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The Evolutionary Trends and Convergence of Cereal Yield in Europe and Central Asia

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Abstract: The state of food security in the world, including that of Europe and Central Asia (ECA), was highlighted in 2020 by the outbreak of the COVID-19 pandemic, when the fact that the food security status of millions of people in ECA, particularly the most vulnerable and those living in fragile contexts, would deteriorate if swift action was not taken as soon as possible became apparent. Improving cereal yield is the key for the ECA to achieve the Sustainable Development Goal (SDG) Target 2.1 to end hunger by 2030. Impressive cereal yield growth has been witnessed within the ECA from 1991 to 2020, but there is still significant variation across the five sub-regions. This paper aimed to analyze the evolutionary trends and convergence of cereal yield in countries of the ECA from 1991 to 2020 for four major cereals: wheat, maize, barley and oats. The findings show that there is strong evidence of σ-convergence and absolute and conditional β-convergence for cereal yield in the ECA, which indicates that countries with low yield in the initial stages have totally experienced higher growth rate, and yield in countries farther away from the steady-state have to have faster growth rate to converge to the steady-state. The presence of club convergence is also identified in terms of geographic location and income level, simultaneously. Therefore, cereal yield in the ECA has converged to the whole and to different groups at the same time, which provides some evidence of agricultural technology spillover effect in the region.

Keywords: cereal yield; Europe and Central Asia; convergence; Sustainable Development Goal; food security; agri-food systems

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1. Introduction

The world is at a critical juncture. Hunger has been on the rise since 2015, and the world has not generally been progressing towards the Sustainable Development Goal (SDG) Target 2.1, of ensuring access to safe, nutritious and sufficient food for all people all year round by 2030 [1]. This is also a crucial moment for the world's agri-food systems, which are placing unsustainable demands on the world's water and energy resources and contributing a hefty share of greenhouse gas emissions [2]. The state of food security in the world, including that of the Europe and Central Asia (ECA), was marked in 2020 by the outbreak of the COVID-19 pandemic and resulting disruptions to markets, trade and food supply chains [3]. Taking the ECA as an example, overall, 22.8 million people (2.4% of the ECA's total population) faced severe food insecurity and 111 million people (11.9% of the ECA's total population) faced moderate or severe food insecurity in 2020, 7 million and 14 million people more than in 2019, respectively [3]. Based on the Food Insecurity Experience Scale (FIES), moderate food insecurity means that people face uncertainties about their ability to obtain food and have been forced to reduce the quality and/or quantity of food they consume at times during the year, due to lack of money or other resources. Severe food insecurity means that people have likely run out of food, experienced hunger and, at the most extreme, gone for days without eating, putting their health and well-being at grave risk [1]. The food security status of millions of people in the ECA, particularly the most vulnerable and those living in fragile contexts, is very likely to deteriorate if swift action is not taken as soon as possible. Therefore, more effort must be urgently done for countries in the ECA to end hunger by 2030, and great importance should be attached to increasing food production, especially in Central Asia, where 18% of the people were facing severe or moderate food insecurity in 2020 [3].

Though expansion in crop-growing areas and yield improvement could increase food production, besides the high cost of ecological destruction, allocating new land for growing crops seems impractical, given limited land resources and a continuing decline of areas suitable for food production, due to urbanization and industrialization [4,5]. Improving yield is the key to increase food production and guarantee future food security [6]. Crop yield could be affected by many factors, such as climate change, agricultural inputs, natural disasters and conflicts [1,7–12]. Taking conflict as an example, due to the war in Ukraine, which broke out on 24 February 2022, and resulting damage to critical infrastructure and disruption to food supply chains and markets, at least 20% of Ukraine's winter crops may not be harvested or planted, which will further reduce global food supply in 2022, with serious implications for the ECA and beyond [13]. This issue is especially serious considering that both the Russian Federation and Ukraine are among the most important producers of agricultural commodities in the world, and play leading roles in supplying global markets with the aforementioned foodstuffs, contributing to high export concentration and, thus, exposing these markets to increased vulnerability to shocks and volatility [14,15]. A more balanced distribution of levels of development or productivity among sub-regions and/or countries could promote resource efficiency, as well as economic and social cohesion in the community [16]. The trend in crop yield and its variability will affect food security and agricultural policies [17], and, then, revealing whether cereal yield has cross-country converged in the ECA is of important practical significance and scientific value.

Research on convergence has emerged from macroeconomic literature and received considerable attention over the past few decades, and the convergence phenomenon is used as a means to test different propositions of the exogenous growth models [5,18,19]. Convergence tests are carried out by three principal methods: σ-convergence, β-convergence, and club convergence [20,21]. The first of these, σ-convergence, studies whether state-level per capita income is becoming more similar over time, whereas β-convergence applies to a state's efforts to increase per capita income within the same distribution [20,22]. Club convergence is based on a panel data model and is proposed to represent the behavior of economies in transition, allowing for a wide range of possible time paths and individual heterogeneity [23], and implies that the growth rates of sub-regions and/or countries with similar initial conditions and structural characteristics (such as preferences, technologies and policies) tend to converge to the same steady-state [21]. The convergence tests are also applied to analyze crop yield. In Russia, yield for several crops declined, leading to gaps between Russia and the global yield leaders that were wider than they were in 1962, and the only crop that showed yield convergence globally was wheat, although several crops in sub-samples displayed convergence [4]. Across districts in Bihar, India's poorest state, rice yield converged towards a common growth path, while the results for wheat and maize were not as conclusive [19]. Crop yield in most countries in Western Africa was converging, but there was no evidence for overall crop yield convergence in Africa [24]. Although there was no evidence of a common rate of wheat yield convergence across Europe, there was evidence of absolute convergence [5]. For all countries along the Belt and Road, instead of one convergence, the wheat yield was converging into three clubs [25]. Of primary focus are the following questions. Is the decentralization of crop yield among different countries narrowing or widening? Is yield convergence likely to happen over time? Does yield converge to the whole and different groups at the same time? These questions are important not only in verifying agricultural technology spillover effect, but the answers to the questions are also vital in helping to evaluate growth prospects for crop yield.

Quantitative studies that analyze crop yield trends [17,26,27], crop yield gaps [7,28,29] and crop yield potentials [30,31] in the ECA have attracted wide attention and achieved many research findings, but empirical studies that assess the convergence of crop yield in the ECA are presently still rare. This study aimed to address the above questions with an emphasis on cereal yield in the ECA from 1991 to 2020.

2. Materials and Methods

2.1. Methods

To analyze cereal yield performance among countries of the ECA, the σ-convergence test, β-convergence test and club convergence test were employed in this study, simultaneously.

