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Short Title: War-related changes in agricultural land condition revealed by multi-temporal NDVI, GNDVI and NDMI analysis

RESEARCH ARTICLE

War-related changes in agricultural land condition revealed by multi-temporal NDVI, GNDVI and NDMI analysis

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Abstract

War-related disturbance of agricultural land can alter crop development by changing soil physical conditions and surface structure. This study used a nine-year sentinel-2 time series (2017-2025) to examine vegetation responses in farmer-managed fields affected by military activity. Normalized Difference Vegetation Index (NDVI), Green Normalized Difference Vegetation Index (GNDVI), and Normalized Difference Moisture Index (NDMI) were analyzed to characterize changes in canopy development and moisture conditions and to identify spatially persistent anomalies within the fields (Kherson region). The analysis showed that the strongest departures from earlier spatial patterns occurred in 2024-2025, when localized areas of reduced vegetation and moisture indices became more pronounced. These patterns were associated with sectors exposed to military disturbance, including vehicle movement and surface damage, indicating that remote sensing can help delineate zones requiring targeted ground verification. NDVI and NDMI provided the most complementary information for identifying war-related changes in agricultural fields. NDVI effectively reflected changes in vegetation vigor and spatial heterogeneity, whereas NDMI provided additional information on vegetation moisture status and possible alterations in the soil-plant water regime. GNDVI showed generally similar spatial patterns to NDVI and therefore provided more limited additional information in this case. Consequently, combining NDVI and NDMI may be a sufficient and efficient approach for rapid screening of mechanically disturbed agricultural fields, while GNDVI can serve as a supplementary indicator when chlorophyll-related changes are of particular interest.

Keywords: Soil structure, Soil management, Remote sensing, Crop production, Yield, Heavy machinery, Contamination, Moisture

Introduction

Agricultural fields located within active or former conflict zone are exposed to a combination of direct mechanical disturbance and indirect environmental stress that can substantially alter both soil functioning and crop performance (Splodytel, et al. 2023). Military vehicle traffic, repeated passage of heavy machinery, shelling, crater formation, and the construction of temporary military infrastructure may compact the soil, disrupt aggregate structure, disturb the cultivated horizon, and modify surface microrelief (Bonchkovskyi, et al. 2023). Such changes can affect infiltration, aeration, water retention, root penetration, and nutrient availability, thereby creating spatially heterogeneous conditions for crop growth (Hryhoriv, et al. 2024, Solokha, et al. 2023, Hryhoriv, et al. 2025). In intensively cultivated farmland, where soil structure and traffic patterns are closely linked to productivity, these disturbances may persist beyond active military operations and continue to influence subsequent agricultural use (Datsko, et al. 2025, Datsko, et al. 2026).

Physical degradation, chemical pollution, organic matter losses, and land inaccessibility accumulate, negatively affecting short and long-term agronomic productivity in conflict-affected areas (Stadler, et al. 2022). The effects of military disturbance are also expressed through changes in vegetation cover (Zakharchenko, et al. 2025). Compacted or physically disturbed soil may restrict root development and water uptake, while damaged crop stands, altered drainage, and localized contamination can reduce plant density, biomass accumulation, photosynthetic activity, and canopy moisture status. These responses are often spatially heterogeneous and may not be adequately captured by point-based field observations alone. Multitemporal satellite imagery therefore provides an important complementary tool for evaluating changes in agricultural fields affected by military activity (Dindaroglu, et al. 2022, Myslyva, et al. 2023, Trofymenko, et al. 2024).

Materials and Methods

Multi-temporal Sentinel-2 multispectral satellite imagery was used to evaluate changes in vegetation condition over 2017-2025 within a study polygon covering 39.97 km² in the Oleshky Sands area, Kherson Oblast, southern Ukraine (approximately 46.69° N, 33.04° E). Images acquired predominantly in summer, mainly in early July, were selected to reduce seasonal variability and compare vegetation conditions at similar stages of crop development. Tree spectral indices were derived from the Sentinel-2 imaginery: Te Normalized Difference Vegetation Index (NDVI), Green Normalized Difference Vegetation Index (GNDVI), and Normalized Difference Moisture Index (NDMI).

Normalized Difference Moisture Index (NDMI)

NDVI was derived using the near-infrared (band 8) and red (band 4) spectral according to NDVI=(B8-B4)/(B8+B4). GNDVI was calculated using the near-infrared (band 8) and green (band 3) bands as GNDVI = (B8-B3)/(B8+B3). NDMI was determined from the near-infrared (band 8) and short-wave infrared (band 11) bands according to NDMI=(B8-B11)/(B8+B11). The resulting index maps were used to evaluate interannual changes and spatial heterogeneity in crop vegetation and moisture conditions within the study area.

