Divergent Trends in Soil Organic Carbon and Gross Primary Productivity of Agricultural Landscapes in Croatia (2000-2022): a Digital Soil Mapping Assessment

Divergentni trendovi organskoga ugljika u tlu i bruto primarne produktivnosti diljem poljoprivrednih krajolika Hrvatske (2000. – 2022.): procjena digitalnim kartiranjem tla.

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DIVERGENT TRENDS IN SOIL ORGANIC CARBON AND GROSS PRIMARY PRODUCTIVITY OF AGRICULTURAL LANDSCAPES IN CROATIA (2000-2022): A DIGITAL SOIL MAPPING ASSESSMENT

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SUMMARY

We conducted the first countrywide research study on the distribution and variation of soil organic carbon (SOC) content, SOC density, soil pH, and gross primary productivity (GPP) in Croatia's agri-ecosystem for a 22-year period (2000-2022). Using the free-geospatial datasets, OpenLandMap and EcoDataCube, we attempted to study time-series trends in 21 administrative counties. The approach involved a 5-year prediction of the soil characteristics, as well as an annual composite of GPP and normalized difference tillage index (NDTI) to represent vegetation indices. Trends were determined through the linear regression of the spatially consolidated mean values at the level of counties. Analysis for the entire country for the five-year mean of GPP and SOC showed a high correlation (r = 0.91). However, a pronounced regional split was observed, whereby in some of the intensive continental agricultural regions, significant depletion of SOC was noted (e.g., Međimurje County: slope = -0.0223 g/kg, R2 = 0.79) and in some of the Mediterranean coastal regions, significant carbon enrichment was documented (e.g. Split‐Dalmatia County: slope = +0.0431 g/kg, R2 = 0.98). Nevertheless, these contrasts a general "greening" trend (increasing GPP) was observed in Croatia. The separation of rising biomass productivity from decreasing soil carbon in northern Croatia suggests that intensive tillage and biomass removal are surpassing carbon inputs. Conversely, southern gains likely reflect perennial systems and land abandonment, demonstrating the utility of earth observation for targeted soil management.

Keywords: Soil Organic Carbon; carbon farming; OpenLandMap; EcoDataCube; Normalized Difference Tillage Index; spatiotemporal trends

INTRODUCTION

Soil organic carbon (SOC) is one of the main indicators of soil quality and is crucial in the global carbon cycle. The Green Deal and Soil Strategy 2030 for the EU make soil health and climate change mitigation/restoration a top priority (Montanarella & Panagos, 2021; Heuser, 2022). These policies place obligations on member states, including Croatia, to regulate soil in order to secure food and climate integration to sustain global soil health (Masson-Delmotte et al., 2022). In the past several years, Croatian legislation, most recently the Law on Agricultural Land, has sought to meet the EU's sustainable soil and land use management goals (NN 64/2025, 2025). Recent international studies have brought to our attention the phenomenon called the "green mirage". The "green mirage" phenomenon occurs when satellite images of a relative zone appear to have increased vegetation and Gross Primary Productivity (GPP), yet their 'greening' is indicative of declining soil carbon (Castro et al., 2025; Srivastava et al., 2024). Thus, a region can appear to be losing value in terms of carbon stored in the ground and sustain a healthy and productive appearance (Lehmann & Kleber, 2015; Sanderman et al., n.d.; Yu et al., 2024). There is a clear geographical duality in Croatian agricul-

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ture. The Mediterranean south is characterized by highly fragmented parcels, widespread permanent crops like vineyards and olive groves, and vast tracts of abandoned marginal land, whereas the Pannonian north is dominated by intense, large-scale arable farming focused on annual crops (Husnjak et al., 2011; Galić et al., 2026). This study uses the NDTI to evaluate the effects of various farming methods throughout these regions. In order to properly distinguish between intensive tillage and conservation methods, NDTI uses shortwave infrared reflectance to measure crop residue cover; higher values imply greater residue retention. This descriptive, hypothesis-driven study's main goal is to assess geographical changes in SOC and GPP throughout Croatia's various agricultural districts. We speculate that although perennial systems in the south facilitate parallel carbon accumulation, intensive farming in the continental north is causing a decoupling of GPP and SOC, resulting in a "green mirage"(Basic et al., 2001). This study offers a unique scientific perspective to understand these dynamics in Croatia. The years 2000-2022 showcase the analysis of trends of SOC and GPP across Croatia's agricultural landscapes using Digital Soil Mapping (DSM) and freely available geospatial data. This shift in understanding soil features is a big step in how agriculture is practiced, moving from the static, out-of-date, maps to more dynamic, functional, value. Soil features are more variable from one spot to another (Auzzas et al., 2024). To understand these ranges and trends is beneficial as it gives us the ability to create tailored approaches that go beyond the metrics to ensure that carbon is truly sequestered in the soil and not at the surface.