2.1.1. The σ-Convergence Test

The concept of σ-convergence focuses on how the level of cross-sectional dispersion, measured as the sample variance, changes over time [22]. In practice, σ-convergence test, also called absolute σ-convergence, is usually measured by the coefficient of variance (CV), which is denoted by the ratio of the standard deviation to the mean, and can be specified as:

$$CV_t = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(yield_{i,t} - \overline{yield_t}\right)} \Big/ \overline{yield_t} \tag{1}$$

where $yield_{i,t}$ and $\overline{yield_t}$ denote country i's cereal yield and its mean at year t, respectively; n denotes number of countries.

The σ-convergence can also be tested by regressing the CV on the time trend [4], which is specified as:

$$CV_t = \alpha + \psi year_t + \varepsilon_t \tag{2}$$

where α is the constant term; $year_t$ is the time trend; ψ is the estimated parameter; and ε_t is the random error term. The σ-convergence is announced when ψ is statistically significant and negative.

2.1.2. The β-Convergence Test

The β-convergence is generally divided into absolute β-convergence and conditional β-convergence [18,32]. Depending on the differences in marginal productivity of capital for the country at different stages of development, absolute β-convergence implies that a less developed country performs better, on average, compared to a more developed country [22]. Absolute β-convergence test can be estimated by:

$$\gamma_{i,t,t+T} = \frac{\ln(yield_{i,t+T}/yield_{i,t})}{T} = \alpha + \theta\ln(yield_{i,t}) + \zeta\ln(Con\_V_{i,t}) + \varepsilon_{i,t} \tag{3}$$

where $\gamma_{i,t,t+T}$ denotes country i's growth rate of cereal yield between year t and year $(t+T)$; $\ln(yield_{i,t})$ and $\ln(yield_{i,t+T})$ is the natural logarithm of country i's cereal yield at year t and year $(t+T)$; $Con\_V_{i,t}$ denotes a set of control variables that may affect cereal yield, including temperature change, natural disasters and use intensity of fertilizers and pesticides; θ and ζ is the estimated values of coefficient of $\ln(yield_{i,t})$ and $\ln(Con\_V_{i,t})$, respectively. Absolute β-convergence is announced when θ is statistically significant and negative. Data of cereal yield for some countries in some years in this study was 0, which created a problem for the use of the natural logarithmic form of cereal yield. By referring to Frankel [33], cereal yield with a value of 0 was assigned a minimum value of 0.001 when conducting model estimation in this study.

Based on the Solow Model [34], the average convergence speed of absolute β-convergence could be measured by [35]:

$$\lambda_{abs} = -\frac{\ln(1+\theta T)}{T} \tag{4}$$

where λ_{abs} denotes average convergence speed of absolute β-convergence.

The concept of conditional β-convergence is linked to the neoclassical growth model, which predicts that the growth rate of a country is negatively related to the distance that separates it from its own steady-state [18,36]. Conditional β-convergence test can be estimated by [37]:

$$g_{yield_{i,t}} = \ln(yield_{i,t}) - \ln(yield_{i,t-1}) = \alpha + \varphi \ln(yield_{i,t-1}) + \tau \ln(Con\_V_{i,t}) + \mu_i + \nu_t + \varepsilon_{i,t} \quad (5)$$

where $g_{yield_{i,t}}$ is the growth rate of country i's cereal yield from year $(t-1)$ to year t; φ and τ is the estimated values of $\ln(yield_{i,t-1})$ and $\ln(Con\_V_{i,t})$'s coefficient, respectively; μ_i is the cross-section effect; and ν_t is the period effect. Conditional β-convergence is announced if φ is statistically significant and negative. The average convergence speed of conditional β-convergence can be measured by:

$$\lambda_{con} = -\frac{\ln(1+\varphi)}{T} \quad (6)$$

where λ_{con} represents average convergence speed of conditional β-convergence.

Note that there can be situations where β-convergence and σ-convergence concepts are not necessarily linked. Indeed, β-convergence is a necessary, but not a sufficient, condition for σ-convergence. Therefore, absence of σ-convergence can co-exist with β-convergence [22].

2.1.3. The Club Convergence Test

Theoretical models of club convergence are characterized by multiple and locally stable steady-state equilibria, when those of σ-convergence and β-convergence imply a globally stable steady-state equilibrium [20]. Considering that countries with similar characteristics have a tendency to converge faster than countries with dissimilar characteristics, the simplest case for empirical analysis on club convergence occurs when groups can be suitably categorized by identifying social or economic characteristics [4,38]. Therefore, based on Model (5), the following two ways were used to carry out club convergence test in this study: (1) sample countries in the ECA were divided into 5 groups based on geographic location: Eastern Europe, Western Europe, Southern Europe, Northern Europe and Central Asia; (2) according to the World Bank's country classification by income level [39], sample countries in the ECA were divided into 3 groups: lower-middle-income economies with a gross national income (GNI) per capita between USD 1046 and USD 4095, upper-middle-income economies with a GNI per capita between USD 4096 and USD 12,695, and high-income economies with a GNI per capita of USD 12,696 or more.

2.2. Data

All the cereal yield data used in this study were collected from the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT; https://www.fao.org/faostat/en/#data (accessed on 8 January 2022)), which is a collection of online databases containing more than 3 million time-series records, covering international agricultural statistics for more than 200 countries. Data in the FAOSTAT are provided by national governments or extrapolated by Food and Agriculture Organization of the United Nations (FAO) staff. The topics which are primarily covered include the following: agricultural production, food security and nutrition, food balance, agricultural trade, agricultural price, land and inputs, population and employment, agricultural investment, climate change, and so on. According to the FAO's definition and standards, cereal specifically covers 15 categories: barley, buckwheat, canary seed, cereals nes, fonio, mixed grain, maize, millet, oats, quinoa, rice paddy, rye, sorghum, triticale and wheat [40].

The research subject of this study was cereal yield in the ECA, which included 44 countries with available cereal yield data during the sample period, specifically consisting of 10 Eastern European countries (Belarus, Bulgaria, Czech Republic, Hungary, Poland, Moldova, Romania, Russian Federation, Slovak Republic and Ukraine), 7 Western European countries (Austria, Belgium, France, Germany, Luxembourg, Netherlands and Switzerland), 12 Southern European countries (Albania, Bosnia and Herzegovina, Croatia, Greece, Italy, Malta, Montenegro, North Macedonia, Portugal, Serbia, Slovenia and Spain), 10 Northern European countries (Denmark, Estonia, Finland, Iceland, Ireland, Latvia, Lithuania, Norway, Sweden and United Kingdom), and 5 Central Asian countries (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan). Among the 44 countries, 12 countries used to be part of the former Soviet Socialist Republics (SSRs) of the Union of Soviet Socialist Republics (USSR), including 4 Eastern European countries (Belarus, Moldova, Russian Federation and Ukraine), 3 Northern European countries (Estonia, Latvia and Lithuania), and 5 Central Asian countries (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan). With the disintegration of the USSR in December 1991, all the 15 former SSRs gained independence during 1990–1991 [41,42], including the above 12 countries. Therefore, considering the availability and completeness of cereal yield data at country level in the ECA, the sample period for this study was determined as the years 1991–2020.