The temporal series analyzed with particular attention to changes observed during the period affected by military activities. However, variations in the spectral indices were interpreted primarily as indicators of changes in vegetation vigor and moisture status rather than as direct evidence of military disturbance, because spectral responses may also be affected by crop type, phenological stage, weather conditions, soil properties, and agricultural management.

Results and Discussion

Physically disturbed soils, especially compacted, cratered, and eroded soils, have reduced water-holding capacity, aeration, and root penetration, which restrict crop growth and make plants more vulnerable to abiotic stress. These soils also showed weaker germination and irregular canopy development, especially in light-textured or sandy soils with low aggregate stability. Satellite-based vegetation analyses provide further evidence of arable land degradation in conflict-affected regions.

The Fig. 1 presents a time series of NDVI maps for the studied area during the summer period from 2017 to 2025. The images are based on satellite data acquired mainly in early July each year, allowing comparison of vegetation conditions at a similar stage of the growing season. The visualization illustrates the spatial heterogeneity of vegetation development within the agricultural landscape and allows the assessment of changes in plant photosynthetic activity over time.

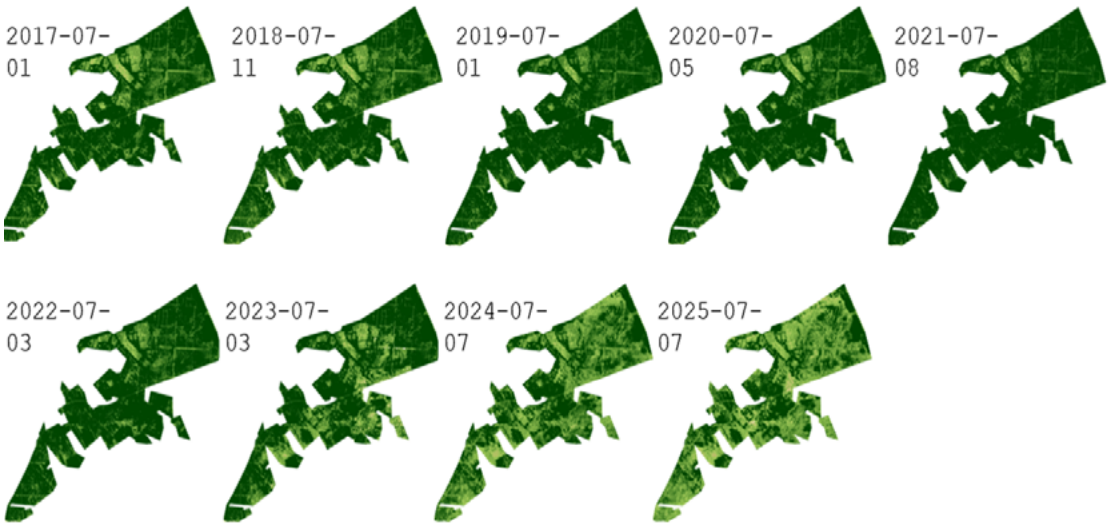


Figure 1. Spatial dynamics of the Normalized Difference Vegetation Index (NDVI) in the studied area from 2017 to 2025 based on satellite images acquired during the summer period.

During 2017-2021, most of the studied area is dominated by dark green tones, indicating relatively high NDVI values and generally good vegetation conditions. In these years, the territory appears more uniformly covered by vegetation, although some areas with lower index values appear as lighter fragments, linear features, or patchy patterns. Such spatial differences may be associated with soil heterogeneity, crop type, sowing dates, agricultural practices, moisture availability, relief conditions, or localized plant stress. In 2022 and 2023, the overall NDVI pattern remains relatively favorable; however, spatial contrasts become more pronounced. Areas with high vegetation activity occur alongside lighter zones, which may indicate reduced plant density or lower vegetation vigor. These differences may result from natural factors, such as annual weather variability, as well as changes in land use, crop management practices, or external stress factors.

The most distinct changes are observed in 2024 and 2025. In these years, the maps show more light green and yellowish-green areas, which may indicate lower NDVI values, reduced photosynthetic activity, thinning crop stands, or disrupted normal crop development. Compared with previous years, the vegetation cover appears less homogeneous, and the contrast between different parts of the studied area becomes stronger. This pattern may indicate degradation processes, stress conditions in agroecosystems, or changes in crop productivity. The increasing intensity of shelling, recurrent fires, the construction of defensive fortifications, direct impacts of military munitions, and the formation of war-induced microrelief are reflected in the condition of the field surface, and this index clearly captures the resulting landscape transformation.