MATERIALS AND METHODS

The analysis used open source geo-spatial data to measure trends of Different indicators of soil such as Soil Organic Carbon (SOC), soil pH, Gross Primary Productivity (GPP), and the Normalized Difference Tillage Index (NDTI). The study covers agricultural land in the administrative boundaries of Croatia, comprised of 21 counties. Soil data were obtained from the OpenLandMap repository (Hengl et al., 2025). We specifically retrieved: SOC: Content (g/kg) and density (kg/m3), both at 30 m resolution. Soil pH was measured in H2O, bulk density fine earth fraction (kg/m3). These datasets were provided as 5-year block predictions for years 2000-2005; 2005–2010; 2010–2015; and annual layers for 2016–2022 and represent the medium-term soil changes. This study's acknowledged shortcoming is the temporal mismatch between 5-year block SOC projections and annual GPP and NDTI data. However, this method is justified since vegetation indices fluctuate seasonally and need annual resolution, while soil carbon changes slowly, making 5-year intervals suitable for identifying significant trends. Vegetation and productivity data were sourced from EcoDataCube and OpenLandMap. GPP annual uncalibrated estimates (gC/m2) at 30 m resolution were used to reflect photosynthetic activity. NDTI was calculated from corrected bimonthly composites (2000-2024) derived from Landsat spectral reflectance bands, which were used to assess tillage intensity and soil exposure and averaged on an annual basis. It should be highlighted that using a static agricultural mask for over 22 years is a methodological disadvantage because it makes it more difficult to dynamically account for changes in land use over time, such as urbanization or farmland abandonment. To ensure the analysis focused strictly on arable land, an Agricultural Land Probability raster was used as a mask, including only pixels with a probability ≥ 0.5. Data processing was carried out using custom Python scripts. First, all raster datasets were clipped to the Croatian county boundaries using the Natural Earth vector dataset at the NUTS2 level. An agricultural mask was then applied to the datasets, and any pixels falling outside this mask or containing missing data were excluded from the analysis. We applied specific scaling to convert the raw digital numbers into physical units. SOC content and density values were divided by 100, while soil pH values were divided by 100 with an added offset of 4. First, GPP values larger than 5000 gC/m2 were filtered out to remove physical outliers. The OpenLandMap repository, which uses Ensemble Machine Learning (EML) models that combine Random Forest and gradient boosting to predict soil parameters from global ground observations and environmental factors, provided the soil data. For each variable, spatiotemporal trends were assessed at the county level by calculating statistical measures (e.g., mean, median, standard deviation) for each time period. We performed linear regression using the *scipy.stats.linregress* function on the temporal sequence of data blocks to determine the slope, intercept, and statistical significance ($p < 0.05$) of the trends. This was done for soil properties at 5-year intervals, and for GPP at annual intervals. To analyze the relationship between vegetation indices and soil health, we determined the Pearson correlation coefficient (r). Specifically, we compared annual NDTI against annual GPP and analyzed the correlation between SOC and mean GPP aggregated over matching 5-year periods.

RESULTS AND DISCUSSION

Soil and vegetation features display a variety of trends within the analysis of national averages. Soil pH levels showed little change as they fluctuated between 4.65 and 4.66, and did not exhibit a strong directional trend1, whereas vegetation activity displayed significant increases. NDTI and GPP demonstrated upward trends from 2000 to 2024, which showed that there was an increase in the primary productivity of farmlands within the previous 20 years. On the other hand, the SOC national average showed fluctuating trends within 2008, 2012, and 2018 (Figure 1).