The definitions and measurement units, and descriptive statistics of 4 control variables are shown in Tables 1 and 2, respectively. The correlation coefficients of cereal yield and control variables are presented in Table 3. Table 3 reveals that all control variables had significant impacts on cereal yield, which provided a justification for further analysis by applying the convergence test.

Table 1. Definition and description of control variables.

Variables	Label	Operational Definition	Measurement Unit	Data Source
Temperature Change	TC	Difference in temperature between adjacent meteorological years	degree celsius	FAO
Fertilizers Use Intensity	FUI	Ratio of amount of fertilizer used in agricultural sector to arable land area	kilograms per hectare	FAO
Pesticides Use Intensity	PUI	Ratio of amount of pesticide used in agricultural sector to arable land area	kilograms per hectare	FAO
Natural Disasters	ND	Ratio of total number of injured, affected, and homeless population as a direct result of natural disasters to total population	%	EM-DAT and WDI

Note: Fertilizers include nitrogen (N), phosphate (P_2O_5) and potash (K_2O); pesticides include insecticides, fungicides and bactericides, herbicides, plant growth regulators, rodenticides, mineral oils, disinfectants and others; natural disasters include geophysical disasters, meteorological disasters, hydrological disasters, climatological disasters, biological disasters and extra-terrestrial disasters. EM-DAT denotes the Emergency Events Database (https://public.emdat.be/ (accessed on 28 January 2022)) of Belgium launched by the Centre for Research on the Epidemiology of Disasters (CRED); WDI denotes the World Development Indicators Database of World Bank (https://data.worldbank.org/indicator?tab=all (accessed on 28 January 2022)).

Table 2. Descriptive statistics of control variables for the period 1991–2020.

Variables	Mean	Minimum	Median	Maximum	Std. Dev.	Skewness	Kurtosis
TC	1.199	−0.794	1.264	3.693	0.715	−0.119	0.044
FUI	154.420	0.404	123.691	1544.889	161.277	3.991	24.507
PUI	2.955	0.006	1.493	37.250	3.784	3.031	14.882
ND	0.129	0.000	0.001	38.835	1.652	20.287	448.718

Note: TC denotes temperature change; FUI denotes fertilizers use intensity; PUI denotes pesticides use intensity; ND denotes natural disasters.

Table 3. Correlation coefficients of cereal yield and control variables.

Variables	Yield	TC	FUI	PUI	ND
Yield	1.000				
TC	0.136 ***	1.000			
FUI	0.604 ***	−0.039 ***	1.000		
PUI	0.344 ***	−0.033 ***	0.332 ***	1.000	
ND	−0.044 ***	−0.015 ***	−0.045 **	−0.046 **	1.000

Note: TC denotes temperature change; FUI denotes fertilizers use intensity; PUI denotes pesticides use intensity; ND denotes natural disasters; *** and ** denote 1% and 5% significance level, respectively.

2.3. Descriptive Analysis on the Evolutionary Trends of Cereal Yield in ECA

Figure 1 shows the evolutionary trends of average cereal yield in the ECA and its 5 sub-regions, and the world during 1991–2020. It can be observed that, average cereal yield in the ECA totally grew with continuous fluctuation and an average annual growth rate of 0.99% during 1991–2020, and, generally, with continuous growth and an average annual growth rate of 1.18% during 1992–2002, but sustained volatility during 2003–2020. Meanwhile, as shown in Table 4, average cereal yield of the world showed a steady growth trend, from 2.898 tons per hectare in 1991 to 4.071 tons per hectare in 2020, with an average annual growth rate of 1.18%. Comparatively, during 1991–2020, the average cereal yield in the ECA was always higher than the world.

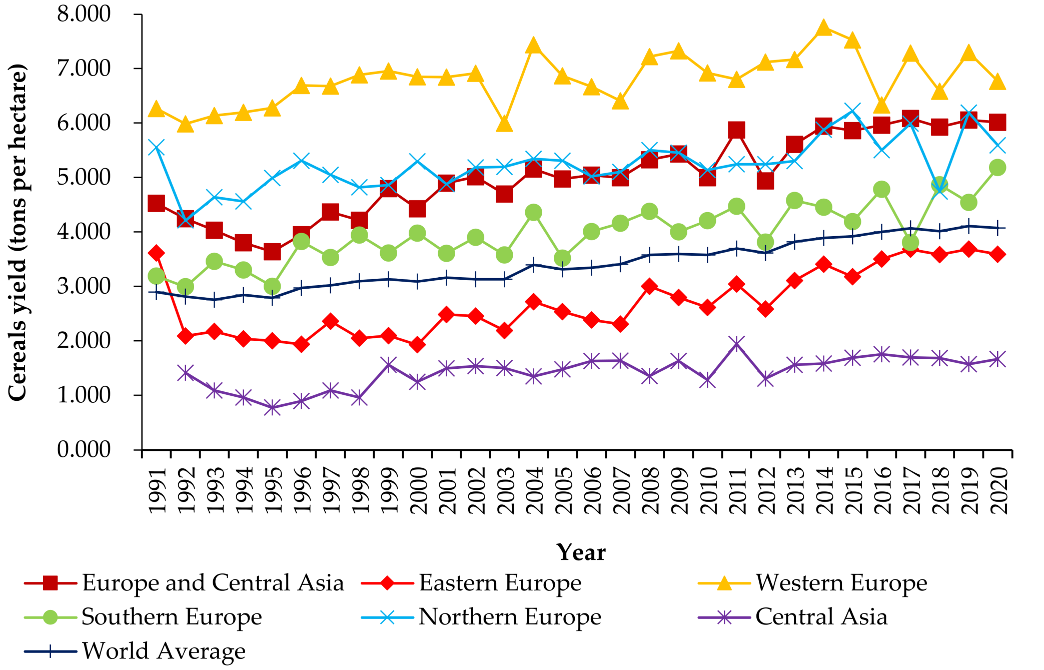

Figure 1. Average cereal yield in the ECA and its 5 sub-regions, and the world during 1991–2020. The *X*-axis represents the year. The *Y*-axis represents the average cereal yield. The data for Central Asia in 1991 is not available in the FAOSTAT.

