
Tea	2015	46.0%	24.7%	2.7%	1.6%	0.2%	1.0%	4.7%	100.0%	80.9%
	2017	47.2%	25.3%	2.8%	1.6%	0.2%	1.5%	5.0%	100.0%	83.5%
	2020	51.1%	24.4%	2.4%	1.2%	0.2%	1.7%	4.1%	100.0%	85.0%
Land 1000 ha	2020	942,470.3	297,319	187,751.9	36,450	32,855	51,089	31,343	3,109,981	1,579,278
% of Asia		30.3%	9.6%	6.0%	1.2%	1.1%	1.6%	1.0%	100.0%	50.8%

Source: Authors' own computation, based on data from (FAO-QV 2022; FAO-QC 2022).

The choice of the countries is justified by the last column of Table 2. This column shows the share of the production values of the seven chosen countries within Asia. For example, oil palm fruit production value of the seven countries represent 99.8% of the production value of all Asia, and that of tea, 80.9% (in 2015), 83.5% (2107), and 85% (2020). The last two lines show the importance of these crops in terms of land use in 2020, by country. The six crops represent 942,470.3 thousand hectares in China, which is 30.3% of the total land area of Asia, while the total land area of the six crops in the seven countries add up to 1,579,278 thousand hectares, covering 50.8% of the total land area of Asia.

The selected countries are also important exporters of all seven products. This means that they cover about 62% of tea, 95% of green coffee beans, 98% of palm oil, 84% of rice, and 73% of cotton exports in 2020; although, the share of bananas is less, only around 14% (FAO-TCL 2022).

2.2. Choice of the Time Periods for Comparing Yield Stability Changes

The FAOSTAT time series spanned a period of 60 years, from 1961 to 2020, which was subsequently divided into two distinct periods.

This was done because of the patterns of the most important environmental change, i.e., global warming. The changing climate requires adaptation strategies from agriculture, and the success of these strategies should be reflected, among others, by the yield stability measures. Therefore, we decided to compute the yield stability indicators for two periods of time, with the cut-point of the 60 years being determined based on the temperature warming trends of the region.

The Goddard Institute of Space Studies is one of the major institutions dealing with climate change research. They publish annual temperature change data for the major geographic zones of the earth (GISTEMP Team 2021). These time series were used for segmenting the 60 years of analysis. The published temperature anomalies measure how much warmer or colder the actual year was at a particular location, than the average of the period 1951–1980 for that place. Regional mean anomalies are computed from temperature anomalies measured at the weather stations of the region. These measurements are used for interpolation based on dividing the Earth into 8000 grid boxes of equal area. Then, weighted averages are computed to provide anomaly values for the eight latitude bands of the earth: the polar region, the midlatitudes, the subtropics, and the tropics for both hemispheres (Lenssen et al. 2019). Table 3 shows the geographical latitude limits of the analyzed countries. Altogether, 86% of the total area of the analyzed countries fall within the equator and the 44° N latitude, 5.8% lies below the equator, and 8.8% above the 44° N. Therefore, it is reasonable to rely on the temperature anomalies of the latitude bands of the equator to 24° N, and 24° N to 44° N in defining the relevant time periods for the analysis.

Table 3. Geographic location of the analyzed countries.

Country	Total Area, Million km^2	Agricultural Area, %	Northest Latitude	Southest Latitude
China *	9.6	12	53°33′ N	20°14′ N
India	3.3	53	37°06′ N	6°45′ N
Indonesia **	1.9	34	6°45′ N	11°0′ S
Japan	0.38	20	45°33′ N	20°25′ N
Malaysia	0.33	26	7°22′ N	0°51′ N
Thailand	0.51	46	20°28′ N	5°37′ N
Vietnam	0.33	39	23°23′ N	7°54′ N

*: 15% of the area over 44°N latitude; 50% of the area south of the equator. **: less than 15% of the area below the equator; Source: authors' own calculation based on public data of (World Population Review Website 2023).

Figure 1 displays the mean temperature shifts on a global scale, and also provides a breakdown of these changes for the specific latitude regions of the analyzed countries. Comparing the temperature anomaly data for the latitudes of the 24–44° N zone and the equator—24° N zone, a polynomial trend of the power 4 is fitted. The two fitted curves meet at 1995, i.e., up to 1994 the area near the equator warmed up more; but after 1995, the northern latitudes show faster warming than the northern latitudes near the equator. The visual analysis of the raw data also suggest that the equatorial zone showed somewhat larger anomalies in the first period, while during the second period, the higher latitudes reflect definitely higher anomalies than the lower latitudes.

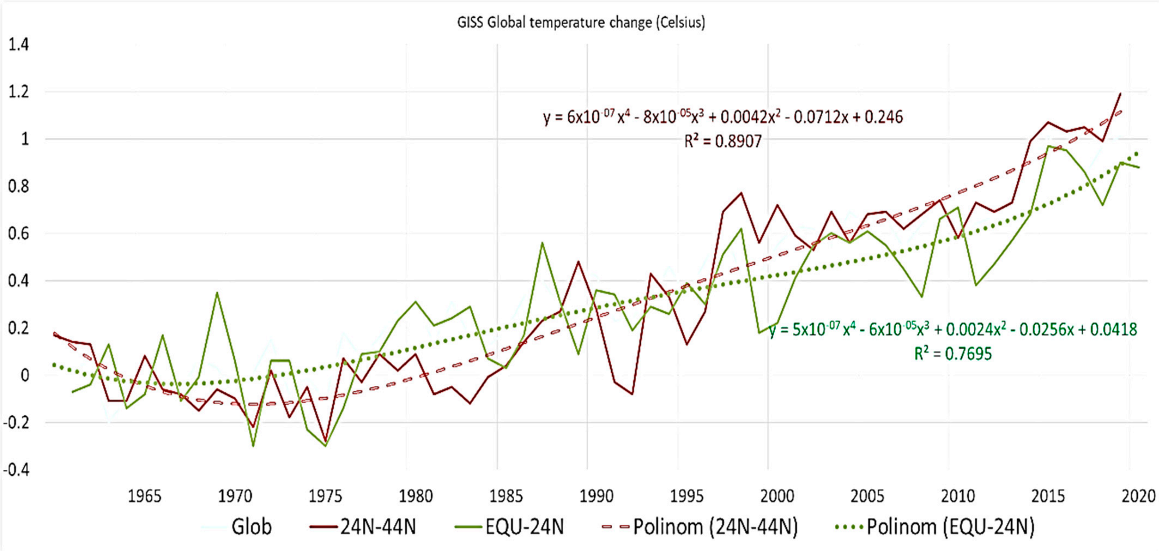


Figure 1. Global temperature anomalies (annual mean temperature—mean temperature of 1951–1980) for the 24–44° N, and for the equator–24° N latitudes. Source: authors' own construction based on data from (GISTEMP Team 2021).