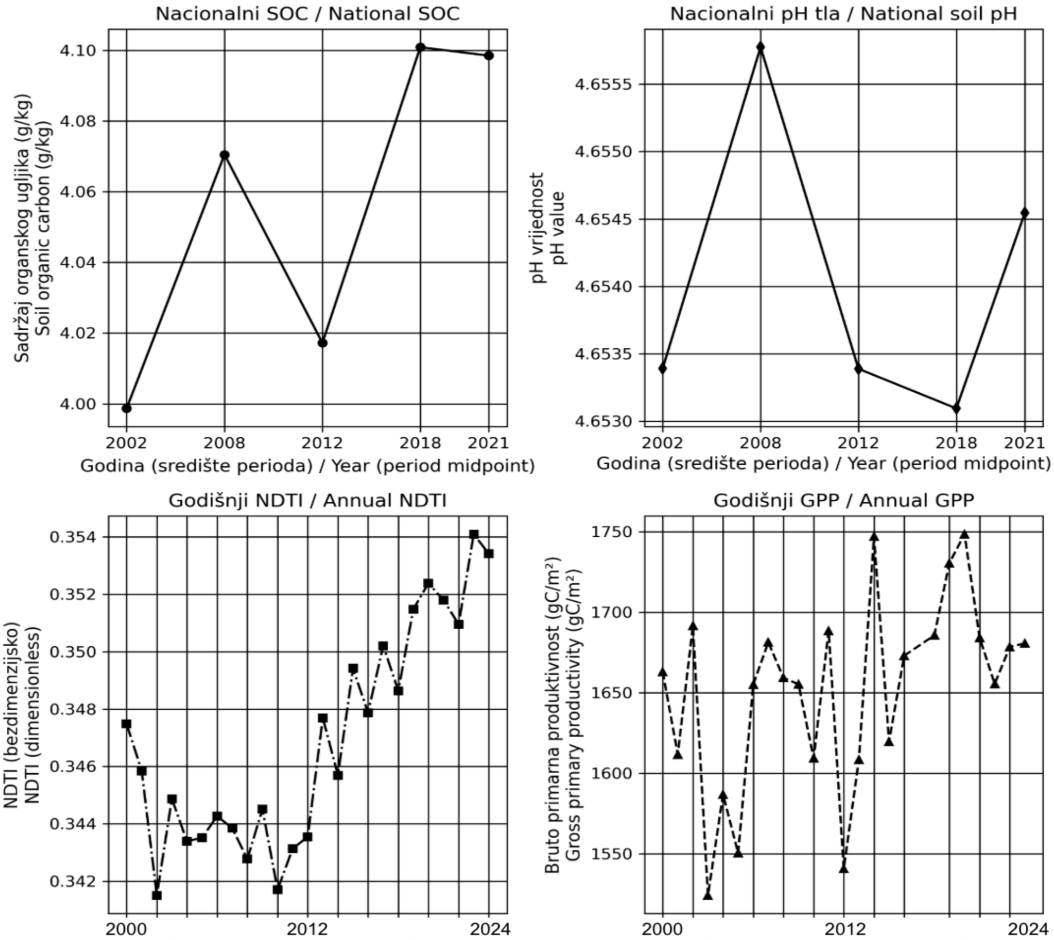

Figure 1. Trends of national averages (2000–2024). The figure shows the time series for (A) Soil Organic Carbon (SOC), (B) Soil pH, (C) Annual Normalized Difference Tillage Index (NDTI), and (D) Annual Gross Primary Productivity (GPP).

Grafikon 1. Vremenski trendovi nacionalnih prosjeka (2000. – 2024.). Slika prikazuje vremenske serije za (A) organski ugljik u tlu (SOC), (B) pH vrijednost tla, (C) godišnji normalizirani diferencijalni indeks obrade tla (NDTI) i (D) godišnju bruto primarnu produktivnost (GPP).

