https://doi.org/10.51885/3134-8009_JES_2026_1_9
SRSTI 89.57.35

USE OF INTEGRAL VEGETATION INDICES IN THE ANALYSIS OF VEGETATION COVER CONDITION AND ITS CHANGE TRENDS BASED ON SATELLITE DATA

СПУТНИКТІК ДЕРЕКТЕР НЕГІЗІНДЕ ӨСІМДІК ЖАМЫЛҒЫСЫНЫҢ ЖАҒДАЙЫН ЖӘНЕ ОНЫҢ ӨЗГЕРУ ҮРДІСТЕРІН ТАЛДАУ КЕЗІНДЕ ИНТЕГРАЛДЫ ВЕГЕТАЦИЯЛЫҚ ИНДЕКСТЕРДІ ПАЙДАЛАНУ

ИСПОЛЬЗОВАНИЕ ИНТЕГРАЛЬНЫХ ВЕГЕТАЦИОННЫХ ИНДЕКСОВ ПРИ АНАЛИЗЕ СОСТОЯНИЯ РАСТИТЕЛЬНОГО ПОКРОВА И ТЕНДЕНЦИЙ ЕГО ИЗМЕНЕНИЙ ПО СПУТНИКОВЫМ ДАННЫМ

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keywords:
Remote sensing, vegetation indices, Integral Vegetation Condition Index (IVCI), drought analysis and monitoring, hydrothermal coefficient (HTC), grain yield.

ABSTRACT
Drought phenomena are among the most significant factors determining the productivity of agroecosystems and the resilience of agricultural production under climate change. For Kazakhstan, the majority of whose territory falls within the zone of risky agriculture, drought monitoring, vegetation cover assessment, and the identification of change trends are of particular importance. The increasing frequency and intensity of dry periods lead to substantial losses in cereal crop yields, directly affecting the country's food security.
Traditional methods for assessing agroclimatic conditions are based on ground-based observations of air temperature and precipitation. Despite their informativeness, these data are limited by the spatial discreteness of the meteorological station network and do not fully reflect the spatial diversity of drought conditions. In this regard, remote sensing (RS) methods have gained particular importance, providing systematic and spatially continuous monitoring of vegetation conditions.
Among the tools of remote sensing, vegetation indices have become widely used for assessing vegetation dynamics, detecting stress conditions, and identifying interannual variations.
The aim of this study is to assess the dynamics of vegetation and drought conditions in the northern regions of Kazakhstan (Akmola, Kostanay, and North Kazakhstan regions) for the period 2000–2023 using vegetation indices, including the developed IVCI index, as well as to verify it against ground-based agroclimatic indicators and cereal crop yield statistics.

Түйінді сөздер:
Спутниктік қашықтықтан зондтау, вегетациялық индекстер, өсімдік жағдайының интегралды индексі (IVCI), қуаңшылық жағдайларын талдау және мониторинг, гидротермиялық коэффициент (HTC), дәнді дақылдардың өнімділігі.

ТҮЙІНДЕМЕ

Климаттың аридтенуінің күшеюі мен қуаңшылық құбылыстарының жиілеуі жағдайында өсімдік жамылғысының жай-күйін талдау және оның өзгеру үрдістерін айқындау үшін интегралды вегетациялық индекстерді әзірлеу мен қолданудың маңызы арта түсуде. Зерттеуде түрлі вегетациялық индекстер әдісі пайдаланылды. Ерекше назар авторлар әзірлеген және алғаш рет Қазақстан аумағында қолданылған өсімдік жағдайының интегралды индексіне (IVCI) аударылды. Зерттеу MODIS спутниктік деректеріне (MOD09Q1, 2000-2023 жж.) негізделген және олар жерүсті агроклиматтық көрсеткіштерімен (Селяниновтың гидротермиялық коэффициенті) мен дәнді дақылдардың өнімділік статистикасымен салыстырылды. Талдау нәтижесінде Қостанай облысындағы метеостанциялардың 75 %-дан астамында IVCI мен HTC арасында күшті және өте күшті корреляция байқалды, ал Солтүстік Қазақстан және Ақмола облыстарында орташа және күшті байланыстар басым болды. Ақмола облысы бойынша Манн–Кендалл сынағы мен Сен еңісін бағалау нәтижелері 2000–2023 жылдар аралығында IVCI өзгерісінің статистикалық тұрғыдан мәнді теріс үрдісін растады, ал Қостанай және Солтүстік Қазақстан облыстары бойынша сызықтық трендтер өсімдіктердің жағдайының жалпы нашарлауын көрсетті. IVCI < 0.3 шекті мәні экстремалды қуаңшылық жылдарын (2008, 2010, 2012, 2023) және олардың кеңістіктік таралу аймақтарын айқындауға мүмкіндік берді. Осылайша, IVCI гидротермиялық коэффициенттің спутниктік баламасы ретінде қарастырылып, Қазақстандағы қуаңшылық жағдайларын мониторингтеудің жаңа құралы болып табылады.

Ключевые слова:
Дистанционное зондирование, вегетационные индексы, интегральный индекс условий вегетации (IVCI), анализ и мониторинг засушливых условий, гидротермический коэффициент (ГТК), урожайность зерновых культур.