Thus, we partitioned the 60-year study period into two distinct segments: the initial period, spanning from 1961 to 1994 (encompassing 34 years), and the subsequent period, covering the years from 1995 to 2020 (encompassing 26 years). These trends suggest that for Indonesia, Malaysia, Thailand, and Vietnam, the second time period may pose less of a challenge than for China, Japan, and for most of India. Therefore, we assume that splitting the analyzed 60 years to a period before 1995 and a period after 1995 would allow a reasonable comparison of stability measures.

Although this way of segmenting the 60 years is certainly not the most rigorous way, we believe that it is still a reasonable, though simple, approach for assessing stability changes in cropping systems of the analyzed region. Our aim here is not to give a scientific segmenting of the 1960–2020 time range by climate change patterns, but to create a basis for a meaningful comparison of yield stability characteristics between a cooler and a warmer time period. Further research will be focused on defining a more rigorous way of segmenting long time periods for analysis and comparison.

2.3. Statistical Analysis, the Computation of the Yield Stability Index

The value of the yield stability index (YSI) was computed for each country, for each crop for the two time periods. The larger the index, the more stable (i.e., less fluctuating) the crop yield in the given time period. The term 'weakly technologized crop' was applied to crops with negative YSI values (i.e., those showing large fluctuations during the analyzed periods (Bacsi and Hollósy 2019a, 2019b; Bacsi and Vizvári 2002).

The computation of the yield stability index (YSI): the index is computed according to the methodology devised by Bacsi and Vizvári (2002), and revised by Bacsi and Hollósy (2019a, 2019b).

Annual yield series of a given crop are collected over a specific number of years for a given country or geographical area. The computation of the measure of fluctuations is the following.

First, we rescale the data by dividing them by the yield series average because the size of the fluctuations naturally depends on the size of the entire time series. As a result, our rescaled yield series show yields in relation to the study period's average yield. The benefit of this strategy is that even when yield levels vary because of production intensity or climate, the rescaled yield series of different crops and different nations become comparable from a stability perspective, as the rescaled values express the actual yield of a particular year as a proportion of the average yield.

A similar effect could be achieved by normalization, which involves subtracting the minimum value and dividing the remaining amount by the difference between the maximum and minimum values. This procedure is also suitable to make the yields of different crops and nations comparable. But since normalization converts each yield series into a 0–1 interval, all variations would likewise become 0–1 fluctuations. A yield series, for instance, with values 90%, 100%, and 110% of the average value would be normalized to produce a series with values of 0, 0.5, and 1 in that order, and the same normalized values would be attached to a series with values 50%, 100%, and 150% of the average. Rescaling, or dividing by the average, accurately conveys the fact that the first series fluctuates significantly less than the second series, which normalization is unable to capture. As a result, the first series becomes 0.9, 1.0, and 1.1, while the second series becomes 0.5, 1.0, and 1.5.

Thus, rescaling is performed to convert the yield series into comparable numbers for this purpose, while maintaining the character of the fluctuation. Then a linear regression line is fitted to the rescaled yield series to identify the yield trend. The difference between the actual rescaled series and the yield values calculated from the fitted line is the series' residual. As the growth trend is the expected yield tendency, the residual values represent the actual fluctuation of the yield series around this trend.

Measuring the size of the residuals is the third stage in determining whether fluctuations are small enough to classify the series as stable or large enough to classify them as unstable. To make this classification, we use the normal distribution for comparison with zero mean, and with standard deviation of the residual series. When we are working with more than one country, i.e., more than one yield series, the average of the standard deviations of the respective residual series is used for the normal distribution. If our residual series have at least as many values in the vicinity of zero (i.e., "small" residuals), as is the case for the normal distribution, we can consider our series stable, and if the case is the opposite, the residual series are unstable.

The index of stability is defined based on the above concept. The range of the rescaled yield residuals are divided into ten equal segments (deciles). When a group of countries is analyzed, the standard deviation for the normal distribution is the average of all the residual standard deviations of the assessed countries, and the minimum and maximum of the residual range are taken as the minimum and maximum of all the countries. Thus, for a given crop, the same residual range and normal distribution is used for the ten segments for each country.

Next, we quantify the difference in the distribution of the rescaled residual values and the normal distribution. If a large number of the residual values fall close to zero, that is, in the segments that are adjacent to the middle segments containing the value zero, then the residual values are stable. Thus, we define the four middle segments as 'favorable segments', and measure the proportion of the rescaled residual values that fall into these segments. This proportion is called favorable residual frequency (*frf*). Unfavorable segments are defined to be the lower three and the upper three segments, because these contain values that are far from zero, i.e., either too low or too high, representing large fluctuations. The proportion of residual values that fall into these unfavorable segments is computed, and called unfavorable residual frequency (*urf*). Then, for the purpose of comparison, the favorable normal frequency (*fnf*) is defined as the proportion of values from the normal distribution that fall into the middle four segments, while unfavorable normal frequency (*unf*) is defined as the values of the normal distribution falling into the unfavorable segments, i.e., the lower or the upper three segments. From the statistical theory of distributions, it is obvious that $frf + urf = 1$ and $fnf + unf = 1$.

Next, the difference between the rescaled residual frequencies and the respective normal frequencies is computed. The favorable difference *is* $fd = frf - fnf$, and the unfavorable difference is $ud = urf - unf$. A positive *fd* value indicates that more residuals fall close to zero than it would for the normal distribution, i.e., our residual series are more stable than the normal distribution. A positive *ud*, on the contrary, means that more residual points fall far from zero, than those predicted from a proper normal distribution, i.e., the fluctuations are larger in absolute value, than for a normal distribution.

A large positive *fd* and a small, negative *ud* are necessary for stability, i.e., for a series that is more stable than the normal distribution. Consequently, the definition of the yield stability index is: $YSI = fd - ud$. It is evident from the mathematical concept of distributions that $ud = -fd$, since $urf = 1 - frf$ and $unf = 1 - fnf$, and then $YSI = 2 \times (frf - fnf)$.

In this manner, it is possible to compare the index values between time periods of varying durations directly. The positive values of YSI indicate that the residual series have more small fluctuations (and consequently, less large fluctuations) than would be predicted from a normal distribution, while negative YSI values mean that the residual series have more frequent large fluctuations than would be expected from a normal distribution. The absolute value of YSI indicates the size, or level of stability, and can be used to compare countries and crops.