Fig. 2 presents a time series of GNDVI maps for the studied area from 2017 to 2025. The GNDVI is used to assess vegetation condition, photosynthetic activity, and the potential chlorophyll content of plants. Unlike conventional NDVI, GNDVI uses reflectance in the green and near-infrared spectral regions, making it more sensitive to changes in plant pigment content, especially during periods of active crop growth.

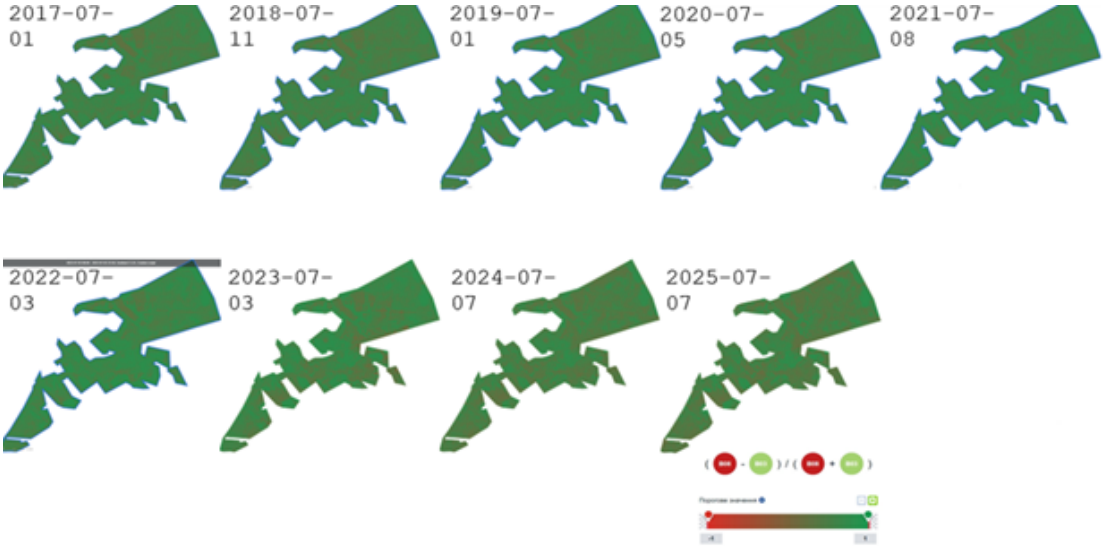


Figure 2. Spatial dynamics of Sentinel-2 the Green Normalized Difference Vegetation Index (GNDVI) within the studied area in 2017-2025 based on summer-period satellite imagery

The index's spatial pattern indicates heterogeneity in vegetation cover within the study area. Different shades of green and brownish-green reflect variations in vegetation intensity, crop density, and plant physiological condition. During 2017-2021, the studied area is characterized mainly by relatively uniform green tones, which may indicate stable vegetation development and comparatively homogeneous crop conditions, the index's spatial variability appears less pronounced, although some local areas with slightly lower GNDVI values are also observed. These differences may reflect soil heterogeneity, moisture availability, crop management, sowing dates, or the types of crops grown in particular parts of the field. In 2022, the general pattern remains broadly similar to previous years, although certain spatial differences between individual parts of the field are visible. In 2023, the contrast becomes more evident: areas with higher index values occur alongside zones with duller green or brownish-green tones. This may indicate decreased plant physiological activity, changes in crop stand density, or the influence of stress factors.

The most distinct changes are observed in 2024 and 2025, as with NDVI. In these maps, the proportion of areas with lower green intensity increases, which may indicate deteriorating vegetation condition, reduced chlorophyll content, inhibited crop growth, or disruption of normal soil-plant system functioning. Compared with the 2017-2021 period, the vegetation cover in 2024-2025 appears less homogeneous, and within-field variability of the index becomes more pronounced.

In the context of studying the consequences of military actions for agricultural lands, this GNDVI dynamics may have important diagnostic significance. A decrease in the index in certain parts of the studied area may be associated with mechanical disturbance of the soil cover, soil compaction, damage to the arable layer, changes in the soil water-air regime, local contamination, or other stress factors affecting crop growth and development. At the same time, interpret such changes with caution, since GNDVI values are also

influenced by annual weather conditions, crop development stage, crop type, fertilisation level, water availability, and agricultural practices. These results can also serve as a basis for selecting areas for field surveys, agrochemical soil analysis, and further monitoring of crop conditions.