АННОТАЦИЯ

В условиях усиливающейся аридизации климата и роста частоты засушливых явлений особое значение приобретает разработка и применение интегральных индексов вегетации для анализа состояния растительного покрова и выявления тенденций его изменений. В работе использован метод различных вегетационных индексов. Особое внимание уделено индексу условий вегетации IVCI, разработанному авторами и впервые примененному для территории Казахстана. Исследование выполнено на основе спутниковых данных MODIS (MOD09Q1, 2000–2023 гг.), сопоставленных с наземными агроклиматическими показателями (гидротермическим коэффициентом Селянинова) и статистикой урожайности зерновых культур. Анализ показал, что в Костанайской области для более 75 % метеостанций выявлена сильная и очень сильная корреляция между IVCI и HTC, в Северо-Казахстанской и Акмолинской областях преобладают умеренные и сильные зависимости. Применение теста Манна–Кендалла и оценки наклона Сенна для Акмолинской области подтвердили статистически значимую отрицательную тенденцию в изменении IVCI за период 2000–2023 гг., а линейные тренды для Костанайской и Северо-Казахстанской областей указывают на общее ухудшение условий вегетации. Пороговое значение IVCI < 0.3 позволило выделить годы экстремальных засух (2008, 2010, 2012, 2023) и пространственные зоны их проявления. Таким образом, индекс IVCI может рассматриваться как спутниковый аналог гидротермического коэффициента и представляет собой новый инструмент мониторинга засушливых условий для Казахстана.

INTRODUCTION

Drought phenomena are among the most significant factors determining the productivity of agroecosystems and the resilience of agricultural production under climate change. For Kazakhstan, the majority of whose territory falls within the zone of risky agriculture, drought monitoring, vegetation cover assessment, and the identification of change trends are of particular importance. The increasing frequency and intensity of dry periods lead to substantial losses in cereal crop yields, directly affecting the country's food security.

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The aim of this study is to assess the dynamics of vegetation and drought conditions in the northern regions of Kazakhstan (Akmola, Kostanay, and North Kazakhstan regions) for the period 2000–2023 using vegetation indices, including the developed IVCI index, as well as to verify it against ground-based agroclimatic indicators and cereal crop yield statistics.

MATERIALS AND METHODS

Kazakhstan is located in the center of the Eurasian continent, spanning latitudes from 40° to 55° N and longitudes from 45° to 87° E. The country includes several natural zones — from forest-steppe to desert — and is characterized by a strongly continental climate. In the northern regions, a moderately continental climate prevails, with sharp temperature fluctuations and insufficient moisture.

A significant portion of Kazakhstan's territory belongs to arid and semi-arid climate zones, where droughts of varying duration and intensity occur almost every year. These events lead to a noticeable decline in grain yields, pasture degradation, and substantial economic losses in the agricultural sector. More than 70 percent of the country's croplands are located in the rain-fed farming zone in the north, where agricultural productivity strongly depends on precipitation and is highly vulnerable to climate risks. (Baisholanov S.S. et al. 2018). The principal grain-producing regions are situated in the northern part of the country. The sown areas account for 24 percent of the total area of Kostanay Region, 34 percent of Akmola Region, and 42 percent of North Kazakhstan Region [VIII National Communication, 2022], Figure 1.

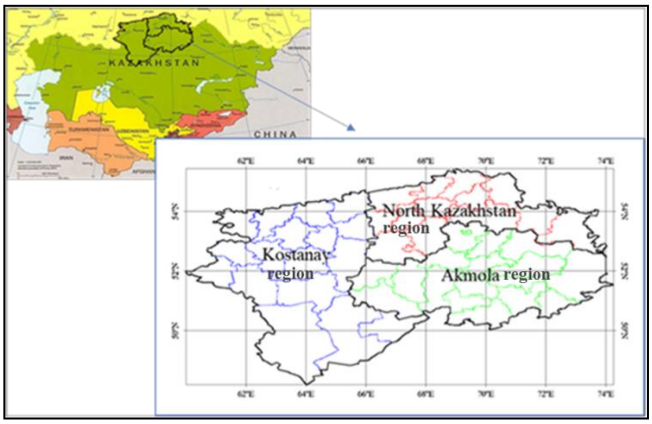

Figure 1. Study area

Note – compiled by the authors

Satellite Data

The study used MODIS Terra surface reflectance data (product MOD09Q1), obtained from Band 1 (red range, 0.620–0.670 μm) and Band 2 (near-infrared range, 0.841–0.876 μm) with a spatial resolution of 250 m. The MODIS composite algorithm produces 8-day images in which the highest-quality observation for each pixel is selected, taking into account viewing angle, cloud cover, shadows, and aerosol load. This minimizes atmospheric and optical distortions and ensures consistency of the time series. To cover the entire territory of Kazakhstan, six tiles (21v03–23v04) were used and merged into a single mosaic. The analysis covered the growing seasons (April–September) from 2000 to 2023, and data processing and index calculations were carried out in the ENVI software environment.