Table 4. Descriptive statistics of average cereal yield in the ECA and its 5 sub-regions, and the world during 1991–2020.

Region	*CV*	Mean	Minimum	Median	Maximum	Std. Dev.	Skewness	Kurtosis
ECA	0.147	5.025	3.639	4.995	6.084	0.737	−0.128	−1.034
Eastern Europe	0.222	2.705	1.931	2.560	3.683	0.600	0.399	−1.272
Western Europe	0.068	6.804	5.984	6.844	7.760	0.463	−0.024	−0.618
Southern Europe	0.138	3.976	2.995	3.962	4.864	0.547	0.144	−0.383
Northern Europe	0.087	5.244	4.212	5.240	6.223	0.456	0.230	0.445
Central Asia	0.202	1.427	0.778	1.504	1.945	0.288	−0.689	−0.207
World Average	0.128	3.408	2.758	3.368	4.108	0.437	0.175	−1.296

Note: *CV* denotes coefficient of variation; measurement unit of yield is tons per hectare.

From the perspective of the 5 sub-regions of the ECA, including Eastern Europe, Western Europe, Southern Europe, Northern Europe and Central Asia, the average cereal yield has been continuously fluctuating during 1991–2020, and, according to the *CV* in Table 4, there has been relatively scattered and variable average cereal yield in Western Europe and Northern Europe, which was less than that in Eastern Europe, Southern Europe and Central Asia. Based on a comparison of average cereal yield in the 5 sub-regions of the ECA, it was found that Western Europe has always been the highest, Northern Europe, Southern Europe and Eastern Europe have been in the middle, and Central Asia has always been the lowest. In 2020, the average cereal yield in Central Asia was only equivalent to 46.51%, 24.67%, 32.19% and 29.87% of that in Eastern Europe, Western Europe, Southern Europe and Northern Europe, respectively. High income countries are better able to invest in knowledge, equipment, fertilizers and crop protection to increase crop yields [7]. During 1991–2020, average cereal yield in Western Europe, Southern Europe, Northern Europe and Central Asia grew at an average annual growth rate of 0.26%, 1.69%, 0.02% and 1.60%, respectively, and only that in Eastern Europe decreased at an average annual growth rate of 0.02%. Comparatively, during 1991–2020, all average cereal yields in Western Europe, Northern Europe and Southern Europe were higher than the world, but Central Asia and Eastern Europe were lower than the world, and only equivalent to 41.01% and 88.15% of the latter in 2020, respectively.

In order to choose the representative cereals for studying the convergence of cereal yield in the ECA, we ranked cereals according to their accumulated area harvested in the ECA during 1991–2020. Table 5 shows the accumulated area harvested and production of various cereals in the ECA during 1991–2020. It was found that 13 cereals were grown in the ECA, and wheat, barley, maize and oats were the top 4 cereals and each had been harvested from more than 230 million hectares of land cumulatively. Therefore, wheat, barley, maize and oats were chosen to conduct the follow-up research in this study. Wheat, barley, maize and oats are all important for achieving food security in the ECA and beyond. Wheat is the most important staple crop in temperate zones [43]. Barley is used worldwide for animal feed and human food, with its main use regarding products for human consumption being its use in the production of alcoholic drinks [44]. Maize plays a particularly important role as a staple food in the diets of millions of people, and is also used as livestock feed [45]. Oats are an important human food for their high content of dietary fibres, phytochemicals and nutritional value [46].

Table 5. Accumulated area harvested and production of cereals in the ECA for the period 1991–2020.

Ranking	Item	Accumulated Area Harvested (Million Hectares)	Accumulated Production (Million Tons)
1	Wheat	2109.688	6778.149
2	Barley	913.548	2759.090
3	Maize	437.037	2588.663
4	Oats	234.012	492.514
5	Rye	195.385	476.793
6	Triticale	79.085	309.295
7	Buckwheat	46.042	36.630
8	Mixed grain	43.481	122.809
9	Millet	27.246	27.972
10	Rice paddy	26.121	129.965
11	Cereals nes	8.747	15.265
12	Sorghum	6.809	25.543
13	Canary seed	0.371	0.397

In the ECA during 1991–2020, 44 countries had complete yield data for barley, 43 for wheat, 36 for maize, and 41 for oats. These countries, and their average yield for 4 major cereals during 1991–2020, are presented in Table 6.

Table 6. Average yield of 4 major cereals in countries of the ECA for the period 1991–2020.

Country	Wheat	Barley	Maize	Oats
Albania	3.348	2.435	4.899	1.701
Austria	5.182	4.897	9.676	3.878
Belarus	2.873	2.669	3.844	2.430
Belgium	6.022	5.403	7.567	3.816
Bosnia and Herzegovina	3.284	2.812	4.288	2.364
Bulgaria	3.519	3.318	4.527	1.757
Croatia	4.475	3.578	5.993	2.635
Czech Republic	4.775	4.079	6.400	3.000
Denmark	7.226	5.294	2.331	4.823
Estonia	2.776	2.439	NA	2.073
Finland	3.612	3.457	NA	3.293
France	6.929	6.186	8.626	4.410
Germany	7.334	6.029	8.840	4.634
Greece	2.603	2.582	10.322	1.894
Hungary	4.314	3.848	6.055	2.503
Iceland	NA	0.699	NA	NA
Ireland	8.700	6.784	NA	7.189
Italy	3.570	3.741	9.280	2.338
Latvia	3.231	2.297	NA	1.913
Lithuania	3.507	2.648	3.735	1.872
Luxembourg	4.198	3.760	5.115	3.359
Malta	3.782	3.226	NA	NA
Montenegro	1.556	1.286	2.018	1.208
Netherlands	8.462	6.298	9.695	5.341
North Macedonia	2.827	2.589	3.910	1.491
Norway	4.389	3.681	NA	3.800
Poland	3.938	3.249	5.789	2.523
Portugal	1.717	1.756	6.329	1.071
Moldova	2.586	2.055	2.952	1.380
Romania	2.999	2.838	3.739	1.755
Russian Federation	2.009	1.862	3.412	1.503
Serbia	2.049	1.801	2.888	1.215
Slovak Republic	4.071	3.467	5.582	2.097
Slovenia	4.407	3.836	7.057	2.633
Spain	2.832	2.720	9.760	1.758
Sweden	6.027	4.291	0.596	3.861
Switzerland	5.818	6.206	9.383	5.119
Ukraine	3.061	2.380	4.241	1.933
United Kingdom	7.749	5.803	NA	5.639
Kazakhstan	0.997	1.151	4.062	1.120
Kyrgyzstan	2.180	1.906	5.491	2.185
Tajikistan	2.003	1.264	7.048	0.868
Turkmenistan	1.847	1.165	1.428	NA
Uzbekistan	3.551	1.464	6.343	0.192

Note: NA denotes not available; measurement unit of yield is tons per hectare.

