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Plot-level Field Monitoring with Sentinel-2 and PlanetScope Data for Examination of Sewage Sludge Disposal Impact

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Abstract

Agricultural use of sewage sludge is one of the means of sustainable environmental management. In order to monitor the short-term effects of sludge disposal a multi-year, high-resolution data collection was planned on arable land in south-eastern Hungary. Data acquisition was applied at the highest temporal and spatial resolution using Sentinel-2 and PlanetScope satellite imagery observing the vegetation period based on vegetation indices (EVI, NDVI) from 2016 to 2021. There were statistical differences in the case of sunflower and maize biomass productions but the spatial and statistical deviations between the affected and non-affected areas of sludge disposal were generally not significant. The sensitivity of EVI in the dense vegetation period and its applicability might be emphasized in a comparative analysis.

Keywords: sewage sludge; agricultural monitoring; Sentinel-2; PlanetScope; spectral index

Introduction

The macronutrient content in the sewage sludge, disposed to the soil and complying with public health and environmental requirements and legislation (biosolid), is similar to that found in animal manure, where the N, P, and organic nutrient content, can be used by plants, can reach 50% (Sagasta et al., 2015; Tomócsik et al., 2016). Field disposal also addresses the problem of disposing of sludge treated as waste, moreover, results in increased crop yields. The increase in humus quality and quantity improves soil water holding capacity and compactness, thus, resulting in a more balanced, stronger vegetation (Simon & Szente, 2000). According to Markowicz, et al. (2021), wastewater disposal up to 15 t/ha is the most efficient way to recultivate certain soils having a nutrient deficit. The use of sewage sludge is encouraged by also the European Union and the Hungarian regulations (e.g. 91/271/EEC, 36/2006 (V.18.)), 40% of the sewage sludge is utilized in agriculture in Hungary (Sewage Sludge Treatment and Utilization Strategy 2014-2023).

On a plot treated with sewage sludge, compared to the other areas, the development of vegetation is more dynamic in principle and has a higher biomass production. Obtaining data and information on vegetation development on regional scale is easy owing to the development of remote sensing in the past 40 years. Multispectral data content of new sensors, of different resolutions which also distinguishes the main cultivated field crops based on the time series, allows the continuous spatial and temporal evaluation locally too, which is greatly supported by the increased number of sensors (Kuenzer et al., 2015; McCabe et al., 2017). The problem is more complex; the different soil types are only allowed to filter and transform sewage sludge by

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biological and chemical processes up to a certain load; furthermore, it is difficult to analyze the small changes in the quantity and quality of organic matter and the yield during 1-2 years. Thus, several years or decades of observation are necessary to assess its effect on soil improvement (Banerjee et al., 1997). Moreover, the land use changes or the climatological parameters influencing the development of plants can also not be omitted (Erdődiné & Kovács, 2021).

In this study, our aim was to observe the effect of sewage sludge disposal on biomass production on arable land plots with the highest possible temporal and spatial resolution, which is a continuation of the earlier evaluation process (Kovács & Ladányi, 2021). The original studying period was broadened to 6 years between 2016 and 2021, and the data of a new sensor was also applied when observing the extended vegetation period from March 1 to September 30.

Data and methods

In addition to multispectral monitoring assessments of land use, damage estimation, and agricultural science applications for yield estimation, there are an increasing number of users that collect very high-resolution precision agricultural data to optimize farming (Kovács et al., 2019; Segarra et al., 2020; Weiss et al., 2020). Regular and detailed examination on plot level requires high- and very high-resolution multispectral recordings (cell size <= 2 m), where remote sensing – e.g. WorldView – can only be implemented extremely costly and in a programmed manner (Kuenzer et al., 2015). Liu et al. (2018) show that archive data collection of high temporal resolution is not feasible with even more sensors. Dove PlanetScope (Planet) recordings, which regularly provide higher temporal resolution than ever before and are available for free after registration in Europe from 2017, are currently being addressed (Roy et al., 2021).

