

ديناميكيات وحساسية المناخ والغطاء النباتي في العراق باستخدام بيانات رصد الأرض طويلة الأمد

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Climate–Vegetation Dynamics and Sensitivity across Iraq Using Long-Term Earth Observation Data

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المخلص

تؤدي تغيرات المناخ إلى تكثيف الإجهاد الحراري والمائي عبر المناطق الجافة، مما يزيد من الحاجة إلى رصد متسق مكانياً وطويل الأمد لاستجابات الغطاء النباتي. العراق معرض بشكل خاص لهذه التغيرات لأن التدرجات المناخية القوية، والجفاف المتكرر، ومحدودية توافر المياه تتزامن مع مساحات شاسعة من الأراضي المطرية والمروية. قامت هذه الدراسة بتقييم ديناميكيات المناخ والغطاء النباتي في العراق من عام 2001 إلى 2025 باستخدام مؤشر الاختلاف

الغطائي النباتي الطبيعي (MODIS NDVI) ، وبيانات هطول الأمطار (CHIRPS) ، وبيانات درجة حرارة الهواء على ارتفاع مترين (ERA5–Land). تم تحليل متوسط هطول الأمطار للفترة من أكتوبر إلى مايو، واتجاهات مؤشر (NDVI) للفترة من يناير إلى مايو، وارتباطات المناخ مع مؤشر (NDVI) بعد إزالة الاتجاه (detrended) على شبكة مشتركة بدقة 0.1 درجة. تم بعد ذلك تصنيف البكسلات النباتية على أنها: حساسة لهطول الأمطار، أو حساسة للحرارة، أو حساسة لكليهما، أو لا تظهر علاقة متوقعة قوية، أو تظهر اتجاهًا قويًا آخر. أظهر هطول الأمطار في الموسم الرطب تدرجًا واضحًا من إجماليات عالية جدًا في شمال وشمال شرق العراق إلى إجماليات منخفضة ومنخفضة جدًا عبر الغرب والجنوب الغربي والجنوب. كان الاختصار ذو الدلالة الإحصائية أكثر انتشارًا بشكل ملحوظ من الاسمرار، حيث تركزت أقوى اتجاهات مؤشر (NDVI) الإيجابية في المناطق الزراعية في الشمال والشمال الشرقي والوسط. بعد إزالة الاتجاهات الخطية، كانت ارتباطات هطول الأمطار مع مؤشر (NDVI) إيجابية في الغالب وواسعة النطاق مكانيًا، في حين كانت ارتباطات درجة الحرارة مع مؤشر (NDVI) ذات دلالة سلبية بشكل رئيسي ومركزة في شمال وشرق وجنوب شرق العراق. هيمنت حساسية هطول الأمطار على التصنيف المتكامل، بينما شكلت الحساسية المزدوجة لهطول الأمطار والحرارة مجموعات متميزة في شمال-وسط وجنوب شرق البلاد. توفر هذه النتائج خط أساس مكانيًا وطنيًا لتحديد مناطق الغطاء النباتي المرتبطة بتقلبات المياه والحرارة بين السنوات. وتمثل فئات الحساسية ارتباطات إحصائية وليست عزوًا سببيًا.

Abstract

Climate change is intensifying temperature and water stress across dryland regions, increasing the need for spatially consistent, long-term monitoring of vegetation responses. Iraq is especially exposed because strong climatic gradients, recurrent drought and limited water availability coincide with extensive rain-fed and irrigated land. This study assessed climate–vegetation dynamics across Iraq from 2001 to 2025 using MODIS normalized difference vegetation index (NDVI), CHIRPS precipitation and ERA5-Land 2-m air temperature. Mean October–May precipitation, January–May NDVI trends and detrended climate–NDVI correlations were analysed on a common 0.1° grid. Vegetated pixels were subsequently classified as rainfall-sensitive, heat-sensitive, sensitive to both, without a strong expected relationship, or displaying another strong relationship direction. Wet-season precipitation showed a pronounced gradient from very high totals in northern and northeastern Iraq to low and very low totals across the west, southwest and south. Significant



greening was considerably more widespread than browning, with the strongest positive NDVI trends concentrated in northern, northeastern and central agricultural areas. After removal of linear trends, precipitation–NDVI correlations were predominantly positive and spatially extensive, whereas significant temperature–NDVI correlations were mainly negative and concentrated in northern, eastern and southeastern Iraq. The integrated classification was dominated by rainfall sensitivity, while combined rainfall and heat sensitivity formed distinct north-central and southeastern clusters. These results provide a national spatial baseline for identifying vegetation regions associated with interannual water and heat variability. The sensitivity classes represent statistical associations rather than causal attribution.

1. Introduction

Climate change is altering the functioning of terrestrial ecosystems through rising temperatures, changing precipitation regimes and increasingly frequent climatic extremes. Global surface temperature during 2011–2020 was approximately 1.1°C higher than during 1850–1900, and further warming is expected to intensify heatwaves, droughts and hydrological variability in many regions (IPCC, 2023). These changes affect vegetation by modifying water availability, evaporative demand, growing-season conditions and plant physiological activity. Nevertheless, vegetation responses are spatially heterogeneous because the effects of temperature and precipitation depend on background aridity, vegetation type, soil properties, land management and the timing of climatic events. In water-limited environments, for example, greater rainfall can enhance vegetation growth, whereas unusually high temperatures may increase evapotranspiration and accelerate soil-moisture depletion. Identifying where vegetation is greening or browning and determining how these changes are associated with climate variability are therefore essential for understanding ecosystem vulnerability under continued global warming.

This need is particularly urgent in the Eastern Mediterranean and Middle East, which is recognized as a major climate-change hotspot. The region is warming substantially faster than the global average and is projected to experience stronger heat extremes, increasing aridity and greater pressure on already limited water resources (Zittis et al., 2022). These climatic pressures interact with rapid population growth, agricultural demand, land degradation and dependence on transboundary water resources, increasing the vulnerability of both natural and managed ecosystems. Vegetation in this predominantly arid and semi-arid region is especially

sensitive to the amount and seasonal distribution of rainfall. Even relatively small departures from normal precipitation or temperature conditions can affect vegetation productivity, rangeland condition, crop development and the risk of drought-related degradation. Consequently, spatially explicit and long-term monitoring is required to distinguish persistent vegetation change from short-lived fluctuations associated with individual wet or dry years.

Iraq represents a particularly important case within this regional context. Its environmental conditions range from relatively humid and mountainous areas in the north and northeast to extensive arid plains and deserts in the west and south. Rainfall is strongly seasonal and occurs predominantly between October and May, while summers are generally hot and dry. This climatic gradient generates pronounced spatial differences in vegetation productivity and water availability. At the same time, Iraq is highly exposed to rising temperatures, recurrent drought, declining or increasingly variable rainfall, water scarcity, salinization, desertification and dust storms (World Bank, 2021; SIPRI and NUPI, 2023). These pressures affect ecosystems and agricultural livelihoods and are compounded by irrigation practices, land-use change and changes in the discharge of the transboundary Tigris and Euphrates rivers. Because rainfall and temperature constraints vary across the country, national averages alone cannot adequately reveal where vegetation is changing or which regions are most strongly associated with water and heat variability.