Ground Data

Verification of the satellite-based vegetation indices was carried out using ground-based agro-climatic and statistical data. The Selyaninov Hydrothermal Coefficient (HTC) was calculated for each year from 2000 to 2023 using temperature and precipitation records from meteorological stations of the Kazhydromet network (meteo.kz). In addition, district-level grain yield statistics for the same period were obtained from official sources of the Bureau of National Statistics of the Republic of Kazakhstan (stat.gov.kz).

Research methods

To identify the characteristics of each current season, ground measurements and vegetation indices are used, Table 1, 2.

Table 1. Satellite indices used in space monitoring of vegetation cover in Kazakhstan

Name	Formula and ranges	Purpose	Comment
Normalized Difference Vegetation Index (NDVI) (Rouse J. W., 1973)	$NDVI = \frac{NIR-RED}{NIR+RED}$ [-1; 1]	NDVI quantifies differences in reflectance under favorable and stressful vegetation conditions and is used to monitor seasonal changes in plant health	NIR is the reflectance in the near-infrared band and RED is the reflectance in the red band
Vegetation conditions index VCI (Kogan F.N., 1997)	$\mathrm{VCI} = \frac{\mathrm{NDVIi} - \mathrm{NDVImin}}{\mathrm{NDVImax} - \mathrm{NDVImin}}$ [0; 1]	Analysis of the impact of weather conditions on vegetation during the growing season; characteristics of weather and humidity conditions	NDVIi, NDVImin and NDVImax correspond respectively to the instantaneous NDVI and the pixel-wise minimum and maximum NDVI values observed throughout the entire multi-year time series
Integrated Vegetation Index IVI (Spivak, L. et al. 2009)	$\mathrm{IVI} = \sum \mathrm{NDVI(t)}$ t- number of days in the season	Analysis of inter-seasonal changes in vegetation conditions	IVI represents the accumulated NDVI over a specified period of time
Integral index of vegetation conditions IVCI (Spivak L., 2009)	$\mathrm{IVCI} = \frac{\mathrm{IVIi} - \mathrm{IVImin}}{\mathrm{IVImax} - \mathrm{IVImin}}$ [0; 1]	Analysis of inter-seasonal changes in the impact of weather conditions on vegetation	IVI_i, IVImin, and IVImax – current, minimum and maximum values for each pixel on a given date across the entire multi-year observation period
Note – compiled by the authors			

Table 2. The HTC calculated from ground-based temperature and precipitation measurements

Name	Formula and ranges	Purpose	Comment
Selyninov Hydrothermal Coefficient (HTC) (Handbook of Drought - WMO, 2016)	HTC = R*10/Σt	Charactere the moisture supply level R - the total precipitation (in millimeters) during the period with temperatures above +10 °C; Σt - the sum of air temperatures (°C) over the same period	Standard (detailed) classification: HTC ≤ 0.3 — very severe drought (extreme drought) 0.3 < HTC ≤ 0.5 — severe drought 0.5 < HTC ≤ 0.75 — moderate drought 0.75 < HTC ≤ 1.0 — mild drought / almost normal 1.0 < HTC ≤ 1.5 — sufficient humidity HTC > 1.5 — very humid Simplified (often used) scale: HTC < 0.5 — drought 0.5–1.0 — normal/satisfactory conditions HTC > 1.0 — wet
Note – compiled by the authors			

In this study, the analysis of vegetation condition and changes was carried out using vegetation indices calculated from MODIS satellite data. These indices represent mathematical combinations of spectral reflectance characteristics in the red and near-infrared bands, allowing for a quantitative assessment of vegetation status in each pixel of the satellite image (Kogan, F.,N. 1990, Kogan, F.,N. 1994, Kronberg, 1988). Both classical indices (NDVI, VCI) and integral indices (IVI, IVCI) were applied, with the latter developed by the authors and used for the first time for the territory of Kazakhstan. As shown in (Vitkovskaya et al., 2024) the use of integral indices made it possible to assess the interannual dynamics and trends of vegetation seasons, as well as to identify periods and regions with extreme drought conditions. An important advantage of these indices is their simplicity of calculation.

When applied in Kazakhstan for the first time, this approach enables detection of the spatio-temporal patterns of drought and the ranking of growing seasons by the degree to which weather conditions affected them (Vitkovskaya et al., 2024).

As (Handbook of Drought - WMO, 2016) notes that the VCI is a primary tool for monitoring drought conditions; it enables assessment of how drought affects vegetation and the determination of the onset, duration, and severity of droughts. VCI is one of the central remote sensing tools for detecting and monitoring drought. The use of VCI in remote sensing helps to understand drought dynamics and to develop mitigation and adaptation measures; the methodology has been tested for Kazakhstan (Gitelson A., et al., 1995; Kogan F., et al., 2003). In practice, a VCI<0.3 (Kogan, 1997) is generally interpreted as indicating drought, and digital VCI maps enable visualization of areas of vegetation stress. Both indices are recognized as classical remote sensing tools and have been widely validated.

These integral indices are used to assess long-term vegetation dynamics: they identify trends of change, rank vegetation seasons by climatic conditions in a multi-year series, and are applicable for long-term forecasting. The Integral Vegetation Conditions Index (IVCI), developed by the authors, is intended to analyze interseasonal variations in the influence of weather on vegetation.