Since both *frf* and *fnf* have values between 0 and 1, the YSI values should, in theory, fall between −2 and +2. These theoretical limits can be considered when evaluating the actual values of YSI computed for a given series in order to determine the actual level of stability attained. Naturally, these lower and upper bounds are approximations rather than exact numbers; their purpose is merely to suggest the range of values that could be found in the index. An even more accurate estimate can be obtained by considering that in a normal distribution with zero mean and standard deviation s, roughly 95% of the values fall between −2 s and +2 s and roughly 68% of its values fall between −s and +s.

For a mathematical formulation of the procedure, see the Appendix A.

The validity of the YSI is derived from the computation method. Considering the fluctuations of the yield series around a yield trend, the index allows that yields show a—hopefully growing—trend over time, due to improvements in agricultural inputs and farming methods. It is natural that yields fluctuate around this trend due to actual environmental anomalies, but fluctuations should be mostly small, and large fluctuations occur rarely. The index measures whether large fluctuations occur more frequently than they should normally (i.e., assuming a normal distribution for the yield series). The positive values of YSI mean that large fluctuations are less frequent than in the normal case, and the larger the positive value, the less frequency of large fluctuations are experienced. With negative YSI, the frequency of the large fluctuations is higher than in the normal case, and the more negative (i.e., smaller) values show more frequent large fluctuations. Because for each particular crop, the reference normal distribution is the same (derived from the average of the analyzed countries), the YSI values for the same crop are comparable across countries.

The computation method gives an index that is directly comparable for time periods of different lengths and crops with different magnitudes of mean yields. As the computation method shows, YSI does not count with the occurrence of small deviations; therefore, its large positive value means that there are very few—if any—large fluctuations, and its negative value indicates that there are many large fluctuations. Based on the computed YSI values, crops with positive YSI are called well-technologized crops for a given country and time period. The term suggests that stable yields are due to a proper farming technology, including the choice and application of inputs, and the timing of the various farming events; therefore, regardless of the annual environmental changes, the crop yields remain close to the expected trend. Thus, the YSI values of the two time periods are compared to assess the improvement or deterioration of technologies in response to the changing patterns of climate.

To illustrate the benefits of YSI as a stability measure, the coefficients of variation ($CV\% = 100 \times$ standard deviation/average of the series, %) are also computed for the same data series. Because the CV% is the usual basis of traditional deviation measures, often used for assessing yield stability (Li et al. 2021; Raseduzzaman and Jensen 2017; Zhang et al. 2021), it is important to see whether YSI can give different information than CV%. As CV% cannot separate frequent small fluctuations from rare large ones, it can give high values for yield series having many small or medium fluctuations, while YSI would consider these series stable. On the other hand, CV% may be relatively small for series having a number of large fluctuations, while YSI considers such series rather unstable. The validity of YSI is strengthened if we could demonstrate that YSI is capable of capturing this difference, which CV% does not reflect. YSI has been applied for coffee, and for many arable and vegetable crops, mainly in Europe, and its validity has already been tested by several authors (Bacsi and Vizvári 2002; Bacsi and Hollósy 2019a, 2019b; Bacsi et al. 2022; Popp et al. 2021; Oláh et al. 2022; Benes et al. 2022).

3. Results

Figure 2 presents the YSI for the two time periods, by crop and country. Positive YSI values mean stable yields, negative values unstable ones, YSI varies between −0.4 and 0.4.

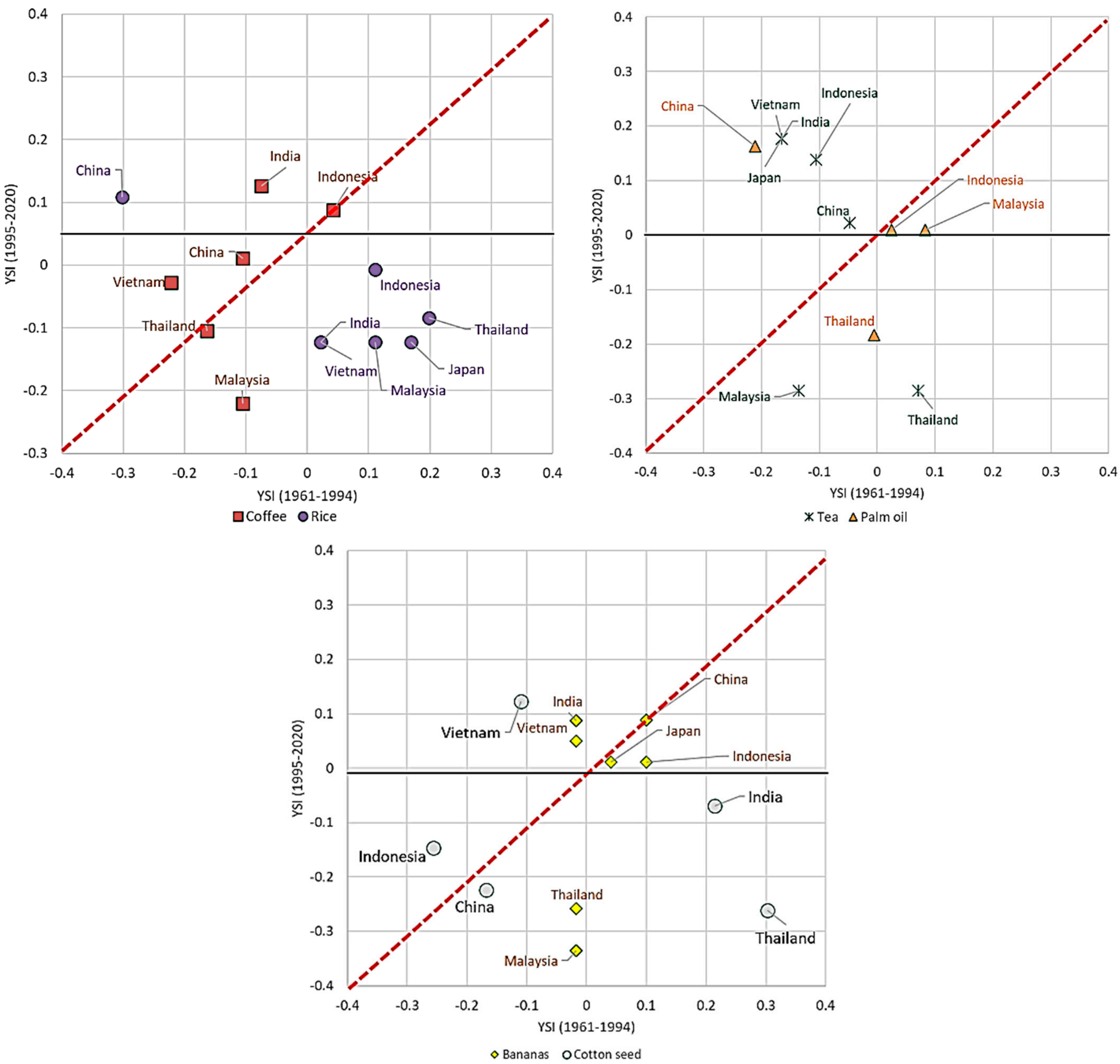


Figure 2. Yield stability index values for the two time periods, six crops and seven countries.