Conventional ground-based observations are indispensable for measuring local environmental conditions, but station networks are often spatially sparse and unevenly distributed, particularly across extensive arid regions. Earth observation provides a complementary means of monitoring vegetation and climate consistently across large areas and over long periods. Satellite-derived vegetation indices offer repeated and spatially continuous measurements of vegetation greenness, while gridded precipitation products and climate reanalyses provide corresponding information on water and thermal conditions. When these datasets are placed on a common spatial grid, they allow pixel-wise assessment of vegetation trends and climate associations that may otherwise be obscured by national or regional aggregation. Long-term records are particularly valuable because they support separation of persistent directional change from interannual variability and reduce the influence of isolated climatic events.

Among the available satellite products, the Moderate Resolution Imaging Spectroradiometer (MODIS) provides one of the most consistent records



for monitoring vegetation dynamics since 2000. The Normalized Difference Vegetation Index (NDVI) derived from MODIS has been widely used to characterize vegetation activity, phenology and long-term greening and browning patterns because of its regular temporal coverage, standardized processing and sensitivity to photosynthetically active vegetation (Huete et al., 2002). For precipitation, the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) product combines satellite-based information with rain-gauge observations to provide a long-term daily rainfall record at 0.05° spatial resolution. CHIRPS was specifically developed to support precipitation-trend assessment and drought monitoring in data-sparse regions (Funk et al., 2015). These observations can be complemented by ERA5-Land, which provides a spatially and temporally consistent reconstruction of land-surface and near-surface atmospheric conditions, including 2-m air temperature, over multiple decades (Muñoz-Sabater et al., 2021). Together, MODIS, CHIRPS and ERA5-Land provide complementary information on vegetation condition, water supply and thermal variability, making them suitable for evaluating long-term climate–vegetation relationships across Iraq.

Previous remote-sensing studies have demonstrated the value of MODIS and related datasets for examining vegetation change, rainfall variability and agricultural drought in Iraq. These studies include assessments of vegetation dynamics at the national scale, investigations of rainfall–NDVI relationships and more localized analyses of drought or vegetation responses in Baghdad and the Kurdistan Region (Naif et al., 2020; Gaznayee et al., 2022; Al-Daoudi and Al-Timimi, 2024; Hatem et al., 2024; Muter et al., 2025). However, much of the existing work has focused on individual climate variables, selected administrative regions, monthly correlations, drought episodes or vegetation trends considered separately from climate associations. Raw correlations between trending climate and vegetation time series can also be misleading because two variables may appear related simply because both change over time. A more integrated national assessment is therefore needed to distinguish long-term vegetation trends from year-to-year covariation and to identify whether different vegetated regions are associated primarily with rainfall variability, temperature variability or both.

Accordingly, the novelty of this study lies not in the individual use of NDVI or rainfall data, but in their integration within a consistent 25-year, spatially explicit analytical framework covering the whole of Iraq. The study combines the spatial distribution of October–May rainfall, significant January–May NDVI greening and browning trends, and

detrended precipitation–NDVI and temperature–NDVI correlations on a common 0.1° grid. Removing the linear trends before calculating the climate–vegetation correlations reduces the risk that relationships are driven solely by shared long-term tendencies. The directional correlations are subsequently integrated into a five-class screening framework that distinguishes areas associated with rainfall variability, heat variability, both climatic factors, no strong expected relationship or other significant response directions. Here, “sensitivity” is used operationally to describe statistically significant interannual associations and does not imply causal attribution.

The overall objective of this study was therefore to characterize long-term climate–vegetation dynamics and their spatial variability across Iraq using Earth observation data from 2001 to 2025. Specifically, the study addressed five questions: (1) Where is precipitation highest during Iraq’s October–May wet season? (2) Where has vegetation significantly greened or browned? (3) Where is vegetation strongly associated with interannual precipitation variability after removing long-term trends? (4) Where is vegetation associated with detrended temperature variability? and (5) Which vegetated regions exhibit rainfall-associated, heat-associated or combined climate sensitivity? Answering these questions provides a spatial basis for identifying potentially climate-sensitive landscapes and supporting ecosystem monitoring, drought assessment, agricultural planning and climate-adaptation strategies in Iraq.

2. Materials and methods

2.1 Study area, analysis period and research design

The analysis evaluated spatial and interannual climate–vegetation relationships across Iraq for 2001–2025. Iraq’s national boundary was obtained from the FAO Global Administrative Unit Layers (GAUL 2015, level 0). All calculations were implemented in Google Earth Engine and harmonized to a geographic grid (EPSG:4326) with a spatial resolution of 0.1° (approximately 11 km). The study used one annual observation per grid cell for each of 25 years. Seasonal windows were selected to represent (i) vegetation activity during January–May, (ii) cumulative water supply from the beginning of the preceding wet season (October) through May, and (iii) thermal conditions during the January–May vegetation period.

2.2 Earth-observation and climate datasets

Vegetation activity was represented by the Normalized Difference Vegetation Index (NDVI) from the Terra MODIS MOD13C1 Version 6.1 Climate Modeling Grid product. MOD13C1 provides 16-day NDVI



composites at 0.05° (approximately 5.6 km). In the Earth Engine asset, the MODIS scale factors and offsets are already applied; consequently, NDVI was retained in its physical range without additional scaling. Observations with SummaryQA values of 0 (good quality) or 1 (marginal quality) were retained, whereas snow/ice and cloudy observations were excluded. A physical range filter of -0.2 to 1.0 was also applied.

Precipitation was obtained from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) daily Version 2.0 product. CHIRPS provides daily rainfall estimates in millimetres per day at 0.05° resolution and combines satellite observations with rain-gauge information. Near-surface air temperature was obtained from the ERA5-Land Monthly Aggregated product. The temperature_2m variable, supplied in kelvin at approximately 0.1° resolution, was converted to degrees Celsius by subtracting 273.15. The selected datasets supplied consistent coverage over the full study interval.

2.3 Seasonal aggregation and spatial harmonization

For each calendar year y , three annual seasonal metrics were generated. First, all quality-controlled 16-day NDVI observations acquired from 1 January to 31 May were averaged to produce a January–May mean NDVI composite. Second, daily CHIRPS rainfall from 1 October of year $y-1$ through 31 May of year y was summed to obtain total wet-season precipitation (mm). Third, the ERA5-Land monthly 2-m temperature images from January through May were averaged to characterize mean vegetation-period temperature ($^\circ\text{C}$). Thus, rainfall preceded and overlapped the NDVI observation period, whereas temperature was contemporaneous with it.