The IVCI index, as an interseasonal analogue of the VCI, is used to analyze drought dynamics and to assess their spatial extent and intensity based on satellite data. It enables ranking vegetation seasons by climatic conditions within a multi-year series and comparing the intensity and duration of droughts across different seasons. Digital IVCI matrices allow visualization of zones with degraded vegetation conditions and quantitative estimation of their area, which is important for ecosystem monitoring.

Digital IVCI matrices offer a powerful way to map the spatial distribution of areas with degraded vegetation and to quantify the extent of those zones—information that is crucial for ecosystem monitoring and assessment. A threshold value of IVCI < 0.3, analogous to the Vegetation Condition Index (VCI) cutoff, is used to flag regions that experienced climatic stress during the growing season. Long-term index time series are essential for detecting changes in land-surface conditions and for separating climatic trends from short-term weather variability. It should be noted that studies using integral indices, which summarize each vegetation season within a long-term dataset, remain very rare.

Long-term indexes time series are a key requirement for analyzing changes in land surface conditions and for distinguishing the influence of climatic trends from short-term weather fluctuations. At the same time, studies using integral indices that characterize the entire growing season within a long-term observational series are extremely rare.

The process of aggregating data from diverse observational systems is characterized by its own set of unique attributes and challenges.

1. Ground-based meteorological measurements, acquired from a sparse and geographically uneven network of observation stations, constitute point-based data collected at discrete intervals throughout the day, including nocturnal observations. To extrapolate values between these discrete nodes, interpolation techniques are employed; however, such procedures inevitably entail a degree of data loss and concomitant reduction in precision. In characterizing the impact of atmospheric conditions on vegetation dynamics, particularly in the assessment of drought severity through ground-based observations, a variety of indices are utilized as input data. These indices include, for example, the Selyninov Hydrothermal Coefficient (HTC), the Standardized Precipitation Index (SPI), and the Palmer Drought Severity Index (PDSI) (Handbook of Drought 2016), all of which are derived from time series of mean monthly or daily air temperature and monthly precipitation totals.

2. Satellite data provides systematically updated and spatially continuous information, making them indispensable for monitoring and analyzing vegetation cover. In addition, the availability of long-term archived data sets allows for retrospective research. Access to low-resolution data is provided free of charge, which expands the possibilities of their use for scientific and applied purposes.

Remote sensing methods based on the analysis of reflectivity values in the red and near-infrared spectral ranges, as well as in the thermal range, make it possible to calculate vegetation indices. These satellite-based indices are integral indicators of vegetation conditions that correlate with temperature and humidity conditions during the growing season.

Drought indices calculated on the basis of contact measurements of temperature and precipitation at meteorological stations and vegetation indices obtained from satellites are two complementary tools for analyzing the state and dynamics of vegetation cover. The possibility of establishing correlations between these indices is due to common environmental factors that affect the state of vegetation.

To compare point-based ground data from meteorological stations and spatially distributed satellite data, a methodology was developed that includes the use of a digital matrix of the vegetation index (IVCI). This technique, described in the work (Spivak F., et al, 2016), allows for a detailed analysis and integration of data obtained by various methods, which helps to increase the accuracy and reliability of research results.

To validate the proposed integral indices IVI and IVCI, they must be compared with ground observations. The comparative analysis was conducted using correlation analysis and the Chaddock scale (Orlov, 2004). This methodological approach facilitated the quantitative evaluation of the strength and nature of the relationship between the examined values. The results are presented in Table 3, which underscores the robustness of the correlation findings and their relevance to the research objectives.

Table 3. Strength of Relationship and Correlation Coefficient Value

Correlation Coefficient	Strength of Relationship
0,91 - 1	Very Strong
0.81 - 0.9	Fairly Strong
0.65 – 0.8	Strong
0.45 – 0.64	Moderate
0,25 – 0.44	Weak
< 0.25	Very Weak
«+» Direct Relationship	«–»Inverse Relationship
Note – compiled by the authors	

RESULTS AND DISCUSSION

Establishment of Correlations Between Terrestrial and Satellite-Derived Drought Indices

Establishing correlations between ground-based and satellite drought indices is important: comparing satellite-derived vegetation indices with parameters calculated from ground-based data is necessary to confirm their adequacy in describing processes within the vegetation cover.

Satellite indices were validated by comparison with ground data: Selyninov HTC time series (a measure of moisture supply) (meteo.kz) and district cereal yield statistics.

The time ranges for calculating HTC and IVCI were chosen to be identical—May to August of the vegetation season. For a detailed joint analysis of the IVCI and HTC indices, 38 meteorological stations located in the northern regions of Kazakhstan were selected. The results of correlation coefficient calculations between the long-term Integral Vegetation Condition Index (IVCI) and HTC for each meteorological station in the northern regions of Kazakhstan over the observation period 2000–2023 are presented in Table 4.