Values above the red dashed line indicate increasing yield stability (i.e., larger YSI values in the second period than in the first one), while values under it reflect decreasing stability from the first to the second period. Most of the coffee values improved (with the only exception of Malaysia), while most of the rice values worsened, with the only exception of China. In China, rice is the main staple food and its production is the core to ensure food security, which is a top priority in the development strategy of China (Wang et al. 2022; Xu et al. 2020). Over the past two decades, China's Super Hybrid Rice Breeding Program has made significant progress (Huang et al. 2017).

The stability of palm oil worsened, except for China, while tea yields became more stable, except for Malaysia and Thailand. The results for bananas are more mixed; India and Vietnam improved banana stability, actually moving from a negative, unstable YSI to a positive, stable value. Vietnam and Indonesia improved their yield stability for cotton, but Vietnam is the only country with stable cotton yields (positive YSI), and Indonesia, in spite of the improvement, is still unstable (negative YSI), though the extent of instability is considerably less in the second period than it was in the first one.

Figure 3 presents the YSI values together with the respective CV% values. According to the concept of YSI large yield fluctuations should show negative YSI values, and stable yields should be associated with positive YSI, with larger absolute values indicating greater extent of stability or instability, respectively.

According to the concept of CV%, however, high CV values indicate instability, while small CV values indicate stability. If YSI were not different from other, standard-deviation-based stability measures, then the conclusions drawn from YSI should be the same as the conclusions drawn from CV%. However, looking at the figure, this is not always true. There are countries and crops with small CVs—i.e., stable—with negative YSI values for rice (China in the first period, Malaysia, Japan, Thailand for the second one), for bananas (Malaysia, Thailand in both periods), when CV indicates stable yields, while YSI points to instability. On the other hand, there are remarkable examples of high CV suggesting instability, and positive YSI, suggesting stability, for tea in Thailand, bananas in Indonesia for the first period, or small CV and a markedly negative YSI for rice and palm oil in China in the same time segment. Similarly, contradictory values are seen in the second time segment for cotton seed and palm oil in Thailand (negative YSI and small CV), tea and cotton seed in Vietnam or coffee in China (high CV, but positive YSI). These values indicate that YSI really gives a different assessment of yield stability than CV%, and the reason of this difference is that YSI is based on measuring only large fluctuations and can provide more finely tuned information regarding yield stability than the traditionally used standard deviations or variances of time series.

Figure 4 compares the average yields and YSI values between the two time periods.

As the figure shows, average yields increased for most countries and crops, with the exception of bananas in Malaysia and Japan, and coffee and cotton in Indonesia. The highest yield increases were experienced for bananas, coffee, tea, rice, cotton seed, and palm oil (i.e., all crops) in China, and for tea in Thailand. However, the positive tendency does not hold for YSI; at least half of the crops expressed higher volatility (i.e., decreasing YSI) with the increasing average yields. This means that although production technologies increased the yield levels, they could not mitigate the adverse effects of the changing environment. A very interesting example is tea in Thailand, with considerable yield increases, but changing its YSI values from the positive in the first period to the negative in the second one.

Table 4 describes the well-technologized crops in both time periods by country. Well technologized crops are those with positive YSI values. As it was shown previously, crops and countries considerably changed in this respect from the earlier to the later time periods. The last two columns of the table show the number of crops with positive YSI values, i.e., the number of well-technologized crops, and the proportion of these crops among the analyzed crops. Similarly, the last two lines of the 1961–1994 and 1995–2020 blocks of the table show the number of positive YSI values per crop, i.e., the number of countries where the crop is grown in a well-technologized way, and the proportion of these countries among the analyzed countries. Negative YSI indicates that the crop is not well-technologized, i.e., management options are not well adapted to the environment. The number of positive values by crops has changed, with bananas, coffee, tea, and palm oil having more well-technologized countries (i.e., positive YSI values) in the second period, while rice and cotton having less countries with positive YSI. Looking at countries, we see that the number and proportion of well-technologized crops (those with positive YSI values) increased for China, India, and Vietnam, and decreased for Malaysia and Thailand, while remained the same for Indonesia and Japan.