MODIS NDVI and seasonally accumulated CHIRPS rainfall were aggregated from 0.05° to the 0.1° target grid using the arithmetic mean of contributing source pixels. For rainfall, daily values were first summed through time at their native resolution; the resulting seasonal totals were then spatially averaged. ERA5-Land temperature was placed directly on the same 0.1° grid. The harmonized annual NDVI, precipitation and temperature layers were stacked with a year band to support pixel-wise temporal analysis. Processing was conducted without intermediate clipping, and final products were clipped to Iraq to reduce unnecessary computation.

2.4 Vegetation mask

Climate–vegetation analyses were restricted to persistently vegetated grid cells. For each pixel, mean January–May NDVI and the number of years with valid NDVI observations were calculated across 2001–2025. Pixels were retained when mean NDVI was at least 0.10 and valid NDVI data

were available for at least 20 of the 25 years. This mask was applied to the NDVI trend, detrended correlation and climate-sensitivity analyses, thereby excluding sparsely vegetated or insufficiently observed areas.

2.5 Analyses linked to the research questions

2.5.1 Spatial distribution of wet-season precipitation (RQ1)

To determine where rainfall was highest during Iraq's October–May wet season, the 25 annual wet-season precipitation totals were averaged pixel by pixel. The resulting map represents mean October–May precipitation in millimetres over 2001–2025. This analysis was performed across the full national territory rather than only within the vegetation mask.

2.5.2 Vegetation greening and browning trends (RQ2)

Long-term vegetation change was quantified for each vegetated pixel by ordinary least-squares linear regression of annual January–May mean NDVI against calendar year. The fitted slope represents the rate of change in NDVI per year: positive slopes indicate greening and negative slopes indicate browning. Trend significance was evaluated from the Pearson correlation between year and NDVI, and only trends with $p < 0.05$ were retained in the final map. Exported values remained in NDVI yr^{-1} ; multiplication by 1,000 was used only for on-screen visualization and did not alter the exported data.

2.5.3 Detrended precipitation–vegetation association (RQ3)

To isolate interannual covariation from shared long-term trends, separate pixel-wise linear trends were fitted to NDVI and precipitation as functions of year. For each variable, the fitted value was subtracted from the observed annual value, yielding annual residuals. Pearson's correlation coefficient was then calculated between the precipitation residuals and NDVI residuals. Relationships were mapped when $|r| \geq 0.30$ and $p < 0.05$. Positive values indicate that years wetter than their local long-term trend tended to have higher NDVI than expected from the vegetation trend; negative values indicate the opposite association.

2.5.4 Detrended temperature–vegetation association (RQ4)

The temperature analysis followed the same detrending procedure. Pixel-wise linear trends were removed independently from January–May temperature and NDVI, after which Pearson's r was calculated between their annual residuals. Only relationships satisfying $|r| \geq 0.30$ and $p < 0.05$ were retained. Negative correlations indicate that years warmer than the local temperature trend tended to have lower-than-trend NDVI, whereas





positive correlations indicate that warmer-than-trend years coincided with higher-than-trend NDVI.

2.5.5 Climate-sensitivity classification (RQ5)

Vegetated pixels were classified using the direction, magnitude and statistical significance of the detrended correlations. A pixel was designated rainfall-sensitive when the precipitation–NDVI relationship was positive ($r \geq 0.30$, $p < 0.05$), and heat-sensitive when the temperature–NDVI relationship was negative ($r \leq -0.30$, $p < 0.05$). These criteria produced five mutually exclusive classes: (1) sensitive to both rainfall and heat, (2) rainfall-sensitive only, (3) heat-sensitive only, (4) no relationship meeting the strength and significance criteria, and (5) another strong significant relationship. Class 5 captured response directions outside the expected stress hypotheses, including negative precipitation–NDVI and/or positive temperature–NDVI correlations.

2.6 Statistical thresholds, outputs and interpretation

A nominal significance level of $\alpha = 0.05$ and a minimum absolute correlation of 0.30 were used throughout the correlation screening. Five GeoTIFF products were exported on the common 0.1° grid: mean wet-season precipitation, significant NDVI trend, detrended precipitation–NDVI correlation, detrended temperature–NDVI correlation and climate-sensitivity class. Empty tiles were omitted, and all outputs were clipped to Iraq.

2.7 Research-question-to-method correspondence

RQ	Purpose	Method	Output
RQ1	Where is wet-season rainfall highest?	Mean of 25 annual October–May precipitation totals	Mean precipitation (mm)
RQ2	Where has vegetation greened or browned?	Pixel-wise linear NDVI trend; retain $p < 0.05$	NDVI trend (NDVI yr^{-1})
RQ3	Where is vegetation associated with precipitation variability?	Pearson r between detrended precipitation and NDVI residuals; $ r \geq 0.30$, $p < 0.05$	Detrended r
RQ4	Where is vegetation associated with temperature variability?	Pearson r between detrended temperature and NDVI residuals; $ r \geq 0.30$, $p < 0.05$	Detrended r
RQ5	Which regions show rainfall, heat or combined sensitivity?	Rule-based classification of significant directional correlations	Five-class map

2.8 Graphical methodological workflow

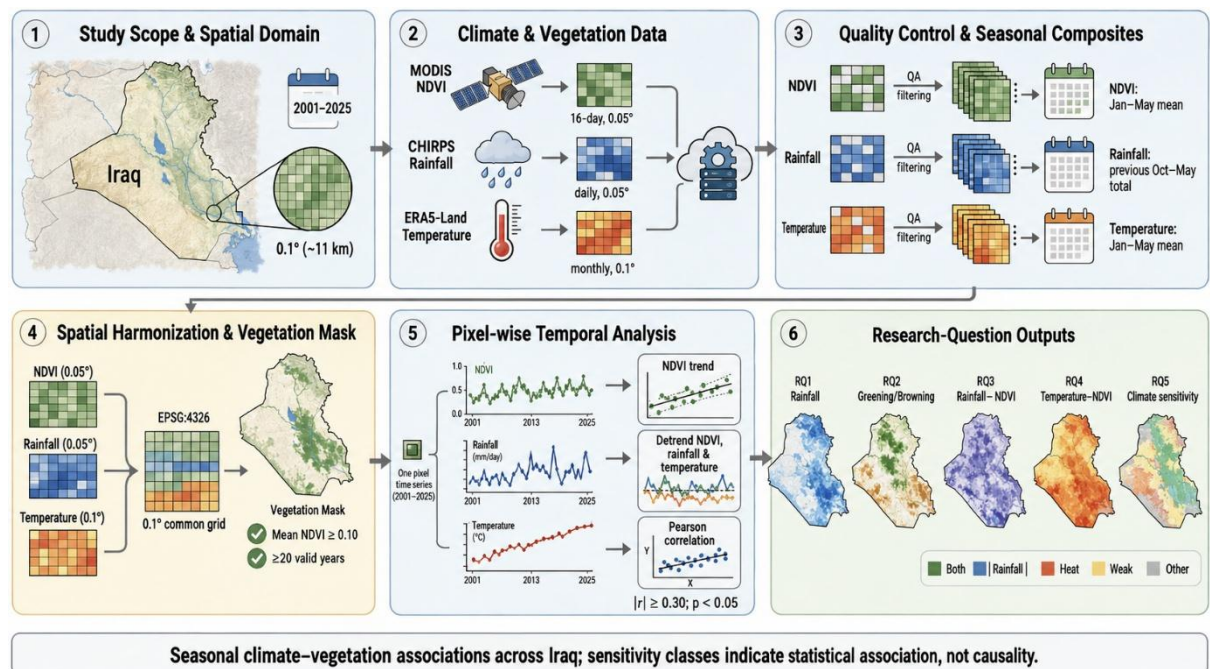


Figure 1. Graphical workflow of the climate–vegetation analysis across Iraq. Seasonal NDVI, precipitation and temperature metrics were harmonized to a common 0.1° grid and used in five research-question-specific analyses. Correlation-based sensitivity denotes statistical association rather than causal attribution.