Table 4. Link between integral vegetation status and hydrothermal drought index

Kostanay Region		Akmola Region		North Kazakhstan Region	
Station	Correlation coefficient	Station	Correlation coefficient	Station	Correlation coefficient
Amangeldy	0.09	Akkol	0.30	Blagoveshchenka	0.73
Bestau	0.45	Arshaly	0.43	Bulaevo	0.70
Dievskaya	0.75	Astana	0.57	Chkalovo	0.51
Karamendy	0.71	Atbasar	0.69	Kishkenekol	0.60
Ekidin	0.58	Balkashino	0.48	Petropavlovsk	0.40
Zheleznodorozhny	0.82	Ereymentau	0.78	Sergeevka	0.59
Zhitikara	0.70	Yesil	0.66	Tayynsha	0.64
Karasu	0.85	Zhaksy	0.85	Timiryazevo	0.54
Karabalyk	0.67	Zhaltir	0.65	Vozvyshenka	0.66
Kostanay	0.78	Kokshetau	0.65	Yavlenka	0.51
Kushmurun	0.82	Stepnogorsk	0.70		
Mikhailovka	0.72	Shchuchinsk	0.75		
Presnogoryevka	0.80				
Rudny	0.71				
Tobol	0.73				
Sarykol	0.80				
Note – compiled by the authors					

Kostanay Region recorded the highest correlations, with over 75% of stations classified as having strong or very strong relationships. North Kazakhstan showed mainly moderate correlations (~50% of stations) and a substantial share of strong correlations (~40%). Akmola was dominated by moderate correlations (≈60%), with strong correlations at roughly 20% of stations.

As for example, a comparison of the vegetation index IVCI with the HTC for several selected districts (Zhaksyn district Akmola region and Auelikolsky district Kostanai region) is presented in Figure 2.

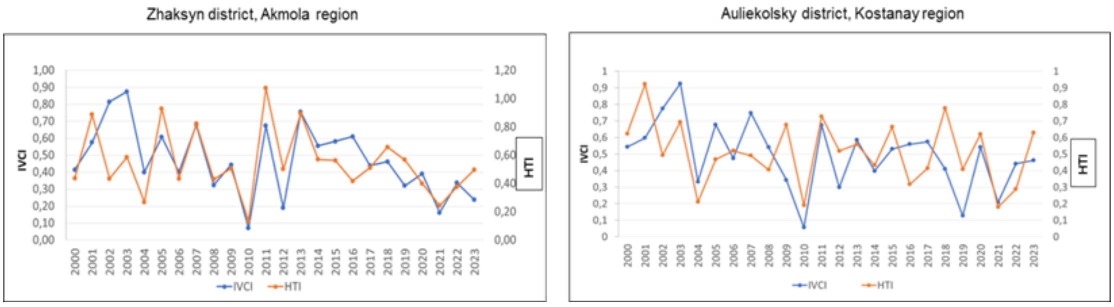

Figure 2. Changes in the HTC coefficient and the IVCI vegetation index (2000-2023)
Note – compiled by the authors

Consequently, the IVCI may be adopted as a remote-sensing proxy for the HTC, facilitating quantitative evaluation of weather-driven vegetation changes when terrestrial data are lacking. Correlation coefficients between the indices and cereal crop yields for multiple districts in northern Kazakhstan (2000–2023) are presented in Table 5.

Table 5. Statistical Association between Integral Vegetation Condition Index and Cereal Yield Averages in Northern Kazakhstan

Region	District	Correlation Coefficient Between IVCI and Cereal Crop Yields	Strength of Relationship According to the Chaddock Scale
Kostanay Region	Zhitikarinsky	0.68	Noticeable
	B. Mailin	0.65	Noticeable
	Kostanay	0.39	Moderate
	Auelikolsky	0.63	Noticeable
	Denisovsky	0.72	High
	Kamystinsky	0.77	High
Akmola Region	Zhaksynsky	0.44	Moderate
	Esilsky	0.72	High
	Atbasarsky	0.54	Noticeable
	Bulandinsky	0.45	Moderate
	Yegindykol	0.54	Noticeable
	Birzhan Sal	0.79	High
Note – compiled by the authors			

Analysis of correlation relationships between crop yield data for 12 districts across two regions showed the following: 33% of the analyzed data demonstrated a high degree of correlation, 42% a noticeable degree, and 25% a moderate degree (according to the Chaddock scale). The obtained correlation values were lower than those between HTC and IVCI, which may be explained by inaccuracies in statistical yield data. A comparison of IVCI and cereal crop yields for two selected districts (Auelikolsky district Kostanai region and Karabalyk district Akmola region) is presented in Figure 3.

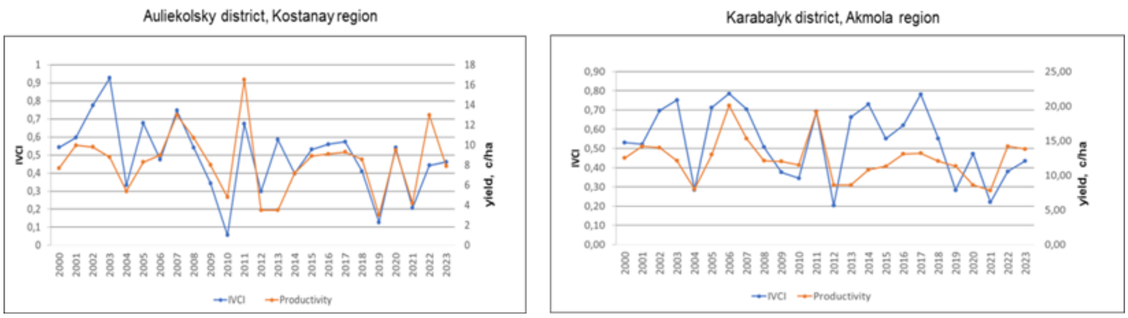

Figure 3. IVCI and average grain yield: temporal comparison (2000–2023)
Note – compiled by the authors