Fig. 3 presents a time series of NDMI maps for the studied area from 2017 to 2025. NDMI assesses the moisture content of vegetation cover and identifies signs of water stress. Unlike vegetation indices that primarily characterize green biomass or photosynthetic activity, NDMI provides information about the water status of agroecosystems because it is based on the relationship between reflectance in the near-infrared and short-wave infrared spectral regions.

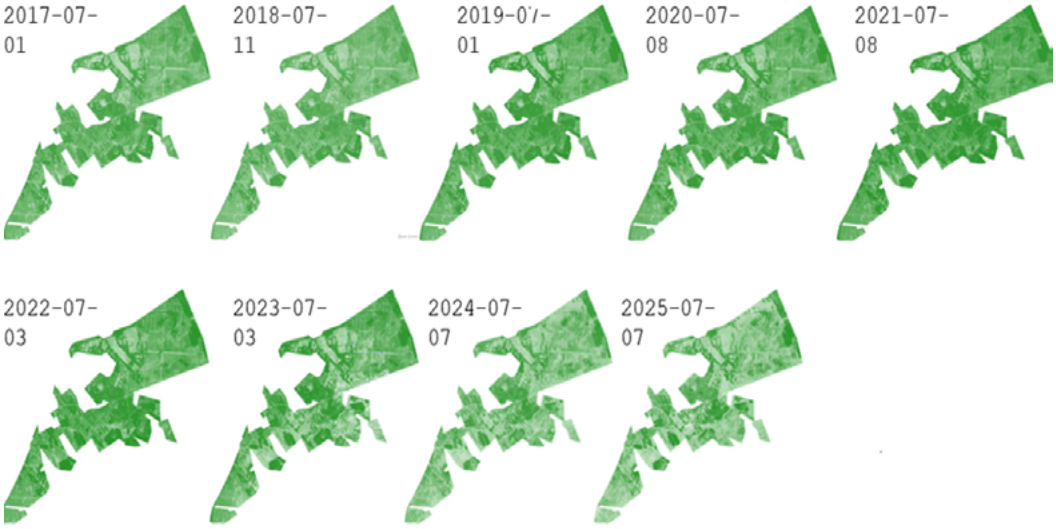


Figure 3. Spatial dynamics of sentinel-2 Normalized Difference Moisture Index (NDMI) within the studied area in 2017-2025 based on summer-period satellite imagery *via* Earth Observation (EO) browser.

During 2017-2021, most of the studied area shows relatively uniform green tones. This may indicate a comparatively stable moisture status of the vegetation cover and the absence of strongly expressed water stress across most of the territory. In 2022 and 2023, spatial differences in the index became more noticeable. Alongside areas with relatively higher NDMI values, lighter zones appear, which may indicate a decrease in vegetation moisture content or less favorable water supply conditions for crops. This heterogeneity may result from annual weather conditions, changes in crop structure, differences in crop management practices, or local stress factors.

The most distinct changes are observed in 2024 and 2025, as with other indices. In these years, the maps show more areas with light green tones, especially in certain parts of the studied territory. This may indicate reduced vegetation moisture content, increased water stress, thinning crop stands, or disruption of normal soil-plant system functioning. Compared with previous years, the spatial pattern of NDMI appears more heterogeneous.

In the context of studying the consequences of military actions for agricultural lands, NDMI is an important indicator because mechanical disturbance of the soil cover may alter the soil water regime. Soil compaction, damage to the arable layer, crater formation, mixing of genetic soil horizons, destruction of soil structure, or local contamination may affect infiltration, water retention, and plant water availability. As a result, even under similar weather conditions, individual parts of the field may show lower NDMI values and signs of water stress. This may indicate deteriorating water status in agroecosystems, increased stress on crop cultivation, or disruption of soil-plant system functioning. The results obtained can be used to identify potential risk zones, plan field investigations, and support further monitoring of agricultural land conditions.

Conclusion

Multitemporal sentinel-2 analyses revealed that the studied agricultural fields developed increasingly pronounced spatial heterogeneity during the observation period, with the clearest changes occurring in 2024-2025. The simultaneous decrease in NDVI, GNDVI, and NDMI in selected field zones indicates deteriorating vegetation condition and moisture status, compared with the more spatially uniform patterns in earlier years. These persistent anomalies were spatially associated with areas subjected to military activity and mechanical disturbance, including vehicle traffic and soil-surface damage. The results suggest that war-related disturbance can leave a detectable spatial imprint on agricultural fields through changes in soil-plant system functioning. Combining satellite monitoring with measurement of soil compaction, structure, moisture regime, and physicochemical properties provides a more reliable basis for assessing damage, monitoring recovery, and planning the rehabilitation of war-affected farmland.

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