3. Results

3.1 Spatial distribution of wet-season precipitation

Mean October–May precipitation displayed a pronounced north–south and northeast–southwest gradient across Iraq (Figure 2). The highest long-term totals occurred in the northern and northeastern parts of the country. Very high precipitation values of 800–920 mm were concentrated along the far northern and northeastern margins, while a broader high-precipitation zone of 600–800 mm extended across much of northern and northeastern Iraq. Moderately high totals of 400–600 mm formed a transition toward the central part of the country. Central Iraq was characterized mainly by moderate precipitation of 200–400 mm, whereas low totals of 100–200 mm covered extensive western, southwestern and southern areas. The lowest class, 60–100 mm, occurred mainly in the southern and southwestern interior.



3.2 Spatial patterns of NDVI greening and browning

Statistically significant NDVI trends were spatially heterogeneous, but positive trends were substantially more widespread than negative trends (Figure 3). Moderate greening rates of $0.003\text{--}0.006\text{ NDVI yr}^{-1}$ occurred extensively across northern, north-central and central-eastern vegetated areas. Strong greening of $0.006\text{--}0.012\text{ NDVI yr}^{-1}$ appeared in concentrated clusters in the north and northeast and in parts of the central agricultural corridor. Weak greening of $0.000\text{--}0.003\text{ NDVI yr}^{-1}$ was more fragmented and extended into western, central and southern areas. In contrast, browning was limited to isolated pixels and small clusters. Most negative trends were within -0.003 to $0.000\text{ NDVI yr}^{-1}$, with scattered occurrences in northern, central and southeastern Iraq. Strong browning rates of -0.006 to $-0.003\text{ NDVI yr}^{-1}$ were rare. Areas left blank were outside the vegetation mask or did not contain a trend meeting the significance criterion.

3.3 Detrended precipitation–NDVI relationships

Significant detrended precipitation–NDVI relationships were overwhelmingly positive across the mapped area (Figure 4). Moderate positive correlations ($r = 0.30\text{--}0.60$) were spatially extensive, while strong positive correlations ($r = 0.60\text{--}1.00$) occurred in multiple clusters across northern, western, central and southern Iraq. The strongest positive relationships were particularly evident in parts of the northern and northeastern region, the western and west-central interior, and sections of the southeastern corridor. Negative correlations were uncommon and restricted mainly to a small number of pixels in southeastern Iraq. Blank areas represent pixels that were masked or did not satisfy both the correlation-strength and significance thresholds.



3.4 Detrended temperature–NDVI relationships

The significant temperature–NDVI relationships were predominantly negative and were less spatially extensive than the precipitation–NDVI relationships (Figure 5). A broad band of moderate negative correlations ($r = -0.60$ to -0.30) extended across northern and north-central Iraq. Additional negative clusters occurred in central Iraq and along the eastern and southeastern parts of the country. Strong negative correlations ($r = -1.00$ to -0.60) were localized, with the clearest concentrations occurring in the east and southeast. Positive temperature–NDVI correlations were rare and occurred only in a small number of pixels near the far northern boundary. Large parts of western and southern Iraq contained no displayed relationship meeting the specified magnitude and significance criteria.

3.5 Climate-sensitivity classification

The integrated sensitivity classification was dominated by rainfall-sensitive pixels (Figure 6). Rainfall sensitivity alone formed the most spatially extensive class, covering broad areas of northern, western, central and southern Iraq within the vegetation mask. Combined rainfall and heat sensitivity formed a distinct belt across north-central Iraq and additional clusters along the eastern and southeastern corridor. Pixels classified as having no strong detected relationship occurred primarily in central-southern and southeastern areas, with smaller discontinuous patches elsewhere. Heat sensitivity alone was extremely limited and appeared only as isolated pixels. The class representing other strong relationship directions was also rare and occurred in a small number of northern and southeastern locations.