Peculiarities of the Integral Index of Vegetation Conditions IVCI

Index IVCI effectively measures temporal changes in vegetation, allowing trend analysis and identification of extreme seasons driven by weather. Developed as a multi-season VCI analogue (Kogan, 1990; Spivak et al., 2008), it detects and rates drought extent/intensity from satellite data. The IVCI allows for the ranking of growing seasons based on weather conditions in a multi-year data series. An IVCI < 0.3 flags areas under season-long stress. Mapped IVCI values show drought-affected zones in northern Kazakhstan (Figure 4).

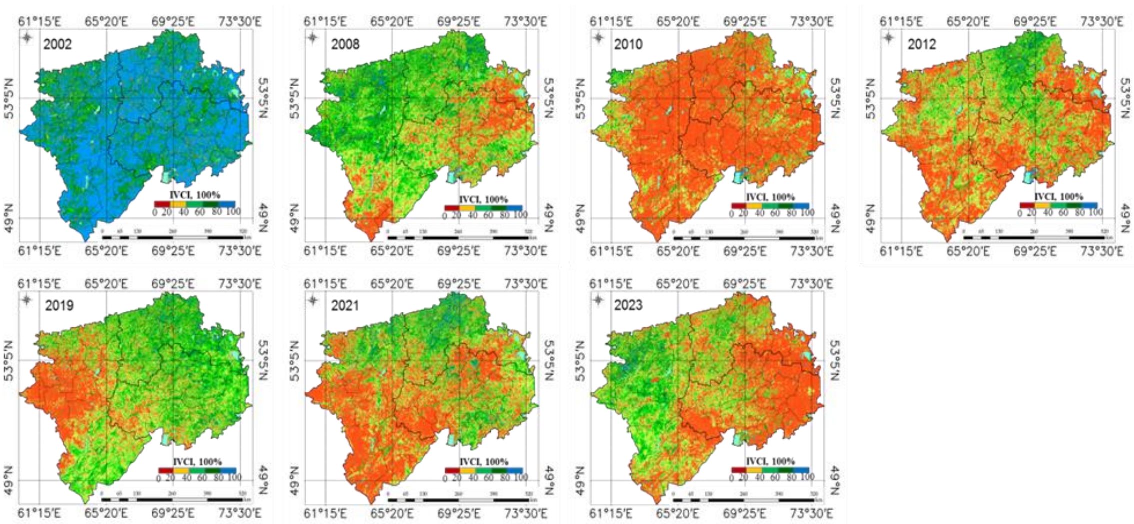

Figure 4. Temporal composite maps of IVCI for chosen growing seasons in northern Kazakhstan
Note – compiled by the authors

Digital IVCI rasters facilitate the spatial delineation and geolocation of areas exhibiting reduced vegetation condition and enable area calculation. Multi-annual IVCI distributions are used to evaluate entire growing seasons and to flag regions with IVCI < 0.3 as season-long vegetation stress.

According to remote sensing data analysis, the years 2002 and 2016 were characterized by the most humid growing seasons across Kazakhstan as a whole. The regions exhibiting the lowest

Integrated Vegetation Condition Index (IVCI) values included: in 2006, the southern part of the Kostanay region; in 2008, approximately two-thirds of the studied area, excluding the northern portions of the Kostanay and North Kazakhstan regions; in 2010, all northern regions of Kazakhstan experienced a severe drought, which was one of the most intensive drought events in the period from 2000 to 2023; and in 2012, the most severe drought in the period from 2000 to 2023 affected all northern (agricultural) and central (pastoral) regions of the republic, leading to significant ecological and economic consequences.

In the context of time series analysis, it is crucial to identify patterns of long-term changes. The underlying trend represents the general pattern of a phenomenon over an extended period, irrespective of random fluctuations. Fluctuations, on the other hand, refer to deviations from this general trend during specific time periods.

The multi-year IVCI values for the growing seasons spanning May to August in the northern regions of Kazakhstan for the period from 2001 to 2023 are presented in Figure 5.