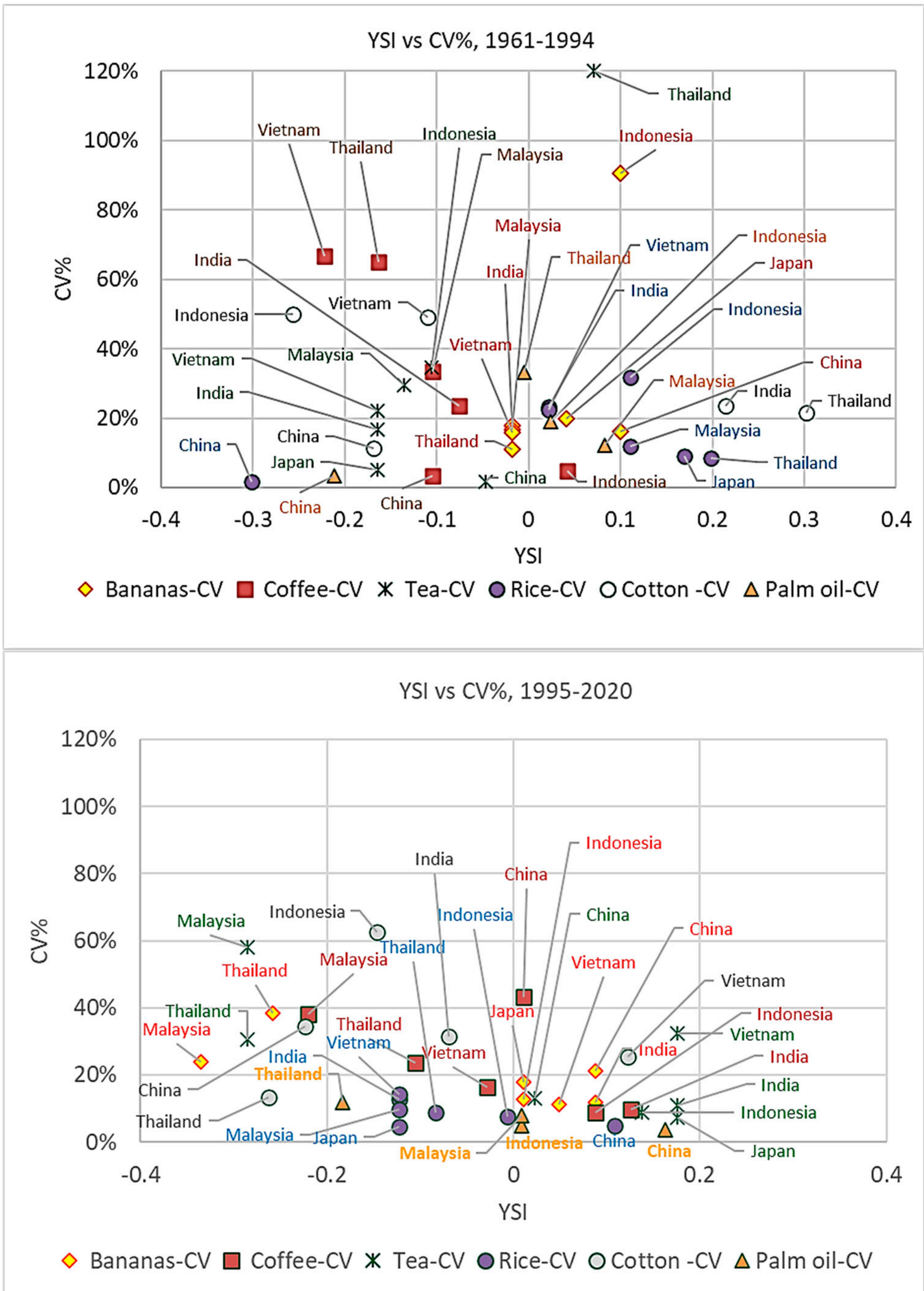
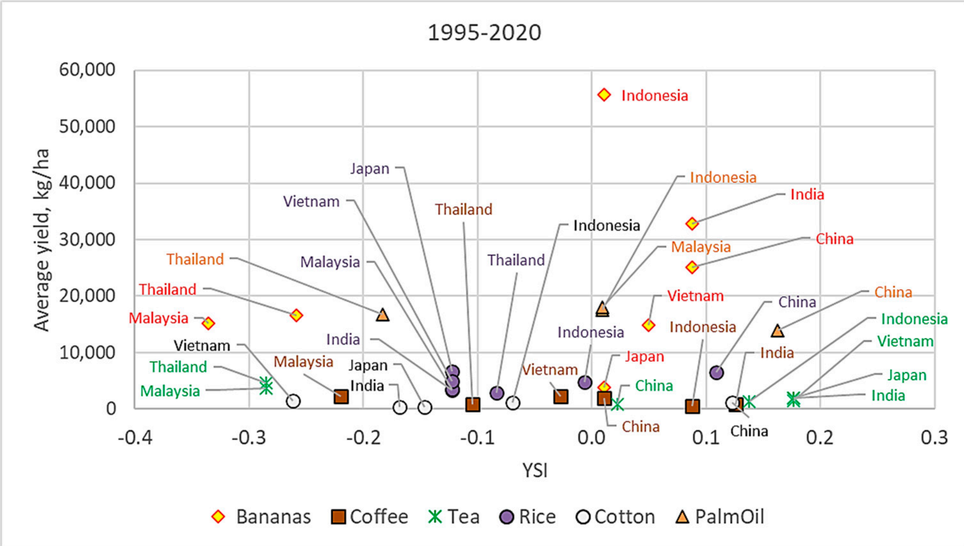


Figure 3. CV% versus YSI, for 1961–1994 and 1995–2020.



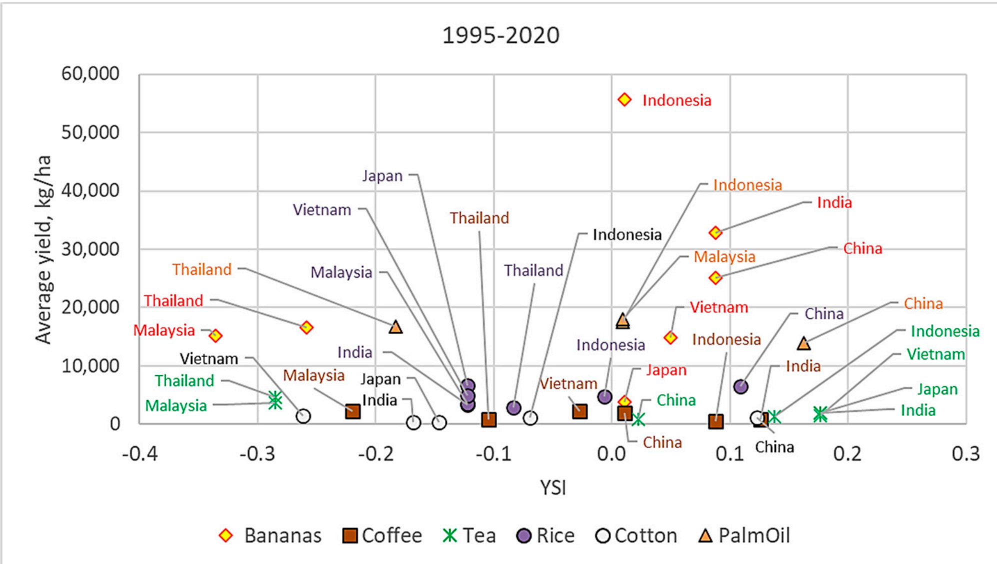


Figure 4. Average yields and YSI values for 1961–1994 and 1995–2020.

Table 4. Well technologized crops in the six countries for the two time periods.