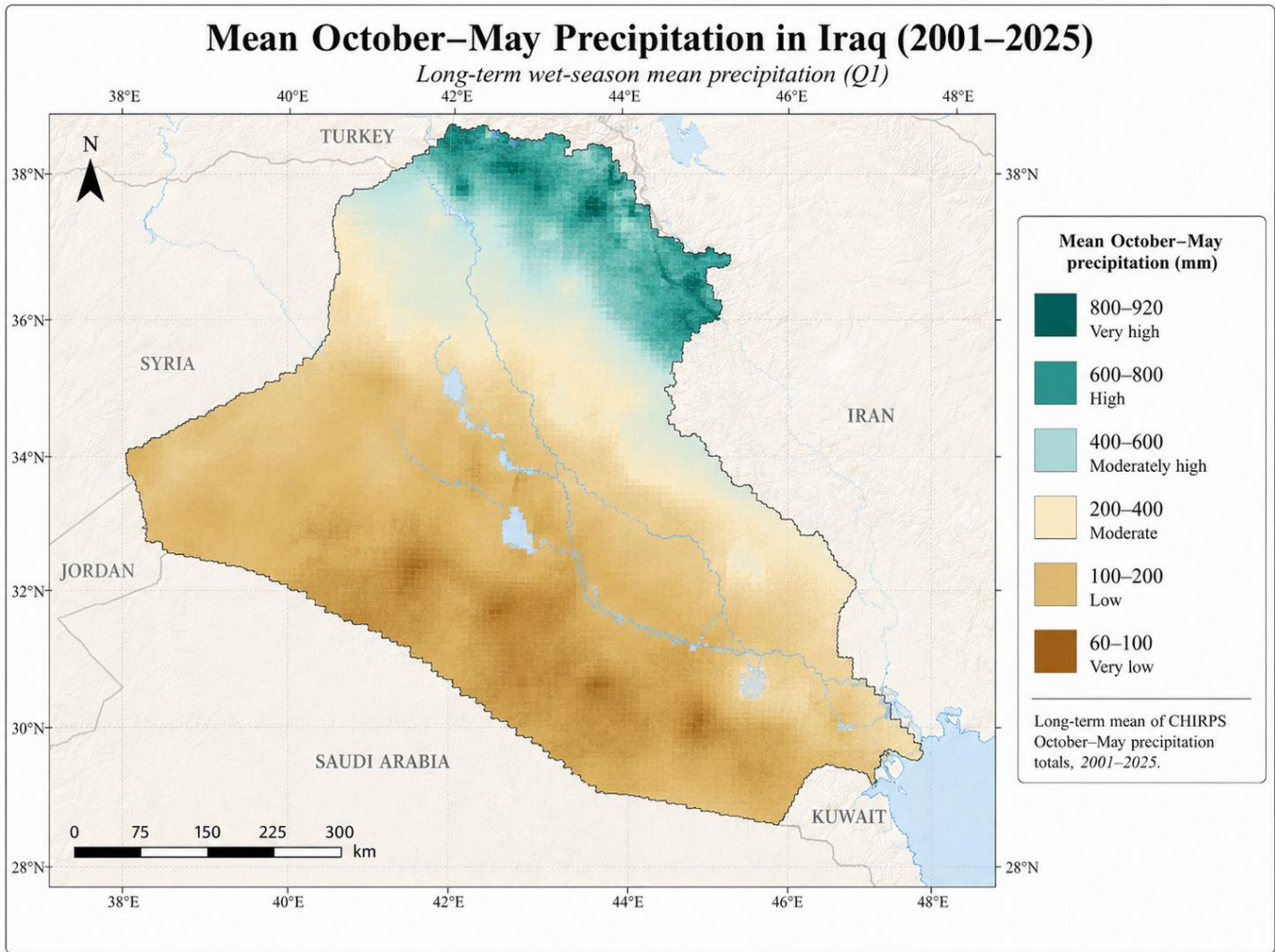


Figure 2. Spatial distribution of mean October–May precipitation across Iraq for 2001–2025. Values represent the long-term mean of annual CHIRPS wet-season totals and are expressed in millimetres.

NDVI Greening–Browning Trend in Iraq (2001–2025)

Significant linear trend in January–May NDVI (Q2)

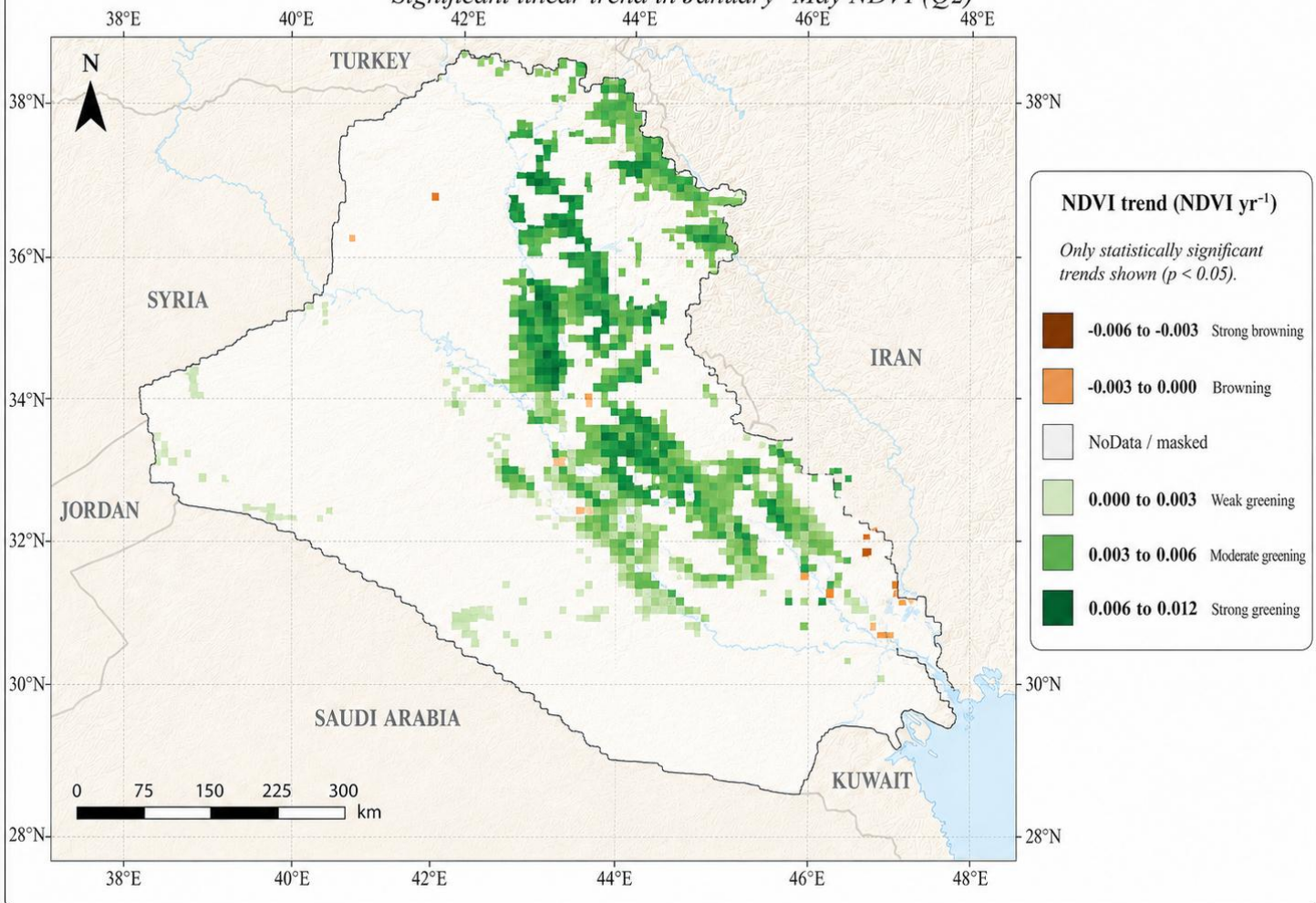


Figure 3. Spatial distribution of statistically significant January–May NDVI trends across vegetated areas of Iraq for 2001–2025. Positive values indicate greening and negative values indicate browning. Only trends with $p < 0.05$ are displayed.