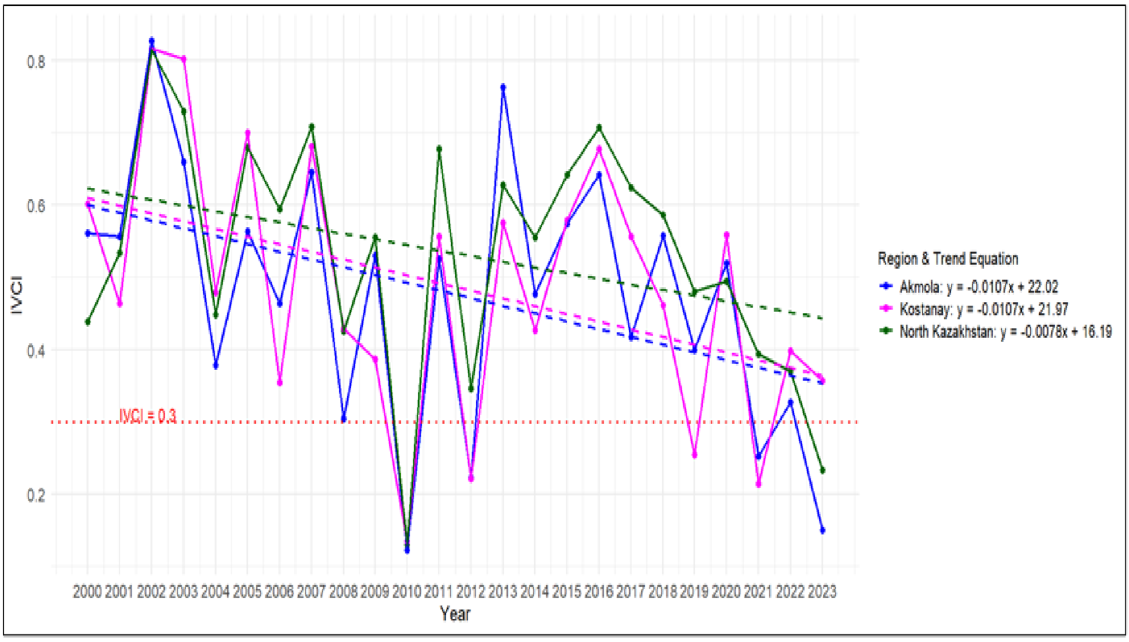

Figure 5. Long-term IVCI values for the territory of the northern regions of Kazakhstan, 2000-2023

Note – compiled by the authors

The graph shows an IVCI value of less than 0.3, which corresponds to arid conditions. Based on this, according to remote sensing data, the following vegetation seasons can be classified as dry to varying degrees: 2008, 2010, 2012, 2023 in Akmola region, 2010, 2012, 2019, 2021 in Kostanay region, 2010, 2023 in North Kazakhstan region.

There is a pronounced negative trends towards a decrease in IVCI values. IVCI linear trend equations (2000–2023): $y = -0.0107 \cdot x + 22.0174$ (Akmola Region); $y = -0.0107 \cdot x + 21.9680$ (Kostanay Region); $y = -0.0078 \cdot x + 16.1885$ (North Kazakhstan Region).

The coefficient k in the linear trend equation ($y = k*x + b$) of the IVCI index distribution characterizes the rate of change in the state of vegetation cover. The highest values of the coefficients for negative IVCI index trends were observed in the Kostanay and Akmola regions. A similar approach is described in (Al Nadabi, et al. 2024).

Analysis of the IVCI Trend in the Akmola Region Using the Mann–Kendall Test and Sen's Slope (2000–2023).

To assess the direction and stability of changes in the Integral Vegetation Condition Index (IVCI) over the period 2000–2023, a nonparametric trend analysis was performed using the Mann–Kendall (MK) test and Sen's slope estimator (Mann, H. B., 1945). This method is widely applied to time series data, particularly in ecological and climatic studies, due to its robustness against outliers and lack of assumptions regarding data normality.

The results of the Mann–Kendall test and Sen's slope estimation for the time series of annual average IVCI from 2000 to 2023 are presented in Table 6. According to the Mann– Kendall test, the obtained τ coefficient = −87.000 indicates the presence of a negative trend in the series of annual IVCI values. The p-value = 0.03239 confirms the statistical significant of this trend at the $\alpha = 0.05$ level. The Z-statistic = −2.1396 also indicates a downward trend, significant within the critical range of the standard normal distribution.

The Sen's slope estimator showed that IVCI decreased on average by 0.01023 units per year. The 95% confidence interval for the slope was from −0.02083 to −0.00091, which does not include zero and therefore confirms the stability and reliability of the observed negative trend.

Table 6. Results of the Mann–Kendall Test Application

Indicator	Value
τ Coefficient (Mann–Kendall)	−87.000
p-value	0.03239
Z-statistic	−2.1396
Sen's Slope (units/year)	−0.01023
95% Confidence Interval (Lower Bound)	−0.02083
95% Confidence Interval (Upper Bound)	−0.00091
Note – compiled by the authors	

Figure 6 presents the annual mean values of IVCI, plotted based on Sen's slope estimation.