The 21 counties revealed major differences in space. Four subplots in Figure 2 show net changes in each county's SOC, soil pH, SOC density, and GPP across Croatia. For net change in SOC concentration, in the top left, county SOC Change (g/kg), most counties are positive, and the most positive (over 0.20 g/kg) are the large increases in Karlovac County and Istria County. Dips in SOC are the largest in Koprivnica-Križevci County and Međimurje County. The top-right represents soil pH change, which showcases a geographical division between soil acidification and soil alkalization. While pH increases in Lika-Senj County and Primorje-Gorski Kotar County, Krapina-Zagorje County, and Karlovac County show the most pronounced decreases, suggesting soil acidification during the study. Bottom-Left is demonstrated SOC density change (kg/m2): Unlike SOC concentration, SOC density shows a predominantly positive trend across almost all administrative units. Istria County and Vukovar-Srijem County lead the gains with an increase of approximately 0.07kg/m2. Only a few areas, such as Krapina-Zagorje County and City of Zagreb, show minor negative changes. Bottom-Right county GPP Change (gC/m2) where the GPP chart shows high variability. Significant positive changes are observed in Istria County and Osijek-Baranja County. In contrast, Lika-Senj County shows a sharp decline in GPP (exceeding -250 gC/m2), indicating a potential reduction in vegetative productivity or biomass accumulation in that region. There should be a clear reason for this discrepancy between increased SOC density and declining SOC concentrations in some areas. Soil compaction and an increase in bulk density, a common physical degradation effect of intense machinery usage in arable farming, frequently lead to increases in SOC density combined with declining SOC mass concentrations (Assessment et al., 2000; Hussain et al., 2021).