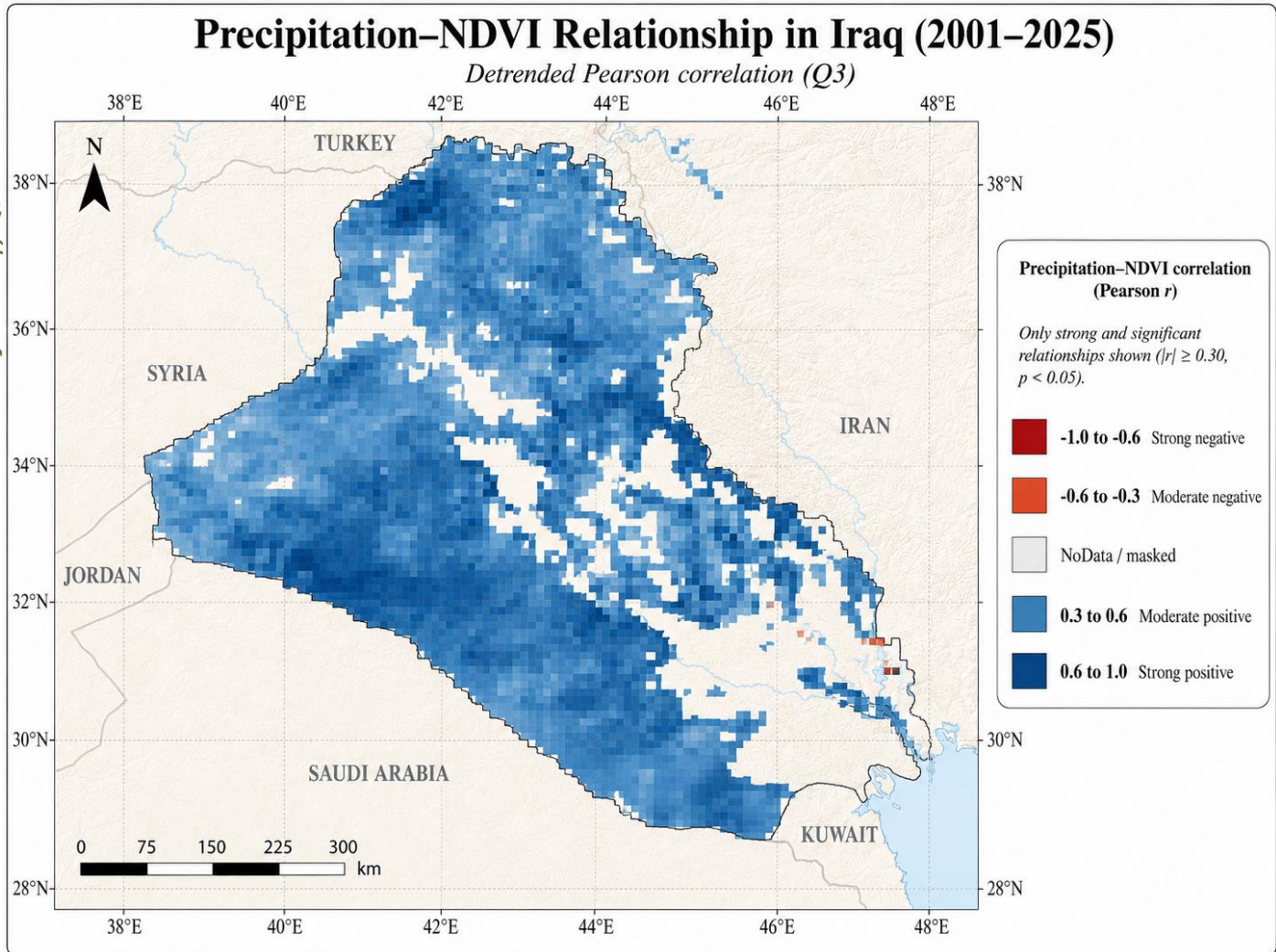


Figure 4. Spatial distribution of detrended Pearson correlations between October–May precipitation and January–May NDVI across Iraq for 2001–2025. Only relationships with $|r| \geq 0.30$ and $p < 0.05$ are displayed.

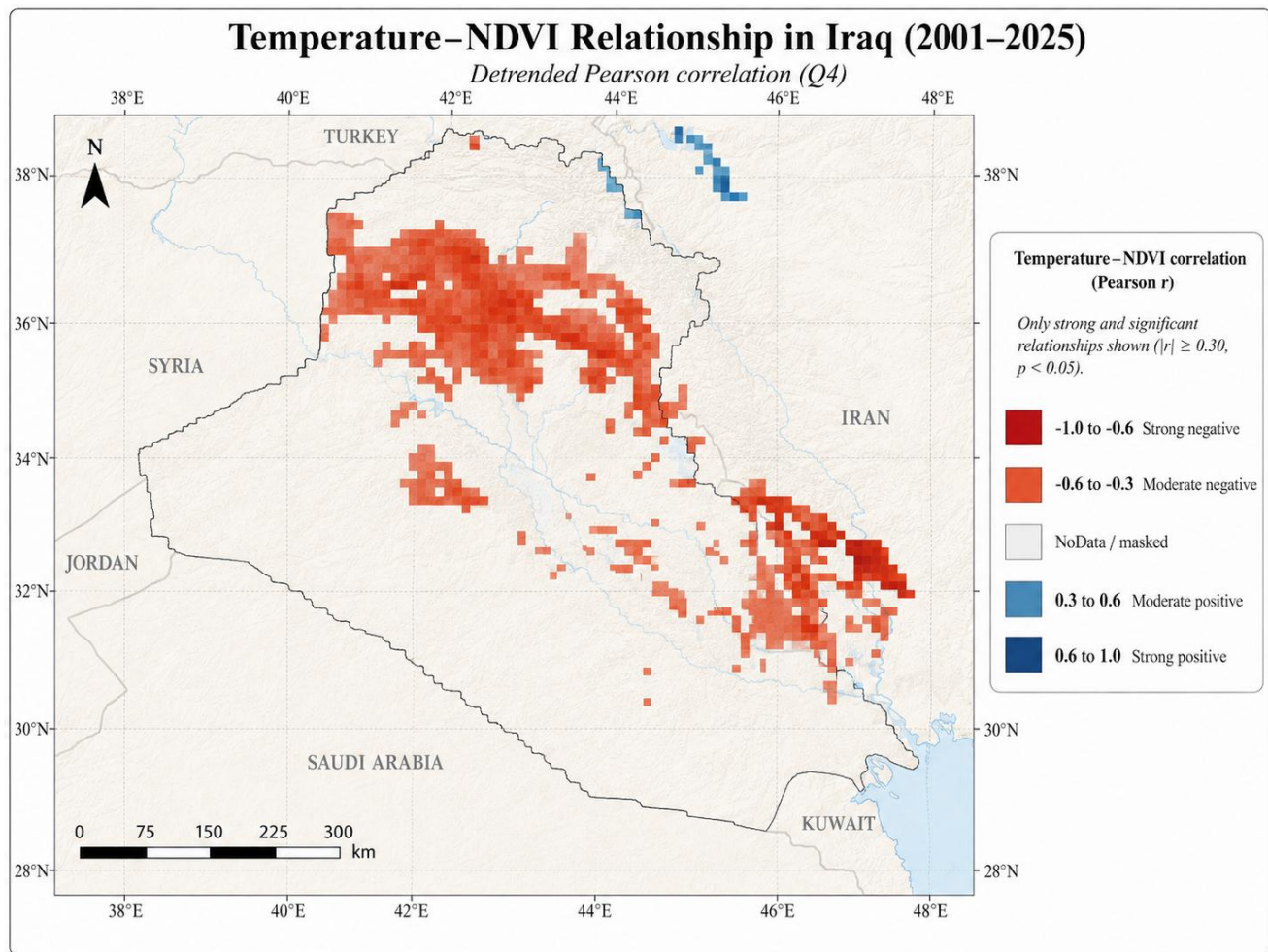


Figure 5. Spatial distribution of detrended Pearson correlations between January–May 2-m air temperature and January–May NDVI across Iraq for 2001–2025. Only relationships with $|r| \geq 0.30$ and $p < 0.05$ are displayed.