Sentinel-2A and -2B (S2) multispectral satellite images were used primarily for the entire investigated period in our study having a spatial resolution of 10 m and a temporal resolution of 3–5 days (Table 1). A total of 145 pieces of images were evaluated, that were all atmospherically corrected, Level-2 processed, cloud-free recordings. On the Tile 34TDS, all sample areas are covered. In 2018-2019-2020, and mostly in August and September, more recordings than average could be expected. Monitoring was limited by the higher cloud cover typical in spring and early summer periods, thus, only 24-40% of all possible summer semester recordings could be used in certain years. There were no satellite images to be evaluated in July 2016 and also for several areas in 2018, and in June 2017.

It is risky to use one single sensor to assess one geophysical variable, thus, all available Level 3A, surface reflectance 4 band Planet data for 2020 were evaluated to monitor vegetation dynamics in more detail, as well as for the verification and validation of S2-based results. In addition to the daily time resolution, 64 pieces of cloud-free satellite images with 3 m resolution were available, furthermore, data from 21 dates were available to compare the results of the two sensors between March 1 and September 30.

Table 1. Applied Sentinel-2 and PlanetScope imagery and their parameters

Satellite / sensor	Multispectral imagery / year	Applied spectral bands, middle of wavelengths	Spatial resolution
Sentinel-2A and 2B	20 images / 2016 14 images / 2017 34 images / 2018 29 images / 2019 26 images / 2020 21 images / 2021	B2: 492.4 / 492.1 nm B4: 664.6 / 665 nm B8: 832.8 / 833 nm	10 m
PlanetScope	64 images / 2020	B1: 485 nm B3: 630 nm B4: 820 nm	3 m

Data: Copernicus Open Access Hub (https://scihub.copernicus.eu/dhus/), Planet Explorer (https://www.planet.com/explorer/)

Less cloudless images were available from LANDSAT-8 (L8) database. L8 and S2 were recorded 15 times on the same days in the summer semesters between 2016 and 2019. The statistical relationship (R2EVI >= 0,8), interpreted by Kovács and Ladányi (2021) when comparing the satellite images, does not allow the values of the two sensors to be used in one time series, while the Planet data are more suitable for validation purposes.

It is advisable to plan the timing of the recording for months determining the development of the given plant (the harvest and 2-3 months before), which is different for each plant species (winter wheat: III-VI months, maize: V-VIII months). The plots in our sample area were usually cultivated with different crops every year, which, together with the high cloud cover that caused problems in image data collection, increases the limitations of the comparison.

The commonly used Normalized Difference Vegetation Index (NDVI) and the improved Enhanced Vegetation Index (EVI), which reduces the impact of the soil and the atmosphere, are applied to measure the photosynthetic activity and the changes in biomass production for decades (Bannari et al., 1995). These indices (VI) are determined by plant wetness and chlorophyll content (Equations 1 and 2).

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

$$EVI = G\frac{NIR - Red}{NIR + C1 \cdot Red + C2 \cdot Blue + L} \quad (2)$$

where NIR indicates the near-infrared band, Red indicates the visible red band, Blue indicates visible blue band, L = 1, C 1 = 6, C 2 = 7.5, and G = 2.5.

According to Huete et al. (2002) EVI is more sensitive in areas more densely covered with vegetation. Differences between plant species, physiological and leaf structure differences can be better indicated. The general overview of NDVI values is useful in observing low vegetation coverage and the temporal dynamics, however, but a value higher than EVI will saturate sooner, and even though phytomass increases, reflectance no longer increases, underestimating biomass production. This may make it difficult to assess the response during the developmental phase of maximum vegetation coverage. The use of EVI or the Red Edge (RE) bands with lower chlorophyll absorption instead of reflectance in the red band is a solution to the latter problem (Clevers & Gittelson, 2013), however, such bands are only available at S2 among the sensors applied in this study. Based on the comparison with reference measurements, the indices made from S2 spectra are well representative of the areas (Plug & Louis, 2020). NDVI can not be omitted from the long-term regional monitoring (Tran et al., 2017), and the EVI and NDVI index values in small and medium-scale studies are able to show the dates and periods of agricultural management (Kovács & Gulácsi, 2019; Szabó et al., 2019). Locally, the main cultivated field crops can be well distinguished, although they can differ significantly from year to year due to local environmental factors (water supply, harvest time, etc.). The values depend on the vegetation density: on those plots where plants hatched rarely, the NDVI values are lower throughout the developmental period (Erdődiné & Kovács, 2021). According to a high-resolution, decades-long multispectral analysis, the short-term effects observed after sewage sludge treatment within a few years are variable, while over a longer period (about 10 years), the change in plant growth is positive (Álvarez et al., 2014).