3. Results

3.1. The σ-Convergence Test

Figure 2 shows the yield *CV* of 4 major cereals in the ECA during 1991–2020. It was found that all the curves of yield *CV* for wheat, barley, maize and oats showed a trend of first increasing and then decreasing. Therefore, these curves provided strong evidence of σ-convergence for the yield of wheat, barley, maize and oats in the ECA for the period 1991–2020.

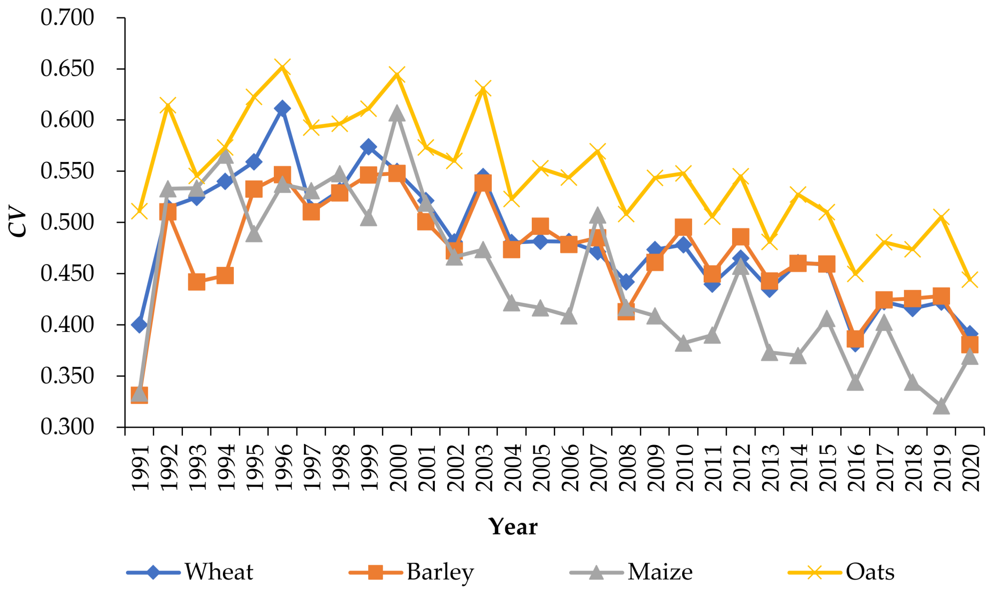

Figure 2. The yield *CV* of 4 major cereals in the ECA for the period 1991–2020. The *X*-axis represents the year; the *Y*-axis represents the *CV* of 4 major cereals' yield; *CV* denotes coefficient of variation.

According to Model (1), a simple regression was conducted. Based on the values of DW-statistics, the autoregressive (AR) term with appropriate lagged periods was added in the regression for eliminating probable self-correlation problems. According to the estimation results presented in Table 7, it was found that the estimated values of year terms' coefficients for all 4 major cereals were statistically significant and negative, meaning that the relative scatter and variability of the 4 cereals' yield decreased over time. This also proved that there was σ-convergence for the yield of wheat, barley, maize and oats in the ECA for the period 1991–2020. Additionally, the results of the Phillips-Perron unit root test showed that the values of yield *CV* for the 4 major cereals showed a stationary trend.

Table 7. Estimates of σ-convergence test.

Variables	Wheat	Barley	Maize	Oats
	Estimate			
$Year_t$	−0.004 *** (−3.167)	−0.003 ** (−2.404)	−0.006 *** (−3.320)	−0.005 *** (−5.612)
AR(1)	0.349 (1.428)	0.301 (1.587)	0.122 (0.366)	0.036 (0.108)
Constant	8.854 *** (3.360)	5.485 ** (2.630)	12.868 *** (3.447)	10.047 *** (5.949)
R-squared	0.537	0.602	0.519	0.548
F-statistic	10.042 ***	5.664 **	9.294 ***	10.503 ***
DW-statistic	1.908	1.917	1.852	1.869
Number of observations	30	30	30	30
	Phillips-Perron unit root test			
CV	−8.936 ***	−6.267 ***	−7.252 ***	−6.183 ***

Note: Numbers in parentheses are values of t-statistics; AR denotes autoregressive; DW denotes Durbin–Watson; *CV* denotes coefficient of variation; *** and ** denote 1% and 5% significance level, respectively.

3.2. *The β-Convergence Test*

Based on Model (3), absolute β-convergence was estimated. According to the values of DW-statistics, the autoregressive (AR) term with appropriate lagged periods was added for eliminating probable self-correlation issues. According to the results presented in Table 8, it was found that all the estimated values of $\ln(yield_{i,t})$'s coefficients for the 4 major cereals were statistically significant and negative, indicating that there was absolute β-convergence for the yield of 4 major cereals in the ECA for the period 1991–2020. Meanwhile, the average convergence speed of absolute β-convergence for wheat yield, barley yield, maize yield and oats yield reached 1.43%, 2.58%, 4.53% and 6.90%, respectively. Therefore, in the ECA, countries with low yield for the 4 cereals in the initial stages experienced higher growth rates over years, and then gradually narrowed the gap with countries with high cereal yield in the initial stages. Comparatively, yield of oats converged faster than that of the other 3 cereals. The reasoning behind absolute β-convergence is that countries with lower initial rates will be readily able to adapt and implement extant technologies [25]. Meanwhile, the results of Phillips-Perron unit root test showed that the values of $\gamma_{i,t,t+T}$ and $\ln(yield_{i,t})$ for the 4 major cereals were trend stationary.

Table 8. Estimates of absolute β-convergence test.

Variables	Wheat	Barley	Maize	Oats
		Estimate		
$\ln(yield_{i,t})$	−0.012 *** (−3.509)	−0.018 ** (−2.631)	−0.025 * (−1.968)	−0.031 *** (−3.309)
AR(1)		0.244 (1.097)		−0.236 (−0.662)
Constant	0.024 *** (5.226)	0.032 *** (4.446)	0.060 ** (2.573)	0.038 *** (4.815)
R-squared	0.628	0.523	0.380	0.411
F-statistic	12.315 ***	7.338 ***	8.267 ***	8.613 ***
DW-statistic	2.014	1.946	1.935	1.928
Number of observations	43	44	36	41
λ_{abs}	1.428%	2.583%	4.530%	6.901%
		Phillips-Perron unit root test		
$\gamma_{i,t,t+T}$	−6.936 ***	−6.963 ***	−6.950 ***	−6.734 ***
$\ln(yield_{i,t})$	−6.831 ***	−7.466 ***	−8.332 ***	−6.237 ***

Note: Numbers in parentheses are values of t-statistics; AR denotes autoregressive; DW denotes Durbin–Watson; ***, ** and * denote 1%, 5% and 10% significance level, respectively.