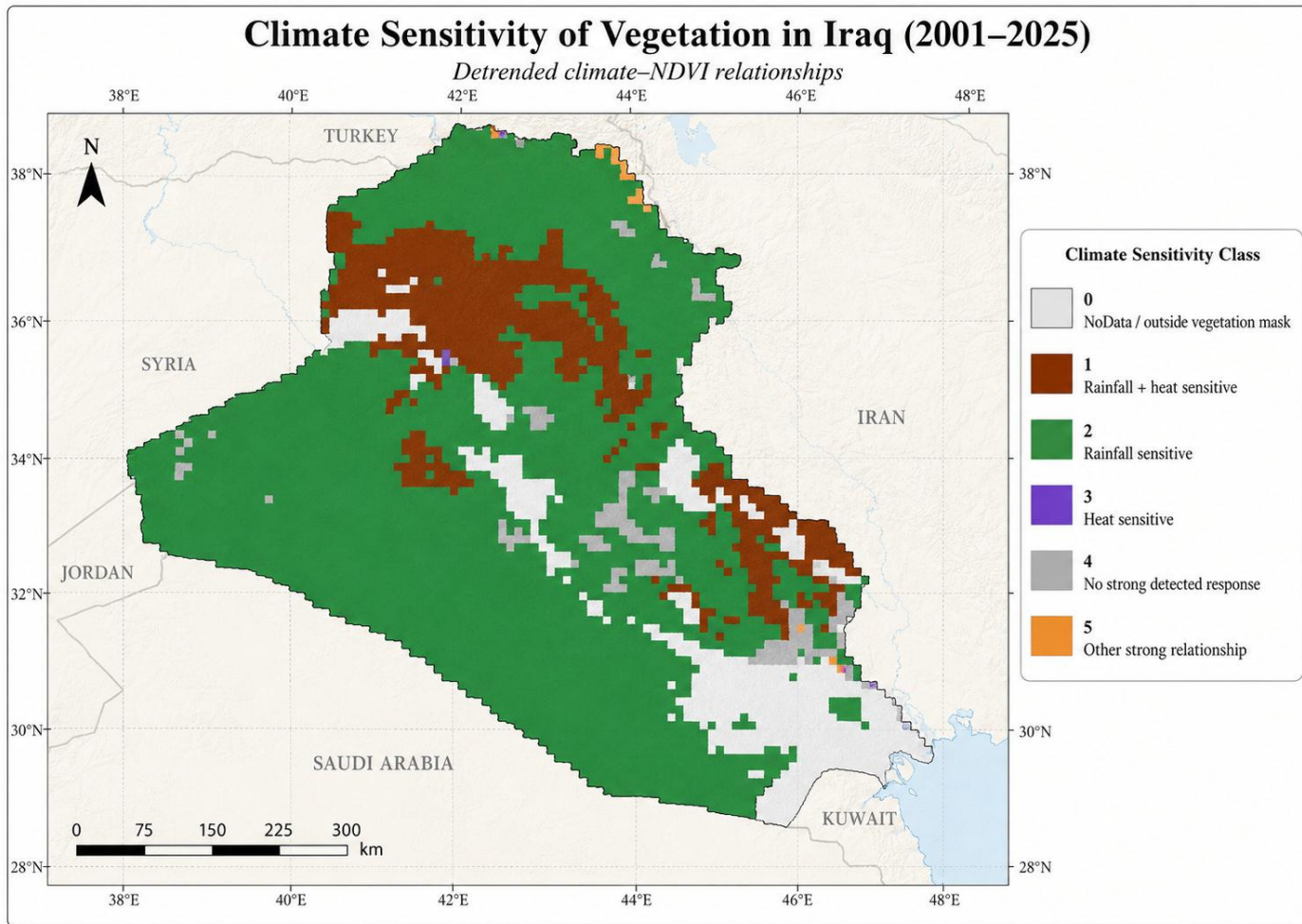


Figure 6. Spatial classification of vegetation sensitivity to detrended precipitation and temperature variability across Iraq for 2001–2025. Classes distinguish combined rainfall and heat sensitivity, rainfall

4. Discussion

4.1 A hydroclimatic gradient structures vegetation dynamics

The results reveal a coherent national-scale sequence linking Iraq's hydroclimatic geography to the spatial organization of vegetation change and climate sensitivity. Mean October–May precipitation declined sharply from the northern and northeastern highlands toward the central plains and the western, southwestern and southern drylands (Figure 2). This pattern is consistent with station-based analyses showing higher precipitation in northern Iraq, much lower totals in the south, and substantial movement of the 250-mm rain-fed agriculture boundary through time (Al-Timimi and Baktash, 2024). The gradient also agrees with the Iraq-wide MODIS and station analysis of Muter et al. (2025), which reported greater rainfall and vegetation density in northern and

eastern regions than in southern and western Iraq. In the present study, however, this spatial climate background was not treated as a direct explanation of NDVI patterns. Instead, it provided the environmental context for separating persistent greening and browning from interannual vegetation–climate covariation.

4.2 Widespread greening does not imply uniform ecological recovery

Significant greening was considerably more extensive than browning during 2001–2025 (Figure 3). Moderate and strong positive trends formed connected clusters across northern, north-central and central-eastern Iraq, whereas significant browning was sparse and spatially fragmented. This broad tendency is consistent with previous MODIS analyses that identified increases in Iraqi vegetation cover during parts of the post-2000 period, particularly in northern Iraq and the eastern alluvial plain (Al-Daoudi and Al-Timimi, 2024). Muter et al. (2025) similarly reported a slight long-term increase in national NDVI, although with strong temporal and spatial variability. The present trend map strengthens this evidence by retaining only statistically significant pixel-wise slopes and by expressing change as an annual NDVI rate rather than as differences among selected years. Nevertheless, greening is an optical canopy signal and cannot, by itself, be equated with ecosystem recovery. In Iraq, positive NDVI trends may represent changes in rainfall, irrigated cropping, cropping intensity, water management, land use or combinations of these processes. The scattered browning pixels likewise cannot be assigned to climate or land degradation from trend direction alone. The detrended analyses are therefore central to interpreting which greening and browning regions also covary with year-to-year climate anomalies.

4.3 Rainfall variability is the dominant climatic correlate of NDVI

The clearest result is the widespread positive association between wet-season precipitation and vegetation activity after removal of their independent linear trends (Figure 4). Positive relationships occurred across most displayed pixels, and strong correlations were present in northern, western, central and southern regions. This means that years wetter than the local precipitation trend generally coincided with January–May NDVI values above the local vegetation trend. The result is consistent with earlier Iraq-based analyses. Daham et al. (2018) found that MODIS vegetation variability in contrasting Iraqi climate regions was more strongly related to accumulated precipitation than to air temperature, while Muter et al. (2025) reported a positive national rainfall–NDVI relationship for 2000–2021. By using detrended pixel series and a wet-season total extending from the preceding October



through May, the current analysis demonstrates that this association is not restricted to a shared long-term trend or a single administrative region.