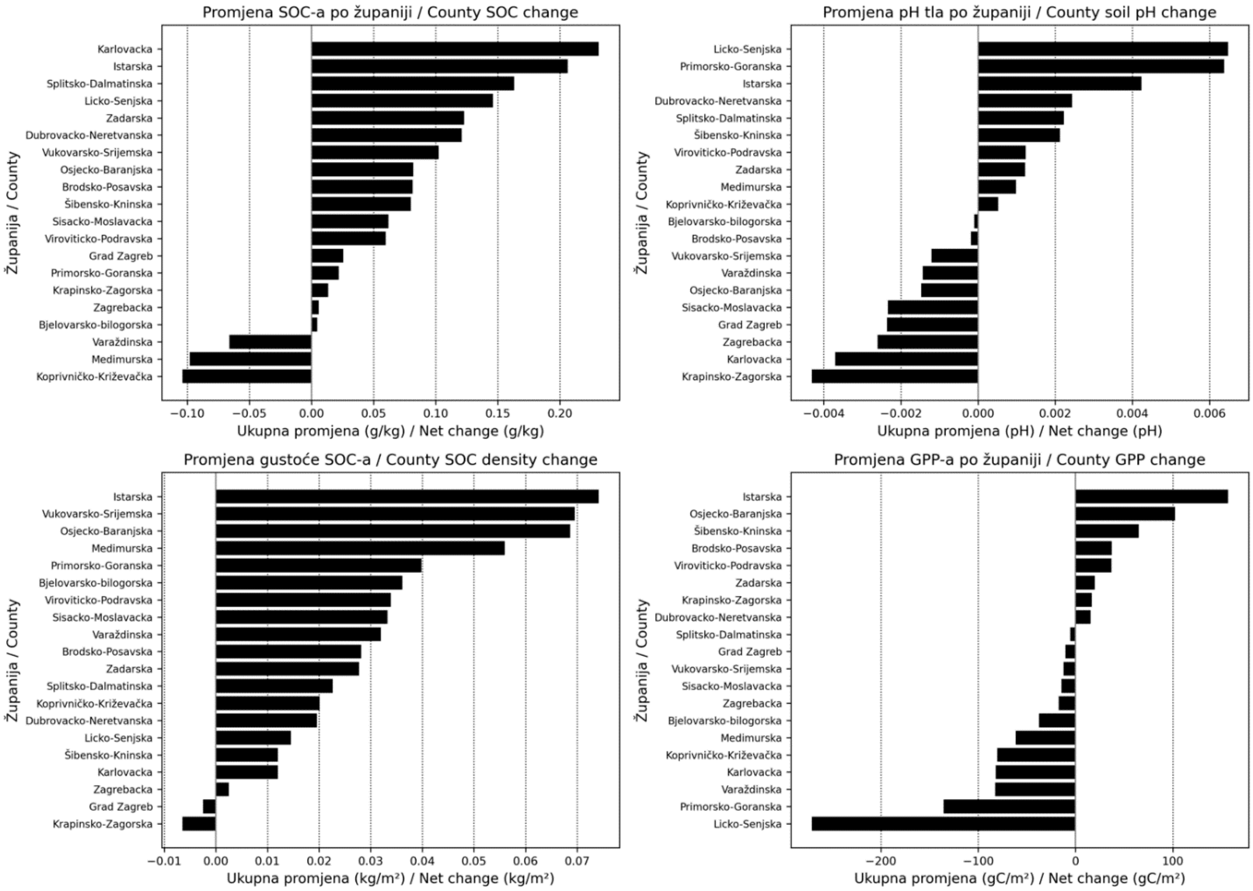

Figure 2. Net changes in soil and vegetation parameters by county. The bar charts represent the total calculated change (slope × time) for: (Top-Left) SOC content, (Top-Right) Soil pH; (Bottom-Left) SOC Density; and (Bottom-Right) Annual GPP.

Grafikon 2. Neto promjene parametara tla i vegetacije po županijama. Stupčasti dijagrami prikazuju ukupnu izračunanu promjenu (nagib × vrijeme) za sljedeće: (gore-lijevo) sadržaj SOC-a, (gore-desno) pH vrijednost tla; (dolje-lijevo) gustoća SOC-a; i (dolje-desno) godišnji GPP.

Significant negative trends, representing a loss of carbon, were found in northern counties such as Koprivnica-Križevci County and Međimurje County. Conversely, southern and eastern counties, including Split-Dalmatia County and Vukovar-Srijem County, showed the highest positive growth in SOC content. Comparing the variables to understand their interactions (Figure 3), a very strong positive correlation ($r = 0.91$) was found between SOC content and GPP when averaged over 5-year periods. Moderate positive correlation ($r = 0.42$) was observed between annual NDTI and GPP, supporting the hypothesis that tillage indices track with photosynthetic activity to some extent. Furthermore, from the standpoint of DSM, a critical examination of the extremely excellent correlation ($r = 0.91$) between 5-year block SOC projections and GPP is required. There is a significant risk of circular reasoning because the OpenLandMap DSM models mostly rely on vegetation-related Earth Observation products as environmental variables. The real relationship may be somewhat inflated by the apparent biophysical coupling, which reflects common data sources rather than absolutely independent variables. In order to evaluate the genuine strength of the SOC-GPP relationship against independent ground-truth data, future research must prioritize eliminating vegetation variables from the DSM training process.

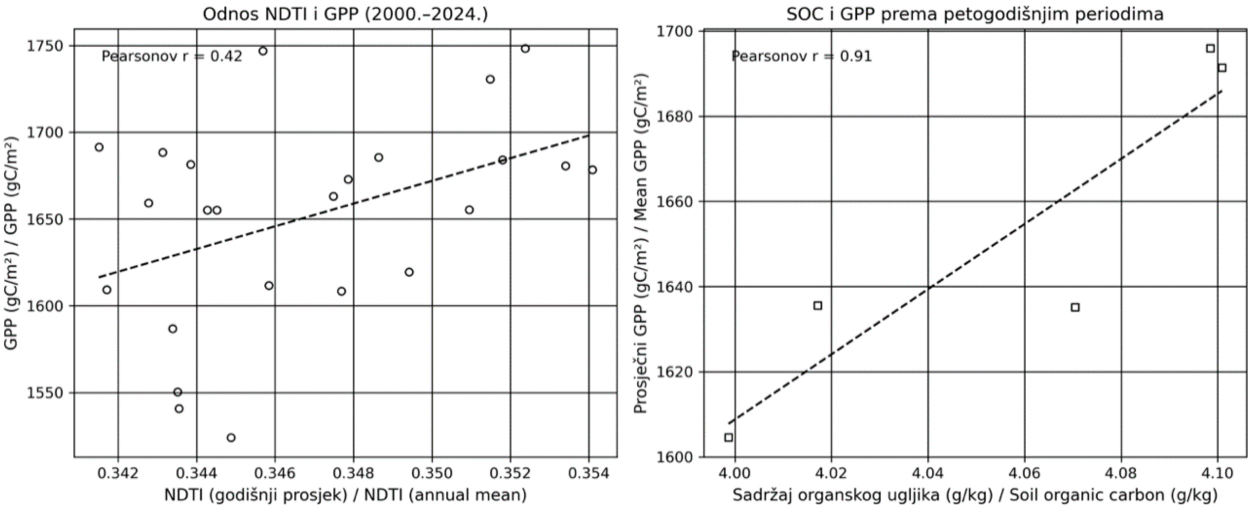

Figure 3. Relationships between environmental variables: Scatter plot of Annual GPP versus Annual NDTI (Pearson's r = 0.42) (on the left) and scatter plot of Mean GPP versus SOC content aggregated by 5-year periods, showing a strong positive correlation (Pearson's r = 0.91) (on the right).