Study area

Data collection based on remote sensing methods was performed for 14 homogenous quadrates having a size of 50x50 m2 on three agricultural plots producing different crops, in parallel with the soil sampling according to Farsang et al. (2020). Certain quadrates represent areas treated with sewage sludge and the adjacent quadrates with very similar properties without treatment served as control areas for the study (Table 2). The sample areas are located in the Great Plain in Hungary, between the River Körös and Maros, near Újkígyós and Kardos settlements (Figure 1.). The quadrates were placed in pairs named the followings: in Újkígyós 1t-2t, 3t-4t, 6t-7t, 9t-10t (coordinates of the plot center: UTM (Zone 34N) X: 503400, Y: 5160000), in Kardos: 10t-11t, 12t-13t (X: 479020, Y: 5181700) and 14t-15t (X: 480630, Y: 5180200).

In the study area, which has been cultivated continuously for decades, mainly maize, winter wheat, sunflowers, furthermore colza, and oil radish are grown. Comparative examination of the yearly changing vegetation is difficult and uncertain, it seemed better to show only the significant differences.

In the Újkígyós study area, 1t-4t quadrates were sampled as treated areas, where sewage sludge was disposed in October 2017. 6t-7t were control areas and partly treated areas, as one year later, in autumn 2018, sewage sludge was dumped here too. Quadrates 9t-10t were untreated, in control areas. Between 2016 and 2021, the surface coverage of the 1t-4t samples, situated on the same agricultural plot in Újkígyós, was different every year, only in 2018 and 2020 the produced crop was the same: winter wheat. In the 6t-7t and 9t-10t quadrates, located on different plots, the same crop, corn, was found in 2017, 2018, and 2020 to facilitate our comparative study, and winter wheat occurred in 2019 and 2021. In the knowledge of the autumn sewage sludge disposal in 2017 and 2018 and the management, the following comparisons were planned in Újkígyós sample areas:

- maize: observation of 6t-10t quadrates as control areas between 2017 and 2018, followed by measures on the 6t-7t in 2020 after sludge disposal and their comparison
- winter wheat: observation of 1t-4t quadrates between 2018 and 2020 show the vegetation development after the sewage sludge disposal in 2017.

Table 2. Crops produced in quadrates of Kardos and Újkígyós parcels between 2016–2021

Újkígyós / quadrates	2016	2017	2018	2019	2020	2021
1t	maize	oil radish[1]	winter wheat	colza	winter wheat	sunflower
2t	maize	oil radish[1]	winter wheat	colza	winter wheat	sunflower
3t	maize	oil radish[1]	winter wheat	colza	winter wheat	sunflower
4t	maize	oil radish[1]	winter wheat	colza	winter wheat	sunflower
6t	colza	maize	maize[2]	winter wheat	maize	oil radish
7t	colza	maize	maize[2]	winter wheat	maize	oil radish
9t	sunflower	maize	maize	winter wheat	oil radish	winter wheat
10t	sunflower	maize	maize	winter wheat	oil radish	winter wheat
Kardos / quadrates	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
10t	sunflower	winter wheat[1]	sunflower	winter wheat	maize	sunflower
11t	sunflower	winter wheat[1]	sunflower	winter wheat	maize	sunflower
12t	sunflower	winter wheat	sunflower	winter wheat	maize	sunflower
13t	sunflower	winter wheat	sunflower	winter wheat	maize	sunflower
14t	sunflower	winter wheat[1]	maize	maize	maize	maize
15t	sunflower	maize	maize	maize	maize	maize

[1] - 2017 autumn: sewage sludge placement; [2] - 2018. October: sewage sludge placement