The dominance of positive precipitation coupling is also consistent with dryland ecohydrology, in which water availability commonly limits canopy development and productivity. Long-term global analyses show strong spatial relationships between precipitation and dryland greenness, although local interannual responses are modified by soils, vegetation composition and land management (Ukkola et al., 2021). More recent work has shown that dryland vegetation sensitivity to precipitation has increased in many regions, implying greater vegetation variability under fluctuating water supply (Zhang et al., 2022). The spatial gaps and differences in correlation strength across Iraq are therefore informative rather than anomalous: they show that rainfall is a dominant climatic correlate without being a complete explanation of vegetation variability. Irrigation, river water availability, soil moisture storage and the timing and intensity of rainfall events may alter the NDVI response even where seasonal rainfall totals are similar. The use of an October–May total captures antecedent and concurrent water supply, but it does not resolve the effects of rainfall frequency, dry-spell duration or short response lags.

4.4 Heat constraint is spatially concentrated and overlaps rainfall sensitivity

In contrast to the geographically extensive precipitation signal, significant temperature–NDVI relationships were spatially restricted and predominantly negative (Figure 5). Negative correlations formed a broad northern and north-central belt and additional eastern and southeastern clusters. Thus, in these locations, warmer-than-trend January–May conditions coincided with lower-than-trend NDVI. Comparable regional contrasts were reported by Daham et al. (2018), who found that precipitation exerted the stronger overall control on Iraqi vegetation while temperature effects varied among climatic regions. A negative temperature association is also consistent with the effect of warming on atmospheric evaporative demand: rising vapour-pressure deficit can reduce stomatal conductance and vegetation growth even where precipitation does not decline (Yuan et al., 2019). Temperature itself is therefore best interpreted here as an indicator of thermal and atmospheric water stress rather than as an isolated physiological driver.

The sensitivity classification integrates these distinct signals (Figure 6). Rainfall sensitivity alone occupied the largest mapped extent, confirming water availability as the dominant climatic axis of interannual vegetation variability. More importantly, combined rainfall and heat sensitivity formed a coherent north-central belt and additional eastern and

southeastern clusters. These are the locations where vegetation was greener in wetter-than-trend years and less green in warmer-than-trend years. Such joint sensitivity is ecologically relevant because reduced water supply and enhanced evaporative demand can act together, increasing exposure to compound hot–dry conditions. The concentration of combined sensitivity does not simply mirror the driest areas: it includes productive northern and central landscapes where interannual vegetation activity is large enough to track both climate signals. By comparison, heat-only sensitivity was rare, indicating that negative temperature associations usually occurred within a broader water-sensitive system.

4.5 Contribution and implications

The principal contribution of this study is the integration of five complementary spatial products within one temporally consistent framework: wet-season rainfall geography, significant NDVI trends, detrended precipitation coupling, detrended temperature coupling and a directional sensitivity classification. Previous Iraqi studies have examined vegetation trends, agricultural drought or NDVI relationships with climate at selected locations or time slices (Daham et al., 2018; Hatem et al., 2024; Al-Daoudi and Al-Timimi, 2024; Muter et al., 2025). The present analysis extends that work by mapping national pixel-wise associations through 2025 after removing linear trends from all correlated variables. This distinction matters because a raw NDVI–climate correlation can be inflated when both variables change in the same direction through time. The resulting maps identify where interannual vegetation anomalies remain coupled to water or heat after that common temporal structure has been removed.

From a monitoring perspective, the rainfall-sensitive class identifies regions in which vegetation condition may provide a spatial indicator of wet-season water variability, whereas the combined class highlights areas where rainfall deficits and anomalous warmth may jointly correspond to reduced greenness. These maps can guide more detailed assessment of rain-fed agricultural zones, rangelands and irrigated corridors, but they are not risk maps by themselves. Ecosystem sensitivity is multidimensional and can vary with the climate variable, temporal scale and vegetation property being observed (Seddon et al., 2016). Consequently, the classes developed here should be used as screening layers for prioritizing field validation and process-based investigation, not as direct estimates of yield loss, degradation or ecological resilience.





4.6 Limitations and research priorities

Several limitations constrain interpretation. First, the 0.1° grid represents areas of roughly 11 km and mixes natural vegetation, cropland, settlements, water bodies and different management regimes. The analysis therefore resolves regional patterns but not field-scale responses. Second, NDVI measures canopy greenness and may be influenced by background soil, vegetation composition and agricultural calendars; it does not directly measure biomass, productivity or ecosystem condition. Third, the correlations are bivariate. Precipitation and temperature effects were analysed separately, without explicit control for irrigation, river discharge, soil moisture, vapour-pressure deficit, land-cover change, salinity or human management. Fourth, linear detrending removes first-order temporal change but does not address nonlinear trends, abrupt land-use transitions or lagged responses. Finally, the reported p-values are nominal because the workflow does not correct for spatial multiple testing or temporal autocorrelation, and the $|r| \geq 0.30$ threshold is a screening rule rather than an ecological breakpoint.

Future work should combine the present maps with annual land-cover and crop-type information, irrigation extent, soil-moisture and vapour-pressure-deficit records, and river-flow or water-storage observations. Partial-correlation, distributed-lag or multivariate time-series models would help separate concurrent water and temperature effects, while false-discovery-rate control and autocorrelation-adjusted inference would strengthen statistical confidence. Pixel-area summaries by governorate, land-cover class and agricultural system are also needed before translating the sensitivity classes into management priorities. These extensions would allow the national patterns identified here to be tested against field observations and linked more directly to drought impacts, crop performance and land degradation.

5. Conclusions

This study provides an integrated assessment of climate–vegetation dynamics across Iraq from 2001 to 2025 using MODIS NDVI, CHIRPS precipitation and ERA5-Land temperature. Wet-season precipitation showed a strong gradient from the humid north and northeast toward the dry west, southwest and south. Significant NDVI greening was more widespread than browning, with the strongest positive trends concentrated in northern, northeastern and central agricultural regions. After linear trends were removed, precipitation–NDVI relationships remained predominantly positive and geographically extensive, whereas negative temperature–NDVI relationships were more localized in northern, eastern and southeastern Iraq. The integrated classification

consequently identified rainfall sensitivity as the dominant response type and delineated north-central and southeastern zones associated with both rainfall and heat variability. These findings show that national greening trends coexist with marked spatial differences in climate association; greening should therefore not be interpreted as uniform ecological recovery. The combined maps establish a reproducible spatial baseline for targeting drought monitoring and more detailed assessment of climate-responsive vegetation. Because the analysis is correlation-based and uses a coarse common grid, the sensitivity classes represent screening indicators rather than causal attribution. Incorporating irrigation, land cover, soil moisture, atmospheric dryness and field observations will be necessary to convert these statistical patterns into process-based assessments of ecosystem and agricultural vulnerability.

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