Table 9 shows average yield in periods of 5 years of the 4 major cereals for the top 5 highest and 5 lowest countries in the ECA, and changes of average yield between the initial 5 years and the last 5 years. It was found that, for a specific cereal, most countries among the 5 lowest countries had higher growth rates than most countries among the 5 highest countries. Taking wheat as an example, the yield growth rate in Kazakhstan, Portugal and Tajikistan reached 31.57%, 48.01% and 257.84%, respectively, and all of these values were significantly higher than those in Germany, Denmark, United Kingdom, Netherlands and Ireland, which also validated the presence of absolute β-convergence.

The specification for the panel data model had fixed and random effects, both of which could be further divided into cross-section and period effect. The Hausman test and redundant fixed effects test should be used to determine the optimal specification for the panel data effect model, with the null hypothesis that the random effect is correlated with the right-hand side variables in the panel equation setting, and cross-section effects are redundant and there are no period effects, respectively [47]. According to the results of the Hausman test shown in Table 10, all the values of chi^2 statistics were statistically significant at 1% significance level, meaning that the null hypothesis was strongly rejected, and fixed effects were more appropriate than random effects. According to the results of the redundant fixed effects test shown in Table 10, all the values of chi^2 statistics were statistically significant at 1% significance level, indicating that the null hypothesis was strongly rejected, and cross-section and period effects should be included simultaneously. Based on Model (4), conditional β-convergence was estimated by using the panel data effect model with cross-section fixed effects and period fixed effects. According to the results presented in Table 10, it was found that all the estimated values of $\ln(yield_{i,t-1})$'s coefficients for all 4 major cereals were statistically significant and negative, indicating that there was conditional σ-convergence for the yields of wheat, barley, maize and oats in the ECA for the period 1991–2020. Meanwhile, the average convergence speed of conditional β-convergence for the yield of wheat, barley, maize and oats reached 1.57%, 1.72%, 1.27% and 2.45%, respectively. Therefore, in the ECA, cereal yield in countries that were farther away from their own steady-state in the initial stages had faster growth rates to converge to their own steady-state over time. Furthermore, the results of the Levin, Lin and Chu unit root test showed that the values of $g_{yield_{i,t}}$ and $\ln(yield_{i,t-1})$ for 4 major cereals were trend stationary.

Table 9. Average yield in each 5 years of 4 major cereals for selected countries in ECA from 1991–1995 to 2016–2020.

Cereal/Country		1991–1995	1996–2000	2001–2005	2006–2010	2011–2015	2016–2020	Changes
Wheat								
Lowest 5	Kazakhstan	0.894	0.848	1.017	1.066	1.162	1.176	31.57%
	Turkmenistan	2.010	1.923	2.989	1.845	1.259	1.460	−27.37%
	Portugal	1.686	1.417	1.143	1.936	1.626	2.495	48.01%
	Montenegro	NA	NA	NA	3.199	3.045	3.092	−3.36%
	Tajikistan	0.872	1.121	1.804	2.477	2.797	3.120	257.84%
Highest 5	Germany	6.599	7.322	7.385	7.454	7.812	7.435	12.67%
	Denmark	6.853	7.185	7.168	7.217	7.374	7.561	10.34%
	United Kingdom	7.290	7.824	7.720	7.829	7.869	7.964	9.25%
	Netherlands	8.227	8.216	8.402	8.519	8.681	8.725	6.06%
	Ireland	7.703	8.594	8.832	8.671	9.354	9.045	17.41%
Barley								
Lowest 5	Turkmenistan	2.058	0.555	0.816	1.379	1.425	1.166	−43.33%
	Kazakhstan	1.021	0.946	1.124	1.200	1.316	1.502	47.06%
	Tajikistan	0.702	0.743	1.354	1.522	1.495	1.907	171.59%
	Montenegro	NA	NA	NA	2.396	2.620	2.698	12.57%
	Iceland	NA	NA	NA	NA	3.187	3.557	11.62%
Highest 5	France	5.698	6.268	6.247	6.360	6.500	6.044	6.08%
	Germany	5.338	5.794	5.915	6.052	6.553	6.525	22.24%
	Switzerland	5.630	6.099	6.092	6.147	6.624	6.648	18.10%
	Netherlands	5.766	6.178	5.951	6.215	6.818	6.858	18.94%
	Ireland	5.800	6.390	6.496	6.754	7.708	7.557	30.28%
Maize								
Lowest 5	Turkmenistan	3.714	0.669	1.032	1.353	1.401	1.139	−69.34%
	Montenegro	NA	NA	NA	3.391	4.391	4.324	27.52%
	Sweden	NA	NA	NA	NA	NA	5.959	NA
	Denmark	NA	NA	NA	4.811	6.074	6.950	44.48%
	Serbia	NA	NA	NA	4.882	5.533	6.914	41.63%
Highest 5	Netherlands	7.938	8.412	8.859	11.456	12.238	9.267	16.74%
	Switzerland	8.476	9.100	8.345	9.445	10.421	10.513	24.04%
	Austria	8.069	9.494	9.615	10.364	9.918	10.597	31.32%
	Greece	9.962	9.669	10.224	10.291	10.921	10.866	9.07%
	Spain	6.792	9.170	9.591	10.057	11.241	11.710	72.39%
Oats								
Lowest 5	Uzbekistan	1.192	1.000	NA	NA	NA	NA	NA
	Kazakhstan	1.261	0.896	1.096	1.132	1.288	1.301	3.24%
	Tajikistan	0.671	0.423	0.805	1.096	0.993	1.352	101.46%
	Portugal	0.821	0.911	0.799	1.385	1.092	1.421	73.18%
	Montenegro	NA	NA	NA	2.137	2.384	2.727	27.61%
Highest 5	Denmark	4.510	5.153	4.927	4.416	5.005	4.924	9.18%
	Netherlands	5.389	5.445	5.496	5.054	5.664	4.997	−7.28%
	Switzerland	5.047	5.321	5.123	5.015	5.161	5.046	−0.02%
	United Kingdom	5.257	5.928	5.869	5.713	5.665	5.403	2.78%
	Ireland	6.540	6.759	7.206	7.372	7.633	7.622	16.54%

Note: NA denotes not available; measurement unit of yield is tons per hectare. Lowest 5 and highest 5 refer to the top 5 countries with lowest yield and top 5 countries with highest yield, respectively. Changes represent growth rate of cereal yield during 2016–2020 relative to that during 1991–1995, and if the data for 1991–1995 was not available, then it was replaced with data from the later sample period in which the data was available.