	Bananas	**Coffee**	**Tea**	**Rice**	**Cotton Seed**	**Palm Oil**	**No. of WT Crops**	**Proportion of WT Crops**
Country				YSI 1961–1994				
China	0.0996	−0.1046	−0.0472	−0.3015	−0.1684	−0.2111	1	1/6 = 0.167
India	−0.018	−0.0752	−0.1648	0.0221	0.2139	NA	2	2/5 = 0.400
Indonesia	0.0996	0.0424	−0.106	0.1103	−0.2566	0.0242	4	4/6 = 0.667
Japan	0.0408	NA	−0.1648	0.1691	NA	NA	2	2/3 = 0.667
Malaysia	−0.018	−0.1046	−0.1354	0.1103	NA	0.083	2	2/5 = 0.400
Thailand	−0.018	−0.1635	0.0705	0.1985	0.3022	−0.0052	3	3/6 = 0.500
Vietnam	−0.018	−0.2223	−0.1648	0.0221	−0.1096	NA	1	1/5 = 0.200
no. of WT countries	3	1	1	6	2	2		
proportion of WT countries	3/7 = 0.429	1/6 = 0.167	1/7 = 0.143	6/7 = 0.857	2/5 = 0.400	2/4 = 0.500		

Table 4. *Cont.*

	Bananas	Coffee	Tea	Rice	Cotton Seed	Palm Oil	No. of WT Crops	Proportion of WT Crops
Country				YSI, 1995–2020				
China	0.088	0.0108	0.0225	0.1087	−0.2234	0.1629	5	5/6 = 0.833, +
India	0.0877	0.1262	0.1764	−0.1221	−0.0696	NA	3	3/5 = 0.600,+
Indonesia	0.0108	0.0877	0.1379	−0.0067	−0.1465	0.009	4	4/6 = 0.667, Ø
Japan	0.0108	NA	0.1764	−0.1221	NA	NA	2	2/3 = 0.667, Ø
Malaysia	−0.3354	−0.22	−0.2852	−0.1221	NA	0.009	1	1/5 = 0.200, −
Thailand	−0.2584	−0.1046	−0.2852	−0.0836	−0.2619	−0.1833	0	0/6 = 0.000, −
Vietnam	0.0493	−0.0277	0.1764	−0.1221	0.1228	NA	3	3/5 = 0.600, +
no. of WT countries	5	3	5	1	1	3		
proportion of WT countries	5/7 = 0.714, +	3/6 = 0.500, +	5/7 = 0.714, +	1/7 = 0.143, −	1/5 = 0.200, −	3/4 = 0.750, +		

Note: '+' increase from 1961–1994 to 1995–2020, 'Ø' no change, '−' decrease. WT—well-technologized; NA—data are not available or the crop is not planted in the certain country.

The largest technological improvement is seen in China that has positive YSI for all crops except cotton seed by the second time period. However, China is among the top countries in both cotton production and consumption (Li et al. 2021; Shahzad et al. 2019). Furthermore, China has implemented intensive farming technologies, such as plastic mulching, plant topping, and pruning over the past four decades (Dai et al. 2015). The second and third places are taken by Indonesia and Japan. Their positions did not change between the two time periods, while India and Vietnam improved their positions, while Malaysia and Thailand deteriorated. Thailand has actually no positive YSI value in any of the crops in the second time period.

4. Discussion

Traditional agricultural practices have been altered by the invention and application of agrochemical technologies such as pesticides, herbicides, and fertilizers since the 1950s and 1960s, when the Green Revolution began. Agrochemicals, machinery, infrastructure, biotechnologies, and land management techniques were developed to improve yields and increase production efficiency. The main drawbacks have been the deterioration of the environment and atmosphere, such as air and water pollution; a decline in biodiversity; and the disruption of entire ecosystems (Ruzzante et al. 2021).

Asia's Green Revolution began in the middle of the 1960s with increasing irrigation investments, the creation of better seed types, and the application of contemporary inputs like pesticides and fertilizers. Concerns about food shortages due to increasing population necessitated technological advancements to reduce the usage of land, and to raise yields with the use of contemporary inputs and high-yielding crops. Mechanization increased as a result of a shortage of farm labor. Improved management techniques, increased chemical fertilizer use, and the adoption of semidwarf, fertilizer-responsive high-yielding cultivars were all implemented in the intensive agricultural systems. Modern cultivars may yield more than their more traditional counterparts, but they may also be more vulnerable to pests and diseases. Alternatively, modern cultivars may be engineered for yield stability, with enhanced resistance against various pests and diseases, superior grain quality, and a shortened cropping season. Chemical inputs have been replaced with knowledge-intensive crop management techniques like timely fertilizer application and extensive pest management. Other advancements include the use of irrigation systems or agricultural technology that is resistant to harsh weather conditions like drought and floods (Estudillo et al. 2023). The results of these developments had their impact on the crop yields and production in Asia.

The YSI was successfully applied for 10 countries and 18 crops for the time period of 1961–2000 (Bacsi and Vizvári 2002; Vizvári and Bacsi 2002), and then for the same crops and countries for 2002–2016 (Bacsi and Hollósy 2019a, 2019b), and for coffee green bean yields of 12 major producers for 1961–1994 and 1995–2020 (Bacsi et al. 2022). These studies compared the production efficiency and reliability of crops that reflect the improvements of production technology in view of climate change and the changing agricultural policies, identifying the suitability of crops and production technologies to the external conditions of the area. These studies already demonstrated the validity of YSI and its advantage over the standard-deviation-based traditional fluctuation measures.

As it was demonstrated in the Introduction, yield stability has been measured usually by the standard deviation, or the CV% of the yield series, and most methods are based on this concept, although they may use sophisticated multivariate statistical measures to decompose the influencing factors leading to instability. As our results show, using a different concept, we may end up with different conclusions, as our YSI values and the conventional CV% values led to different conclusions regarding crops and countries.

Comparing the two time periods (1961–1994 and 1995–2020), we could see the impacts of the warming climate, together with the adaptation responses that various Asian countries applied in response, by the changing values of YSI. Looking at the proportion of well-technologized countries, we see that in rice production, the adaptation was not very successful because in the first, cooler period, 86% of the countries produced stable yields, while in the warmer, second period, only 14% (one country, China) could produce stable yields. Similar results are found for cotton, for which the proportion of well-technologized countries decreased from 40% to 20%, from the cooler period to the warmer one. Coffee in Asia, however, benefited from the warming, with 50% of the countries becoming stable from the earlier 17%. Similar improvement is seen for tea, with 14% of the countries producing stable yields in the cooler period and 71% of them in the warmer period. The proportion of well-technologized countries also increased regarding palm oil yields, from 50% to 75%, indicating a successful adaptation response for the warming climate. In banana production, the adaptation response was similarly successful because instead of the 43% of countries showing stable yields in the first period, 71% of the producers achieved stable yields in the second period.

Results comparing crops or crop genotypes for their adaptability to environmental changes are abundant, although not for the same countries and crops as in the present paper.