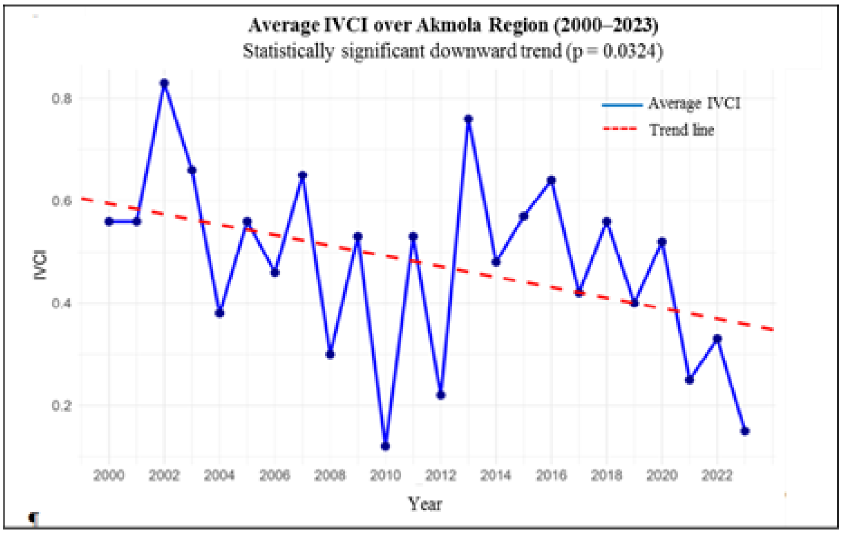

Figure 6. Averaged IVCI over the territory of the Akmola Region and the trend line (linear regression) for the period 2000-2023

Note – compiled by the authors

The dynamics of the annual mean IVCI values presented in Figure 6 clearly demonstrate a long-term weakening of vegetation activity in the Akmola Region. A distinct downward trend is observed, with local fluctuations corresponding to years of extreme drought. The combined application of the Mann–Kendall test and Sen's slope estimator revealed a statistically significant and consistent decline in IVCI values in the Akmola Region over the past two decades. Analysis of Figure 6 confirms that the periods of most pronounced vegetation stress occurred in 2008, 2010, 2012, and 2023, and that even after short-term improvements, the overall trend remains negative. The identified negative trend reflects the intensification of arid processes and the degradation of vegetation cover, highlighting the high sensitivity of the Integral Vegetation Condition Index (IVCI) to climatic fluctuations.

Thus, the IVCI index can be regarded as a reliable indicator of long-term changes in vegetation condition and a valuable tool for assessing the consequences of aridization in the northern agricultural regions of Kazakhstan.

CONCLUSION

The validation of the proposed Integral Vegetation Condition Index (IVCI) has demonstrated robust empirical support. Satellite-derived data were meticulously cross-validated against field-based metrics, specifically the Selyninov Hydrothermal Coefficient (HTC) and agricultural yields in non-irrigated regions where crop production is solely dependent on meteorological variables such as precipitation and temperature. This rigorous cross-validation process is essential for ascertaining the accuracy and reliability of remote sensing monitoring techniques. The high degree of correlation between satellite-derived vegetation indices and ground-based measurements underscores the efficacy of these techniques in providing accurate assessments of vegetation health and productivity.

The research confirmed the high informativeness of vegetation indices for assessing vegetation condition and identifying its change trends across Kazakhstan. The IVCI index, which was first developed by the authors to monitor the state of vegetation in Northern Kazakhstan, proved to be very effective. Its comparison with ground-based data — the Selyninov Hydrothermal Coefficient and statistical data on cereal crop yields — revealed significant correlations, confirming the reliability and practical applicability of the proposed methodology.

The application of the Mann–Kendall test and Sen's slope estimator made it possible to identify a statistically significant negative trend in IVCI changes in the Akmola Region, while linear trends for the Kostanay and North Kazakhstan Regions also indicated a deterioration in vegetation conditions during 2000–2023. The use of the threshold value IVCI < 0.3 allowed the identification of years with extreme droughts (2008, 2010, 2012, 2023).

The study deduced from the long-term distribution of the IVCI index that the negative trend in this index indicates an increase in the adverse effects of weather on vegetation. Furthermore, the long-term distribution of the IVCI index clearly identifies the vegetation seasons most severely affected by drought, which are suitable for further investigation.

The IVCI index can be considered a satellite analogue of the Hydrothermal Coefficient (HTC) and serves as a new tool for assessing and monitoring drought conditions in the agricultural regions of Kazakhstan. The obtained results demonstrate the potential of using this index for operational assessment of agroclimatic risks and yield forecasting under limited ground observations.

A promising direction for future research is the integration of IVCI with climate models and higher spatial resolution datasets (e.g., Sentinel, Landsat) to refine the spatial structure of drought phenomena and assess their impact on agroecosystems.

CONFLICT OF INTEREST: The authors declare no conflict of interest.

FUNDING: This work was carried out Scientific Research" program of the Ministry of Science and Higher Education of the Republic of Kazakhstan for 2025–2027, under the project titled: "Development and Training of a Chatbot for the Analysis and Forecasting of Dynamic

Processes Based on Earth Remote Sensing Data" (Grant No. AP26198325).

ACKNOWLEDGEMENTS: The authors express their gratitude to the Ministry of Science and Higher Education of the Republic of Kazakhstan.

AI TECHNOLOGY USE STATEMENT: The authors of this scientific article declare that no artificial intelligence technologies were used in the preparation of the manuscript.

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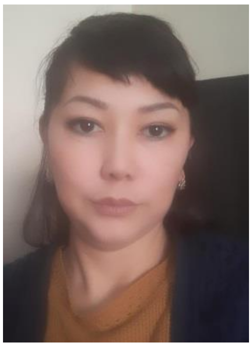

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