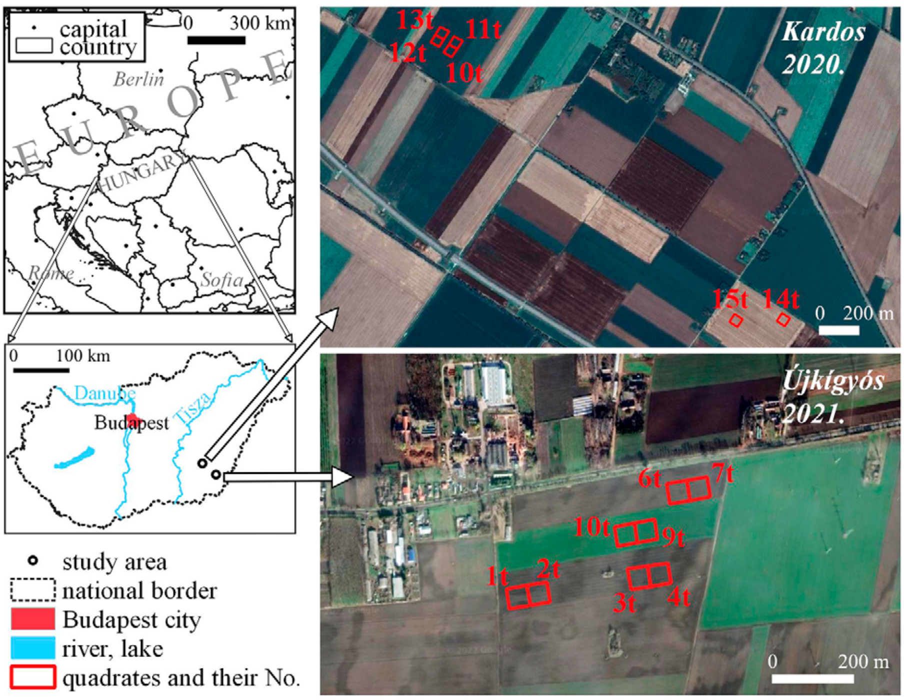

Figure 1. Sample quadrates near Kardos (No. 10t-15t) and Újkígyós settlements (No. 1t-4t, 6t-7t, 9t-10t) located on the Great Hungarian Plain, Hungary (background: GoogleEarth)

Regarding the control areas, the investigation possibilities are limited, as only 9t-10t were without sewage sludge disposal in 2019 and 2021that could be assessed.

- sunflower: control quadrates (9t-10t) in 2016 can be compared with the values of the 1t-4t in 2021 showing the effect of the 2017 sewage sludge disposal.
- colza: observations in 6t-7t as controls in 2016 can be compared to the 1t-4t areas following the disposal in 2019.

Planet images applied in this area in 2020 are good additional data for several crops; e.g. for maize, winter wheat, and oil radish.

In the Kardos study area, 10t-11t and 12t-13t quadrates are within a plot as shown in Figure 1, with the same management pattern varying from year to year; sunflowers were produced in 2016, 2018, and 2021, and winter wheat in 2017 and 2019. The land use in 14t and 15t quadrates in 2016 was still sunflower, but in 2017 only 14t had winter wheat cover while in 15t corn was grown. Between 2018 and 2021, maize production was already uniform. 10t-11t and 14t were allocated on plots where sewage sludge was disposed in autumn 2017, 12t-13t and 15t were used as control areas. The following comparisons were planned in the Kardos sample areas (three types of plants were grown during the study period):

- maize: after the disposal in 2017, the differences with 10t-11t in 2020 are assessed and 12t-13t quadrates are used as a control. As a consequence of the disposal of sewage sludge, between 2018 and 2021, the values of the parcels according to 14t must deviate from the values of 15t
- winter wheat: in the case of 10t-13t quadrates the biomass production of the year 2017 can be compared with 2019. In the 10t-11t, the impact of the sewage sludge disposal in 2019 can be assessed
- sunflower: the control value in 2016 on the 10t-13t quadrates might be compared with the values of 2018 and 2021 showing the effect of placement.