As a major staple food, one of the most frequently analyzed crops is rice. Assefa et al. (2021) analyzed rice-based cropping systems in Bangladesh from 2016 to 2019 and found that rice yields greatly depended on year, i.e., weather and location, and on variety, and other management decisions too. They also established that crop yield variations contributed greatly to the economic risk of farmers. Another study of rice production (Khumairoh et al. 2018) found the same dependence of rice yield variability on weather and other environmental factors, but according to their results, yields in conventional management systems showed much higher fluctuation (with CV = 22%) than in organic farming systems (CV = 14%), though the yield levels were generally lower in the latter one. Lee et al. (2016) tested yield stability for South Korea for seven crops, including rice, and found that rice was the most stable crop in terms of yield and of price fluctuations compared to potatoes, peppers, beans, radishes, cabbage, and maize. Bose et al. (2014) analyzed 12 rice genotypes in India during 2009–2012 in field experiments with different management practices for their adaptability to different environments according to various yield stability measures, relying on mean yield and fluctuation, but these various measures gave different results.

For cotton yield analysis in India, yield gap analysis, i.e., the difference of expected research station yields and the actual farm yields, showed that this difference depends on the planted variety and also on the application of inputs and other management practices (Elum and Sekar 2015). This underlines that yield variability may be due not only to the differences of the environment, but also on farmers' management decisions in the case of cotton, too. In China, cotton production at a high yield level is largely due to adoption of a series of intensive farming technologies, but unfortunately, at the price of enhanced pollution from chemicals (Dai and Dong 2014). These authors state that cotton seed yields also varied according to location and environment, as well as the management practice applied, such as grain-cotton intercropping or sole cotton systems. Climate change, with rainfall uncertainties in the cotton-growing regions of China contributed to a decreasing yield trend between 1960 and the 1990s, while a recovery was experienced in the second half of the 1990s. The scale of cotton planting had an influence on yield stability, the small scale production resulting in yield instability, due to low mechanization, greater waste of water and fertilizer, and other production inefficiencies (Dai and Dong 2014).

For coffee, there are more similar results as ours. Bacsi et al. (2022) conducted a yield stability analysis for coffee producer countries using the same methodology as the present paper for the major coffee producers in Africa, South America, and Asia. This analysis contained India and Indonesia, with the same results as ours, while Africa proved to be less stable, South America less stable in the first period and more stable in the second period, than our Asian sample. Another study for coffee (Benes et al. 2022) applied the same concept of YSI as ours, but with a refinement of the segmentation procedure for assessing the stability of roasted coffee quality from 14 green coffee varieties over the world. This analysis proved that not only the yield quantity, but the yield quality can show fluctuations according to coffee variety and processing technology.

Regarding tea, a study about the impacts of agrometeorological variables on tea yield variability in south India during the period of 1981–2015 (Raj et al. 2019) applied CV% values to show that both climate variability and geographical location influenced tea yields considerably, with the contributions of climate factors—especially temperature variability—accounting for approximately 84.8% of the yield variability. Variations in yields and quality in the different environments were tested in Kenya for 20 cultivars in three locations (Nyabundi et al. 2016), and as most tea husbandry practices being uniform across tea growing regions, the choice of cultivar could lead to moderate variations of CV = 14.77%. A much earlier study (Singh et al. 1995) for 1988–1992 for 13 genotypes of tea in northeast India measured yield stability by mean square deviation, and found that this index was 20 times higher for the most unstable cultivars than for the most stable ones, again indicating the different adaptability of genotypes to different environmental conditions.

A recent study on palm oil yield stability in Indonesia (Iddris et al. 2023) assessed the effects of conventional vs. reduced fertilization rates and herbicide vs. mechanical weeding. During the four-year experiment of 2017–2020, neither the cumulative yields nor the yield stability indicators differed significantly by the management options. In an earlier study, palm oil yield and temporal stability were tested during 15 years of a field trial in Sumatra, Indonesia, from 1998 to 2015, based on CV as the measure of stability (Tao et al. 2017), finding strong effects of climate on yield fluctuations, while other management differences had little impact. The results showed that yields varied in the range of CV = 15% to 20%, according to various management options, but without significant differences. An earlier study about 38 oil palm cultivars in four locations in Malaysia analyzed genotype yield stability by environment (Rafii et al. 2012), finding that seven genotypes were stable and had consistent performance over the environments based on yield standard deviation and CV values, with CV% of 31.1% to 41.1% for the 38 cultivars. An earlier research (Okoye et al. 2011) compared 15 oil palm genotypes in Nigeria to test yield stability across four environments, applying various statistical methods for assessing stability, including total deviation from a yield regression line, with CV varying between 25% and 45%. Significant interaction was found between genotypes and environments, suggesting specific adaptation, but different measures of stability indicated slightly different assessment of genotypes. Two genotypes proved to be high yielding with stable performance, so farmers could be assured of reliable yield from season to season.

Climate variables showed a negative significant relationship on production banana yields in the Philippines (Anzures et al. 2022); therefore, farmers have to be prepared for the adverse risks of climate change on their crops. Salvacion (2020) assessed the effect of climate on banana yield also in the Philippines from 1991 to 2016, finding that 71% of banana producing areas experienced significant increasing yield trends, while only 10%

were significantly affected by climate. Compared to rainfall, temperature had the greater influence on yield variability, but its effects varied from positive to negative between geographical locations. The adaptation pattern of genotypes and their yield stability were examined in banana production in Nigeria (Tenkouano and Baiyeri 2007) using several statistical methods based on the AMMI analysis. Yield stability and adaptation pattern of genotypes showed that the most stable cultivars had lower yield averages, while the highest yielding variety was found to be the most unstable. Varma and Bebber (2019) showed that for 27 countries in Africa, Asia, and South America, the changing climate between 1961 and 2019 had a positive effect on banana yields on average. Based on the estimation of yield trends, and the deviation of actual yields from the trend they estimate that African producers will continue to see benefits of climate warming on yields in the future, although other regions may face negative impacts. Climate and technology will both have their influences on yield, and quantifying them allows us to estimate which countries are at risk from climate change and which ones are capable of mitigating its effects, or capitalizing on its benefits.

Several other empirical results exist for crops not covered in our analysis, e.g., for oats in Ethiopia (Kebede et al. 2023), for chickpeas in India (Kumar et al. 2020), energy crops in the EU (Popp et al. 2021), maize in several locations (Kang 1993), and cereals and vegetables in Europe and North America (Bacsi and Hollósy 2019a, 2019b), using various methods for evaluating yield stability, but all agree that both climate impacts and the impacts of management decisions regarding farming technology interact in creating actual yield fluctuations. Shojaei et al. (2021) used the AMMI methodology for maize in Iran, comparing 12 maize hybrids under different environmental conditions for a two-year study using similar stability measures as Bose et al. (2014). Their results also showed different stability rankings by choice of stability index, and the same genotype may show different stability values in different environments. In our findings, we also found that the same crop shows different stability results in different countries, which is attributable partly by the choice of the crop variety (genotype) used in the particular countries, and partly to the environments and the applied farming technologies. Very similar results were found for barley genotypes in Iran (Khanzadeh et al. 2017), again with AMMI-based analysis, pointing at the fact that in choosing the crop variety that is capable of adapting to the unpredictable environment, a yield stability evaluation is a good choice, and this consideration should be usefully applied in crop breeding programs.