Grafikon 3. Odnosi između varijabli okoliš: dijagram raspršenosti godišnjega GPP-a u odnosu na godišnji NDTI (Pearsonov r = 0,42) (lijevo) i dijagram raspršenosti srednjega GPP-a u odnosu na sadržaj SOC-a agregiranih po petogodišnjim razdobljima, koji pokazuje snažnu pozitivnu korelaciju (Pearsonov r = 0,91) (desno).

Our analysis reveals a distinct spatial polarization in Soil Organic Carbon (SOC) trends across Croatia. While the national average suggests a complex fluctuation with a recent recovery, county-level data expose opposing dynamics between the continental north and the coastal south (Jug et al., 2025). The strongest negative trends were observed in northern counties, such as Koprivnica-Križevci County (R2 = 0.63) and Međimurje County (R2 = 0.79). These regions represent the intensive agriculture of Croatia, where the observed decline in SOC suggests that organic matter mineralization rates are exceeding carbon inputs (Ogle et al., 2012; Poeplau & Don, 2013). In these regions, although there is an increase in Gross Primary Productivity (GPP), the carbon biomass in intensive arable systems is removed rather than returned to the soil with each harvest (Follett, 2001). As such, soil sequestration is not a given in systems characterized by a high rate of photosynthesis, annual tillage, and frequent crop removal (Jug et al., 2024a). In contrast, the Mediterranean countries of Split-Dalmatia County and Istria County showed the most remarkable positive changes in soil organic carbon (SOC). In coastal regions, there is a lot of land fragmentation, a rural exodus, and the resulting abandonment of marginal agricultural land has created a positive environment for the natural (Brilli et al., 2019; Hussain et al., 2021; Khangura et al., 2023). The transformation of farmland into shrubland and later forest results in increased root biomass and the accumulation of litter, which increases SOC stocks (Tóth et al., 2007; Panagos et al., 2022). Also, the coastal zone with its olive groves and vineyards is dominated by perennial systems, which tend to have permanent grass cover in the rows, thereby minimizing soil disturbance and promoting carbon sequestration (Lizaso et al., 2018). SOC and GPP correlate strongly (r=0.91) amid general greening, but Pannonian high-GPP/falling-SOC trends signal a critical decoupling (Panagos et al., 2024; Bogunovic, 2025). This can be explained by the "priming effect" and the stoichiometry of intensive agriculture. Although GPP has increased due to improved cultivars and climate warming, the carbon input to the soil in these systems is transient (Han et al., 2025; Zheng et al., 2024). High inputs of fresh carbon from root exudates stimulate microbial activity (Kuusemets et al., 2025), which accelerates the decomposition of older, stable soil organic matter to balance nitrogen and phosphorus requirements (Zheng et al., 2024). Tillage and heat make North Croatia a carbon source, so GPP fails as a sequestration proxy (Zhang et al., 2022). A critical scrutiny of the high correlation between 5-year block SOC predictions and GPP is necessary from a digital soil mapping (DSM) perspective (Radočaj et al., 2024, 2025). Since many DSM models utilize vegetation indices as key environmental covariates, there is an inherent risk of circularity (Ali et al., 2024; Ma et al., 2024). These observed trends may partially capture the model's reliance on vegetation data as opposed to just the soil data (Hengl et al., 2021; Joshi et al., 2023; Radočaj et al., 2024). It should also be noted that the use of static agricultural masks for 22 years limits the analysis since land-use changes, such as urbanization or abandonment, are not captured dynamically. Finally, annual composites may suffer from atmospheric noise. These findings suggest that current EU Common Agricultural Policy (CAP) and GAEC standards are insufficient to prevent soil carbon loss in intensive systems (Montanarella & Panagos, 2021; Heuser, 2022; Panagos et al., 2024). Without a shift toward regenerative practices such as no-till farming, cover cropping, and the integration of woody perennials, Croatian agriculture will continue to operate with a negative carbon budget

(Chowdhury et al., 2021; Francaviglia et al., 2018). Future studies should prioritize validating these trends with ground-truth time-series sampling, such as LUCAS soil monitoring data, to further calibrate the remote sensing signal.