The Újkígyós quadrates are located on the alluvial fan of the Mureş 90-92 m above sea level, while the Kardos sample areas are situated on the edge of the alluvial fan at an elevation of 84-85 m above sea level (Mezősi, 2017). The soil type is the same on all study areas: calcareous Chernozem which makes comparison possible. Based on the digital soil maps (DOSoReMI[1]), the particle size fraction of the upper 0–30 cm soil layer is 10% -10% -25% for clay, loam, and sand in the Újkígyós plots, respectively, meaning that soil water retention capacity is poor. The topsoil texture is loam (sandy loam) having an organic matter content of 2-3%. In the Kardos plots, soils have a good water retention capacity due to more clay and loam fractions but less sand: 30% -35% -5%, and the organic matter content is higher here: 3-4%. The value expressing natural soil fertility for the study areas is 70-80% in Kardos compared to 50-60% in Újkígyós study areas. There were no significant changes in the basic soil parameters in the Újkígyós sample area in the last 5 years besides the sewage sludge discharges, only N and P content increased (Ladányi et al., 2020).

Agricultural production is affected by climate change in the sample area. Between 1981 and 2020, the average annual temperature increased by + 1.8–1.9 °C, and the number of heat-wave days increased by more than 14 days. In the last 40 years the precipitation showed a 10% increase in the annual amount, and extreme rainy days, having more than 20 mm precipitation, dominate. As a result, the longest dry periods appear to be shortened (Lakatos et al., 2021). In Hungary, there is a moderate drought every second year and a strong drought every third year (Buzási et al., 2021) and according to Mezősi et al. (2016) as a result of the increasing impact of drought, the role of tillage will come to the fore in the next 2-3 decades. The farming and tillage of the near future are basically determined by the rapid changes in the seasons. By 2100, half-year-long summers can be expected in the northern hemisphere (Wang et al., 2021).

In our sample area, the average temperature of the summer semester is + 0.8–2 °C higher each year compared to the period between 1970 and 2000. 2017-2018-2019 was the hottest period; the deviation from the average exceeded even +3 °C in several months. Although the climate was cooler than average in the spring of 2020-2021, the positive difference was still significant in the summer months (July 2021: +4.6 °C). Precipitation amount only exceeded the 30-year average (368.4 mm) in 2019 (453 mm), while 13% less precipitation than the average fell in the 6 studied years. A longer, continuous dry period from March to July 2017 and throughout the first half of 2021; in the last year, only 45% of the average has fallen (Figure 2). There are outstanding rainy months every summer for the rest of the years; June 2016, March 2018, May and July 2019, and March and June 2020.

The daily meteorological drought index (HDI) shows the same as the climatic data presumed (Fiala et al., 2018); more than 30% of the studied period is characterized by drought; 6.5% by severe drought (HDI>=2), and 25% by moderately drought (HDI> = 1.5). In the study area, 2018, 2019, and 2020 were the least dry years; it was only August 2018 and April 2019 that were characterized by moderate droughts, and June and July in 2017 also showed moderate droughts with slightly higher values. The driest year was 2021 when a continuous moderate drought was experienced between June and September, moreover, August and September showed high drought. The sensitivity of the groundwater level to climatic effects, which determines the water supply, increases towards the central part of the alluvial fan (Újkígyós), while towards the edge of that (Kardos) it decreases (Rakonczai & Fehér 2015).