Table 10. Estimates of conditional β-convergence test.

Variables	Wheat	Barley	Maize	Oats
Estimate				
$\ln(yield_{i,t-1})$	−0.365 *** (−17.568)	−0.393 *** (−17.938)	−0.308 *** (−14.298)	−0.509 *** (−20.357)
Constant	0.478 *** (18.052)	0.437 *** (18.350)	0.510 *** (15.124)	0.451 *** (20.301)
$\ln(Con\_V_{i,t})$	yes	yes	yes	yes
Cross-section fixed effects	yes	yes	yes	yes
Period fixed effects	yes	yes	yes	yes
R-squared	0.309	0.294	0.281	0.331
F-statistic	7.410 ***	6.958 **	5.964 ***	8.007 ***
Number of observations	1247	1276	1044	1189
λ_{con}	1.567%	1.722%	1.270%	2.454%
Redundant Fixed Effects Test				
Cross-section/periodchi^2	355.067 ***	353.669 ***	253.205 ***	392.123 ***
Hausman Test				
Cross-section/periodchi^2	213.209 ***	234.031 ***	124.719 ***	333.381 ***
Levin, Lin & Chu unit root test				
$g_{yield_{i,t}}$	−26.327 ***	−30.056 ***	−17.920 ***	−21.643 ***
$\ln(yield_{i,t-1})$	−22.836 ***	−21.077 ***	−16.294 ***	−21.764 ***

Note: Numbers in parentheses are values of t-statistics; *** and ** denote 1% and 5% significance level, respectively.

3.3. The Club Convergence Test

Table 11 shows the estimates of the club convergence test based on geographic location. After controlling cross-section and period fixed effects, it was found that all the estimated values of $\ln(yield_{i,t-1})$'s coefficients for the 4 major cereals among the 5 groups were statistically significant and negative, proving evidence of club convergence for the yield of wheat, barley, maize and oats in the ECA from 1991 to 2020 at geographic location level. Comparatively, the average convergence speed for the yield of the 4 major cereals in Eastern Europe was always the highest, while that in Western Europe was always the lowest.

Table 12 shows the estimates of club convergence test based on the World Bank's country classification by income level. After controlling cross-section and period fixed effects, it was found that all the estimated values of $\ln(yield_{i,t-1})$'s coefficients for the 4 major cereals among the 3 groups were statistically significant and negative, proving evidence of club convergence for yields of wheat, barley, maize and oats in the ECA from 1991 to 2020 at income level. Comparatively, the average convergence speed for the yield of the 4 major cereals in the upper-middle-income economies was always the highest.

Table 11. Estimates of club convergence test based on geographic location.

Variables	Wheat	Barley	Maize	Oats
Eastern Europe				
$\ln(yield_{i,t-1})$	−0.711 *** (−14.197)	−0.714 *** (−13.768)	−0.751 *** (−15.545)	−0.796 *** (−13.791)
Constant	0.856 *** (14.490)	0.758 *** (13.995)	0.751 *** (17.483)	0.568 *** (13.800)
$\ln(Con\_V_{i,t})$	yes	yes	yes	yes
Cross-section fixed effects	yes	yes	yes	yes
Period fixed effects	yes	yes	yes	yes
R-squared	0.659	0.662	0.797	0.618
Number of observations	290	290	290	290
λ_{clu}	4.276%	4.317%	4.798%	5.480%
Western Europe				
$\ln(yield_{i,t-1})$	−0.128 *** (−3.945)	−0.160 *** (−4.353)	−0.165 *** (−4.358)	−0.149 *** (−4.171)
Constant	0.245 *** (4.216)	0.269 *** (4.695)	0.355 *** (4.566)	0.226 *** (4.336)
$\ln(Con\_V_{i,t})$	yes	yes	yes	yes
Cross-section fixed effects	yes	yes	yes	yes
Period fixed effects	yes	yes	yes	yes
R-squared	0.366	0.325	0.447	0.370
Number of observations	203	203	203	203
λ_{clu}	0.473%	0.601%	0.621%	0.556%
Southern Europe				
$\ln(yield_{i,t-1})$	−0.387 *** (−9.198)	−0.493 *** (−11.709)	−0.282 *** (−7.563)	−0.537 *** (−10.281)
Constant	0.493 *** (11.997)	0.437 *** (18.136)	0.504 *** (8.178)	0.339 *** (10.455)
$\ln(Con\_V_{i,t})$	yes	yes	yes	yes
Cross-section fixed effects	yes	yes	yes	yes
Period fixed effects	yes	yes	yes	yes
R-squared	0.762	0.784	0.421	0.460
Number of observations	348	348	319	319
λ_{clu}	1.685%	2.345%	1.141%	2.652%
Northern Europe				
$\ln(yield_{i,t-1})$	−0.650 *** (−14.458)	−0.319 *** (−6.829)	−0.185 * (−2.372)	−0.632 *** (−11.272)
Constant	1.161 *** (21.812)	0.406 *** (7.163)	0.177 ** (3.148)	0.786 *** (11.395)
$\ln(Con\_V_{i,t})$	yes	yes	yes	yes
Cross-section fixed effects	yes	yes	yes	yes
Period fixed effects	yes	yes	yes	yes
R-squared	0.673	0.518	0.426	0.716
Number of observations	261	290	87	261
λ_{clu}	3.618%	1.327%	0.705%	3.450%
Central Asia				
$\ln(yield_{i,t-1})$	−0.303 *** (−4.663)	−0.386 *** (−5.161)	−0.167 *** (−3.423)	−0.636 *** (−6.307)
Constant	0.217 *** (4.895)	0.121 *** (3.964)	0.277 *** (4.183)	0.109 ** (3.136)
$\ln(Con\_V_{i,t})$	yes	yes	yes	yes
Cross-section fixed effects	yes	yes	yes	yes
Period fixed effects	yes	yes	yes	yes
R-squared	0.417	0.423	0.675	0.549
Number of observations	145	145	145	116
λ_{clu}	1.242%	1.684%	0.629%	3.488%

Note: Numbers in parentheses are values of t-statistics; ***, ** and * denote 1%, 5% and 10% significance level, respectively.

Table 12. Estimates of club convergence test based on World Bank's country classification by income level.