5. Conclusions

Our research findings demonstrate that the yield stability index (YSI) is a valuable metric for evaluating crop yield stability. Unlike traditional dispersion measures, YSI only considers significant deviations as instability, thus providing a unique approach to assessing the suitability of crops and technologies across different countries and time periods. By focusing on large deviations, the YSI is able to indicate changes in the efficiency of production technology over time, with positive index values indicating the technology's ability to respond to year-to-year environmental variations. Moreover, increasing index values in later time periods can reflect the development of more efficient technology. It is important to note that such changes cannot be solely attributed to a less climatically variable time period, as the index compares each country's performance to the average stability of the same years. Our findings for the empirical analysis of six crops in Asia show that the index measures the technological improvements for the analyzed seven countries and identifies the countries reflecting the most significant development, as well as those falling behind. Various crops respond differently to environmental changes. Our findings show that for bananas, coffee, tea, and palm oil, the production technology became stable in more countries in 1995–2020 than in 1961–1994, i.e., more countries could implement production technologies better suited to the changing environment. On the contrary, for rice and cotton seed, the majority of the analyzed countries could not maintain the stability of the earlier period during the warmer later years. These results are applicable to guide production technology developments and the introduction or abandonment of certain crops in certain geographical zones, especially with regard to the implications of climate change (Ochieng et al. 2019) and global warming. In order to achieve optimal crop distribution and agricultural management to overcome limitations and enhance production amidst climate change, it is crucial to comprehend the distributions of areas with high/low yields and stable/unstable yields, as well as to pinpoint the factors that limit yield and yield stability (Zhao et al. 2018). Furthermore, increasing the both the yield of a crop and its stability are important to achieving the sustainability of crop production (Xu et al. 2020), and provide sufficient food-related income for agricultural regions.

Selection of a crop variety for yield stability is an important farm management tool, especially in environments that are variable and unpredictable. Therefore, the selection of a crop genotype, not only for high yields, but also for yield stability that can give guidance for any breeding program, is of vital importance (Khanzadeh et al. 2017). This approach can also be applied in developing feasible farm management practices that can be recommended to farmers, keeping in mind the need for proper variety selection for adaptability—i.e., high yield and stability, with regard to the unpredictable environment, especially climate trends. The marketing companies dealing with farm inputs could also include this aspect in their marketing strategies, pointing out that specific crop varieties are better adapted to the varying environmental conditions by providing reliable, stable yields. The public authorities, dealing with strategies of agricultural development should also consider this aspect. They could be aware of which crops in their country seem to be stable, and as our concept of well-technologized crops indicate, which farming practices (including crop varieties) are best adaptable to the actual environmental conditions of their country. Good stability values may be due to a crop variety being able to utilize the changing environmental conditions, or that agricultural research successfully developed management practices applicable under these varied conditions. The low yield stability value for a crop, on the other hand, may indicate that either agricultural research should find better management practices, including genotypes, or that due to the changing climate patterns, the crop may be simply unable to survive in the particular region in the future. These considerations may be useful in delineating the future of agricultural developments, and the possible need for supporting farmers to change their farming practices in adapting to the future situation. As Kang (1993) states, growers cultivating unstable crop genotypes suffer economically due to yield fluctuations; therefore, a greater emphasis on performance stability would benefit growers. However, as Bose et al. (2014) showed, different stability measures can lead to different conclusions, which underlines the importance of understanding the inherent meaning of a stability index: to choose the most suitable one.

The limitations of the present research are related to the YSI computation methodology. The reference to a normal distribution used for evaluating the crop yield fluctuations and the time periods considerably influence the YSI value. Currently, the normal distribution is based on the average of selected country yields, and the time periods are based on weather series, using careful and slightly subjective judgement. However, further research is being conducted to find a technically more automatic solution to this problem, thereby making various crops, countries, and time periods generally comparable.

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Appendix A

Mathematical description of the computation of YSI for a particular crop

1. x_{it}: the crop yield for country i, and year t, for i = 1. . .K countries and t = 1. . .N years
2. $x_{iA} = (\Sigma_{t=1...N}\ x_{it})/N$ the average crop yield for country i, during the time period t = 1. . .N
3. $y_{it} = x_{it}/x_{iA}$ the crop yield for country i, and year t expressed as a proportion of the mean yield
4. a linear regression line is fitted to the y_{it} crop yield series, and its equation is $z_{it} = a \times t + b$, *where* z_{it} is the estimated value of the line at time t.
5. $r_{it} = y_{it} - z_{it}$ is the residual series for country i, and year t
6. s_i = the standard deviation of the residual series r_{it} for t = 1. . .N
7. $s = (\Sigma_{i=1...K}\ s_{it})/K$, the average value of the countrywise standard deviations
8. $N(0,s)$ is the normal distribution of zero means and s standard deviation, and $F(u)$ is the value of its distribution function at u, i.e., $F(u) = P(x < u$; when x is a value taken from $N(0,s))$
9. $MAX = \max\{r_{it},\ t = 1...N;\ i = 1...K\}$ and $MIN = \max\{r_{it},\ t = 1...N;\ i = 1...K\}$, and $d = (MAX - MIN)/10$
10. *Let us define* 10 *intervals as*: $I_1 = [MIN; MIN + d)$; $I_2 = [MIN + d; MIN + 2d)$;. . . $I_9 = [MIN + 8d; MIN + 9d)$; $I_{10} = [MIN + 9d; MAX)$
11. *Then the 'favorable' intervals are* I_4, I_5, I_6, *and* I_7, *while the 'unfavorable' intervals are* I_1, I_2, I_3, *and* I_8, I_9, I_{10}
12. for a series taken randomly from the normal distribution defined in *[8]*, the proportion of the values falling into the 'favorable' intervals is computed using the distribution function $F(u)$ as $fnf = F(MIN + 7d) - F(min + 3d)$
13. the proportion of the r_{it} values falling into the 'favorable' intervals is frf_i = *{count of* r_{it} $(t = 1...N)$ *for which* $MIN + 3d \leq r_{it} < MIN + 7d\}/N$
14. $YSI_i = 2 \times (frf_i - fnf)$ for i = 1. . .K

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