[1] https://dosoremi.hu/maps/

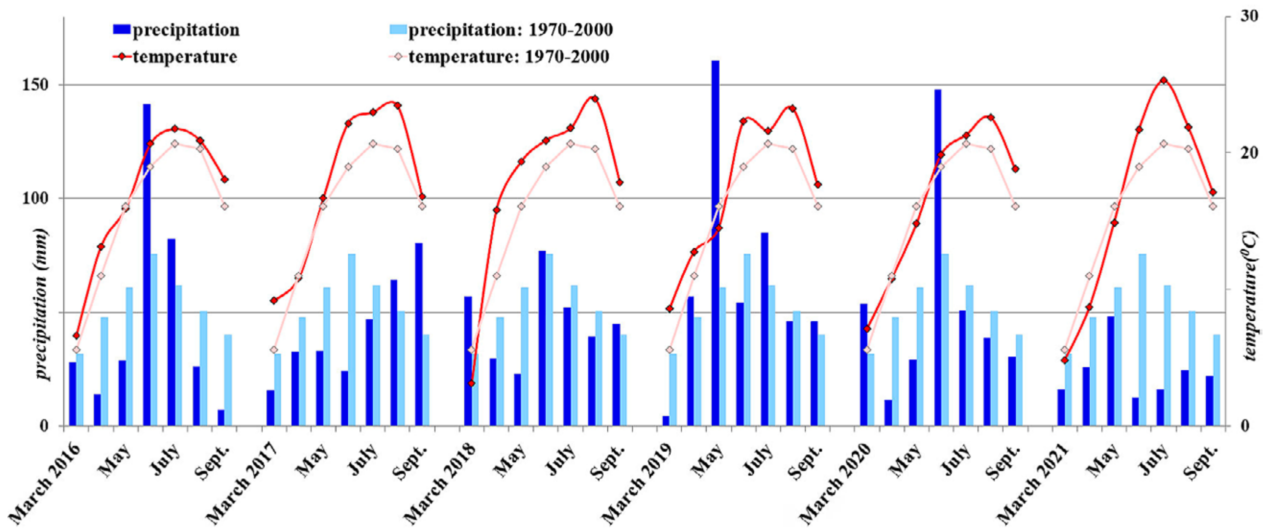

Figure 2. Precipitation and temperature in Békéscsaba station in the period of 2016–2021
Data: Ogimet.com (http://www.ogimet.com/gsynres.phtml.en);
Operatív Vízhiány Értékelő és Előrejelző Rendszer (http://aszalymonitoring.vizugy.hu/)

Results and Discussion

The difference in the growing cycle of the crops and the changes in land use in the plots are clearly visible in the VI values, and the curves follow the vegetation development well (Figures 3–6).

In a data set of quadrat-pairs with identical land-use values, the sensitivity of the index means that EVI shows significant differences within the plot, while NDVI rarely does. We also see a difference between 1t-2t and 3t-4t pairs in the same plot, which can be as high as 0.15 NDVI and 0.2 EVI in the June 2016 maize crop. In the same area, the average EVI difference for the 2017 oil radish crop is 0.1-0.15 in May-June, and a difference of 0.15 EVI is found in September after the 2020 harvest. This includes the difference between the May-June 2021 EVI of 0.1 and the August 2021 EVI of 0.15-0.2 for the sunflower crop. Interestingly, in the 10t-13t quadrates of the Kardos sample area, we observed 0.1-0.15 EVI differences already in August and September, but only in 2017, 2020, and 2021. Similarly, August shows a larger – 0.15-0.2 – EVI and NDVI divergence for 14t-15t in 2018.

The highest average VI values above 0.9 (up to 0.98) occur in June in almost all cases, regardless of the crop. Many NDVI averages above 0.9 were observed in sunflower, winter wheat, and maize growing areas in June 2017 and 2021, the summer months of the driest years. Only the high average EVI values were deviated from this and only in Újkígyós study site, where they were approximately 0.1 lower and only in May (2016 and 2020) in colza and oil radish areas. For the whole analyzed period 2016-2021, neither Újkígyós nor Kardos study areas show a significant change in biomass product for either index. The time series of treated by sewage sludge and non-treated parcels could be compared for the months of May-July 2018-2021 in Kardos study area thanks to the plots producing similar crops. Small extent, but both NDVI and EVI show systematically higher average values in the sludge-treated plots.

The EVI is very rarely higher than the NDVI value, only in the case of dense vegetation. The difference is typically around +0.08-0.2, which can be as high as +0.35-0.4 during the peak biomass production period; the difference between NDVI and EVI in Újkígyós study area is larger and typically smaller in areas treated with sewage sludge. Dense vegetation should be interpreted in terms of EVI, but the increase in biomass production can be well distinguished by NDVI, and sometimes the difference between vegetation types can be also better assessed. It makes sense to use the two indices together in the assessment, as exemplified by the different VI values of the 6t-7t areas in 2016 and 2017.

The effect of sewage sludge disposal on maize has been investigated in several locations. On the 14t quadrate of Kardos, values of the 15t were used as controls for 2018, 2019, and 2021[2] VI values after the year 2017 sewage sludge placing (Figure 7.). For the 6t-7t quadrates of Újkígyós, we compare the years that precede (2017, 2018) and the years that follow (2020) the placement in 2018.