CONCLUSIONS

Our spatial study shows a clear regional heterogeneity in soil organic carbon dynamics throughout Croatian agriculture during the last 22 years. Our findings reveal that this "greening" does not always translate into soil carbon sequestration, even if satellite-derived GPP shows an overall rise in biomass production. High productivity combined with diminishing SOC in northern Croatia's intensive agricultural systems suggests that present intense farming methods and biomass clearance are depleting belowground carbon reserves, the phenomenon typical of a "Green Mirage." On the other hand, land abandonment and the predominance of perennial crops with little soil disturbance are the main causes of SOC recovery in the Mediterranean region. The temporal mismatch between 5-year SOC data and annual vegetation indices, the incapacity of a static agricultural mask to capture dynamic land-use changes over two decades, and the possibility of circular reasoning in DSM models that use vegetation covariates to predict SOC are some of the significant methodological limitations that affect these findings. Despite these limitations, the wider interpretive consequences are evident: in order to attain true soil resilience, EU policies must use targeted Earth Observation data to monitor true biophysical soil health and increasingly prioritize and incentivize regenerative practices over short-term yield metrics. We can transform Croatia's landscape from a climate danger into a strong, carbon-secure basis for the next century by integrating intelligent technologies like DSM with regenerative farming.

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DIVERGENTNI TRENDOVI ORGANSKOGA UGLJIKA U TLU I BRUTO PRIMARNE PRODUKTIVNOSTI DILJEM POLJOPRIVREDNIH KRAJOLIKA HRVATSKE (2000. – 2022.): PROCJENA DIGITALNIM KARTIRANJEM TLA

SAŽETAK

Ova studija pruža sveobuhvatnu procjenu prostorno-vremenske dinamike sadržaja SOC-a, gustoće SOC-a, pH vrijednosti tla i bruto primarne produktivnosti (GPP) diljem poljoprivrednoga krajolika Hrvatske tijekom razdoblja od 22 godine (2000. – 2022.). Koristeći javno dostupne geoprostorne skupove podataka s platformi OpenLandMap i EcoDataCube, analizirali smo trendove vremenskih serija u 21 administrativnoj županiji. Metodologija je integrirala petogodišnje blok-predikcije svojstava tla s godišnjim kompozitima vegetacijskih indeksa, specifično GPP-a i normaliziranoga diferencijalnog indeksa obrade tla (NDTI). Trendovi su kvantificirani linearnom regresijom na prostorno agregiranim srednjim vrijednostima na razini županija. Analize na nacionalnoj razini ukazale su na snažnu pozitivnu korelaciju (r = 0,91) između prosječnoga GPP-a i SOC-a u petogodišnjim intervalima. Međutim, pojavila se jasna regionalna divergencija: neke od regija s intenzivnom kontinentalnom poljoprivredom doživjele su značajno iscrpljivanje SOC-a (npr. međimurska: nagib = -0,0223 g/kg, R2 = 0,79), dok su mediteranska područja pokazala znatnu akumulaciju ugljika (npr. splitsko-dalmatinska: nagib = +0,0431 g/kg, R2 = 0,98). Unatoč tim kontrastima, na razini cijele zemlje uočen je univerzalan trend „ozelenjivanja" (povećanje GPP-a). Razdvajanje (decoupling) rastuće produktivnosti biomase od opadajućega ugljika u tlu u sjevernoj Hrvatskoj sugerira da intenzivna obrada tla i uklanjanje biomase nadmašuju unos ugljika. Nasuprot tome, na jugu vjerojatno odražavaju trajne sustave i napuštanje zemljišta, što pokazuje korisnost promatranja Zemlje (earth observation) za ciljano upravljanje tlom.

Ključne riječi: organski ugljik u tlu; ugljična poljoprivreda; OpenLandMap; EcoDataCube; normalizirani diferencijalni indeks obrade tla; prostorno-vremenski trendovi.

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