Variables	Wheat	Barley	Maize	Oats
Lower-middle-income economies				
$\ln(yield_{i,t-1})$	−0.247 ***	−0.576 ***	−0.170 **	−0.591 ***
	(−3.522)	(−5.847)	(−3.221)	(−6.058)
Constant	0.267 ***	0.317 ***	0.344 ***	0.189 ***
	(4.067)	(5.871)	(3.735)	(4.622)
$\ln(Con\_V_{i,t})$	yes	yes	yes	yes
Cross-section fixed effects	yes	yes	yes	yes
Period fixed effects	yes	yes	yes	yes
R-squared	0.517	0.502	0.498	0.493
Number of observations	116	116	116	116
λ_{clu}	0.977%	2.958%	0.643%	3.079%
Upper-middle-income economies				
$\ln(yield_{i,t-1})$	−0.433 ***	−0.580 ***	−0.368 ***	−0.640 ***
	(−10.926)	(−9.966)	(−8.566)	(−11.567)
Constant	0.501 ***	0.351 ***	0.450 ***	0.330 ***
	(17.694)	(10.013)	(8.930)	(11.300)
$\ln(Con\_V_{i,t})$	yes	yes	yes	yes
Cross-section fixed effects	yes	yes	yes	yes
Period fixed effects	yes	yes	yes	yes
R-squared	0.821	0.447	0.391	0.504
Number of observations	348	348	348	319
λ_{clu}	1.959%	2.995%	1.585%	3.526%
High-income economies				
$\ln(yield_{i,t-1})$	−0.350 ***	−0.315 ***	−0.248 ***	−0.415 ***
	(−13.853)	(−12.669)	(−9.444)	(−14.522)
Constant	0.535 ***	0.426 ***	0.471 ***	0.470 ***
	(14.140)	(13.090)	(10.028)	(14.671)
$\ln(Con\_V_{i,t})$	yes	yes	yes	yes
Cross-section fixed effects	yes	yes	yes	yes
Period fixed effects	yes	yes	yes	yes
R-squared	0.326	0.298	0.274	0.342
Number of observations	783	812	580	754
λ_{clu}	1.484%	1.305%	0.983%	1.851%

Note: Numbers in parentheses are values of t-statistics; *** and ** denote 1% and 5% significance level, respectively. Lower-middle-income economies include Kyrgyzstan, Tajikistan, Uzbekistan and Ukraine; Upper-middle-income economies include Albania, Belarus, Bosnia and Herzegovina, Bulgaria, Moldova, Montenegro, North Macedonia, Romania, Russian Federation, Serbia, Kazakhstan and Turkmenistan; High-income economies include Austria, Belgium, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

4. Discussion

This study revisited the topic of cereal yield convergence in the ECA through econometric analysis, which enriched and expanded the research on cereal yield in the ECA and provided some new empirical evidence on cereal yield convergence. Considering that research and development (R&D) is a public good with geographical spillover effects, and there are increasing returns to human capital [24], the presence of cereal yield convergence in the ECA has put forward some evidence of agricultural technology spillover effect in the region. This is consistent with previous studies that showed that wheat yield converged at a global level [24] and in European countries [25], rice yield converged towards a common growth path across districts in India's poorest state [19], and crop yield converged into several clubs or groups of African countries [4] and countries along the Belt and Road [5].

Considering that the yield gap among 5 sub-regions in the ECA is still large in recent years, especially between Central Asia and the other 4 sub-regions, the agricultural technology diffusion and uptake is still limited, and the possible main reasons for this are that some countries in the ECA lack information and communications technology (ICT) and strong agricultural extension services. Taking Central Asia as an example, since independence in 1991, the creation of suitable extension advisory services was not on the agenda of the agricultural reforms, and most farmers do not have an agricultural background, while extension systems do not exist, or are very weak, during the earlier phases of transition [48–50]. In most Central Asian countries, many non-governmental organizations (NGOs) have been set up to provide extension services that were formerly provided by research institutes, and these NGOs focus on establishing expensive advisory units rather than helping poor farmers in rural areas, which results in slow improvement in agricultural yield [49–51]. Therefore, continued elimination of barriers to agricultural technology diffusion to improve cereal yield is highly recommended for the ECA to achieve the SDG Target 2.1 to end hunger by 2030. In particular, the global impact of the COVID-19 pandemic is expanding daily, and between present disruptions and future threats to the food supply chain, the COVID-19 outbreak has generated extreme vulnerability in the agriculture sector, and agricultural extension and advisory services systems have played an indispensable role at the frontline of the response to the pandemic in rural areas [50]. At this critical moment, all available instruments, institutions and stakeholders from both public and private sectors and civil society in the ECA and beyond should be mobilized immediately, and more projects aimed at supporting public and private extension service providers to improve technical capacities and enhanced knowledge of modern crop management should be developed and implemented [50,52], so as to drive the transformation of agri-food systems and the construction of sustainable and resilient agri-food systems in the ECA.

Some limitations of this study and potential directions need to be addressed in future research. Firstly, temperature change, natural disasters and intensity of use of fertilizers and pesticides were chosen as the control variables in this study. Factors that may also affect cereal yield, but are difficult to quantify at the national level, or suffer from lack of complete statistics over the long-term, such as quality of cereal seed, quality of arable land, ratio of amount of agricultural machinery used in the agricultural sector to arable land area and educational attainment of labor force in agriculture, could be incorporated into future analysis. Secondly, other convergence test methods could be used to further verify the robustness of findings in this study, such as the logt test [23]. Thirdly, because the war in Ukraine is still ongoing, its actual impact on agricultural production and food security in the ECA and beyond needs to be constantly observed and evaluated.

5. Conclusions

Using the 1991–2020 panel data of countries in the ECA, this study quantitatively analyzed the evolutionary trends and convergence of cereal yield in the ECA for 4 major cereals: wheat, maize, barley and oats. The following conclusions can be drawn. Firstly, there are significant regional differences in absolute quantity and growth rate of cereal yields in the ECA, cereal yield in Central Asia has always been the lowest among the 5 sub-regions in the ECA, and wheat, barley, maize and oats are the top four harvested cereals. Secondly, the yield relative variability for the four major cereals has decreased significantly over time, which indicates σ-convergence of cereal yield. Thirdly, for the four major cereals, countries with low yield in the initial stages have totally experienced higher growth rate over time, and yields in countries that are farther away from their own steady-state have experienced faster growth rate to converge to the steady-state over time, which identifies the presence of absolute and conditional β-convergence, respectively. Fourthly, by further analyzing the results for countries grouped with similar characteristics, for the four major cereals, the presence of club convergence is identified at geographic location and income level, simultaneously. Faced with worse food insecurity status in recent years, continued elimination of barriers to agricultural technology diffusion, by further strengthening cross-border cooperation within and outside the region to improve cereal yield and construction of resilient agri-food systems in the ECA are highly recommended, especially in Central Asia, where the water-energy-food-ecology (WEFE) system is particularly vulnerable [53,54], and financial and technical support from the international community is urgently needed.

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