[2] Despite Table 2 data in 14t, 15t quadrates no maize was grown in 2020 as clearly shown in VI data series.

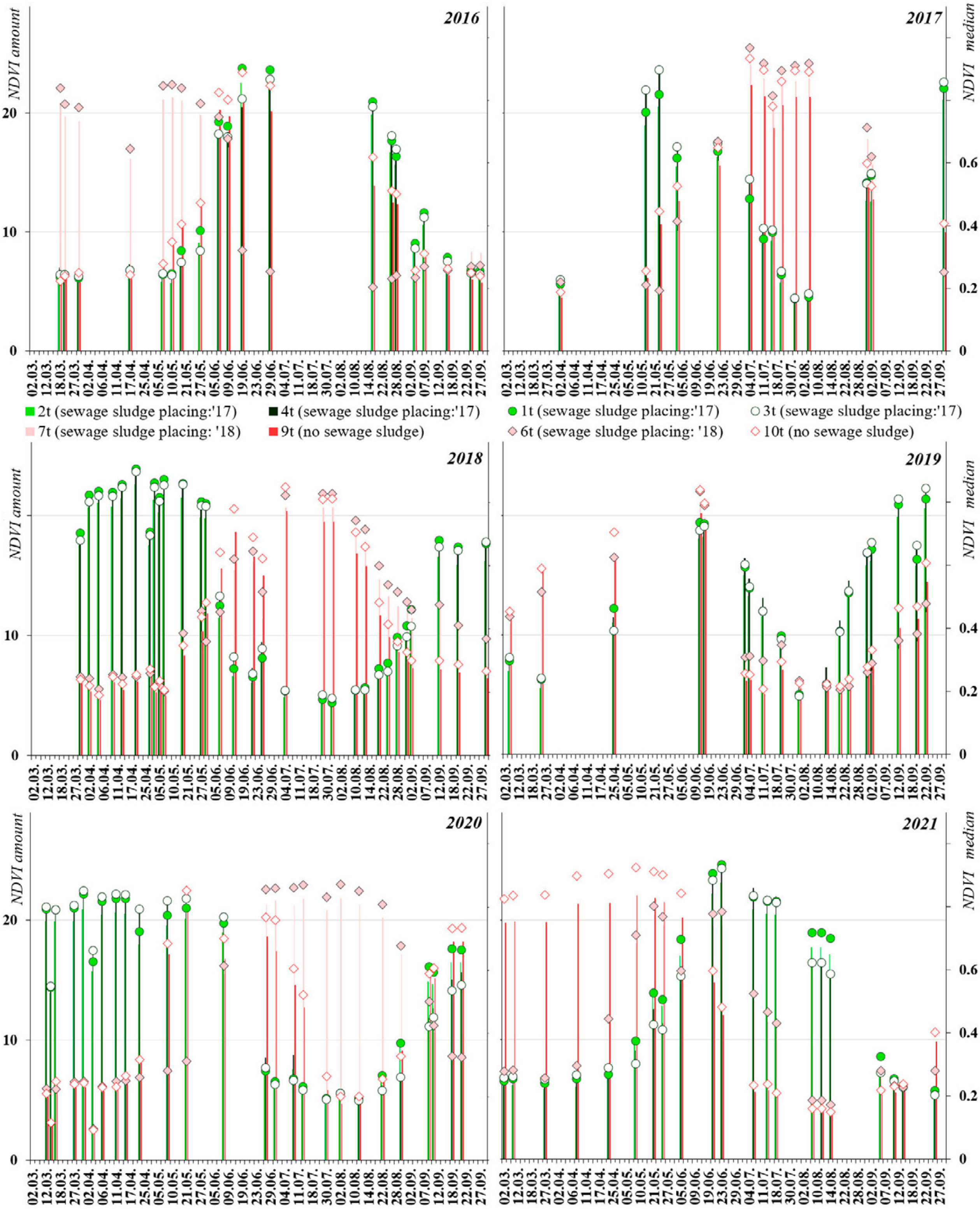

Figure 3. NDVI values of quadrates of Újkígyós study site between 2016 and 2021 (points: NDVI median, columns: NDVI total) (1t-4t: sewage sludge placing in 2017; 6t-7t: sewage sludge placing in 2018; 9t-10t: no sewage sludge)

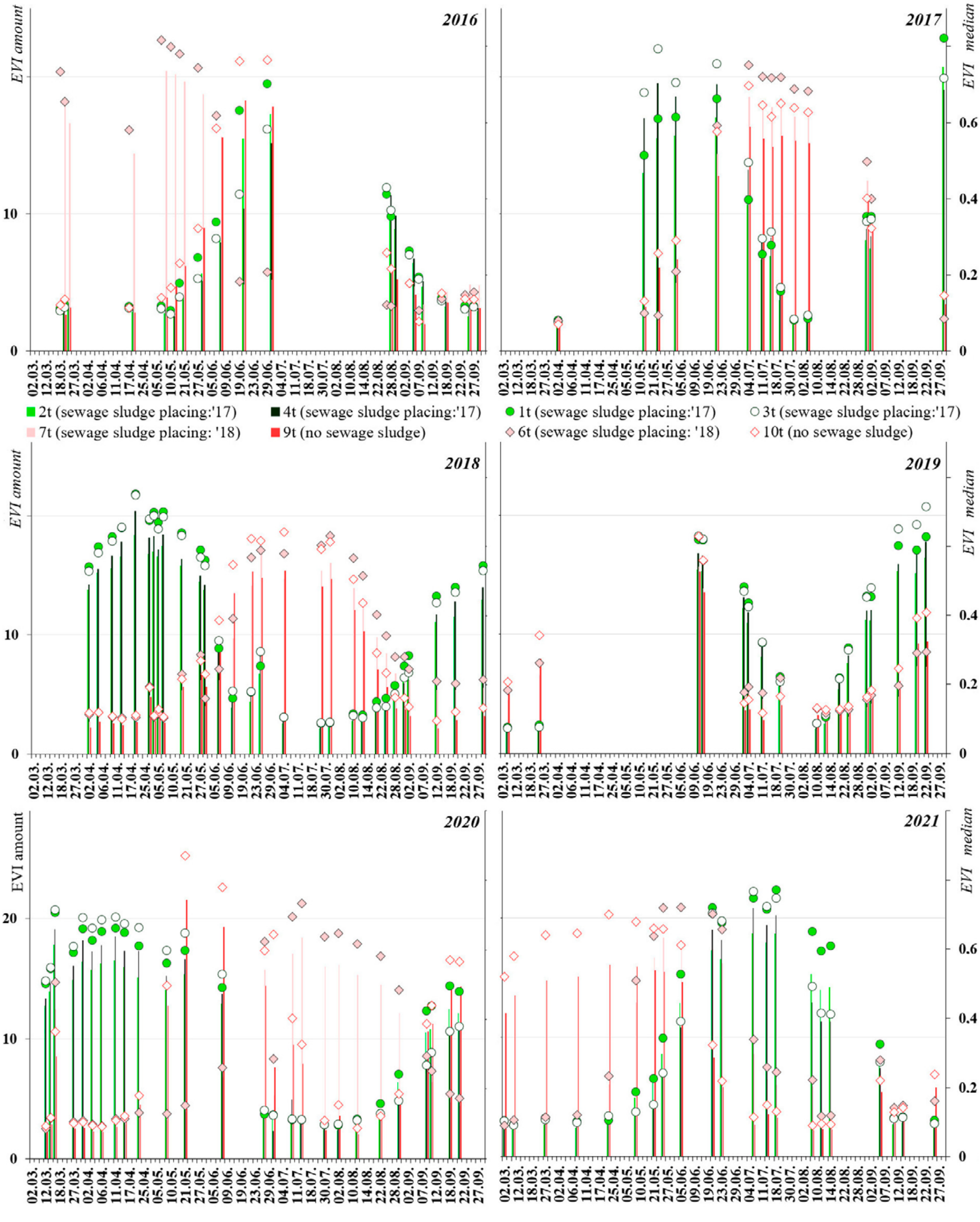

Figure 4. EVI values of quadrates of Újkígyós study site between 2016 and 2021 (points: EVI median, columns: EVI total) (1t-4t: sewage sludge placing in 2017; 6t-7t: sewage sludge placing in 2018; 9t-10t: no sewage sludge)

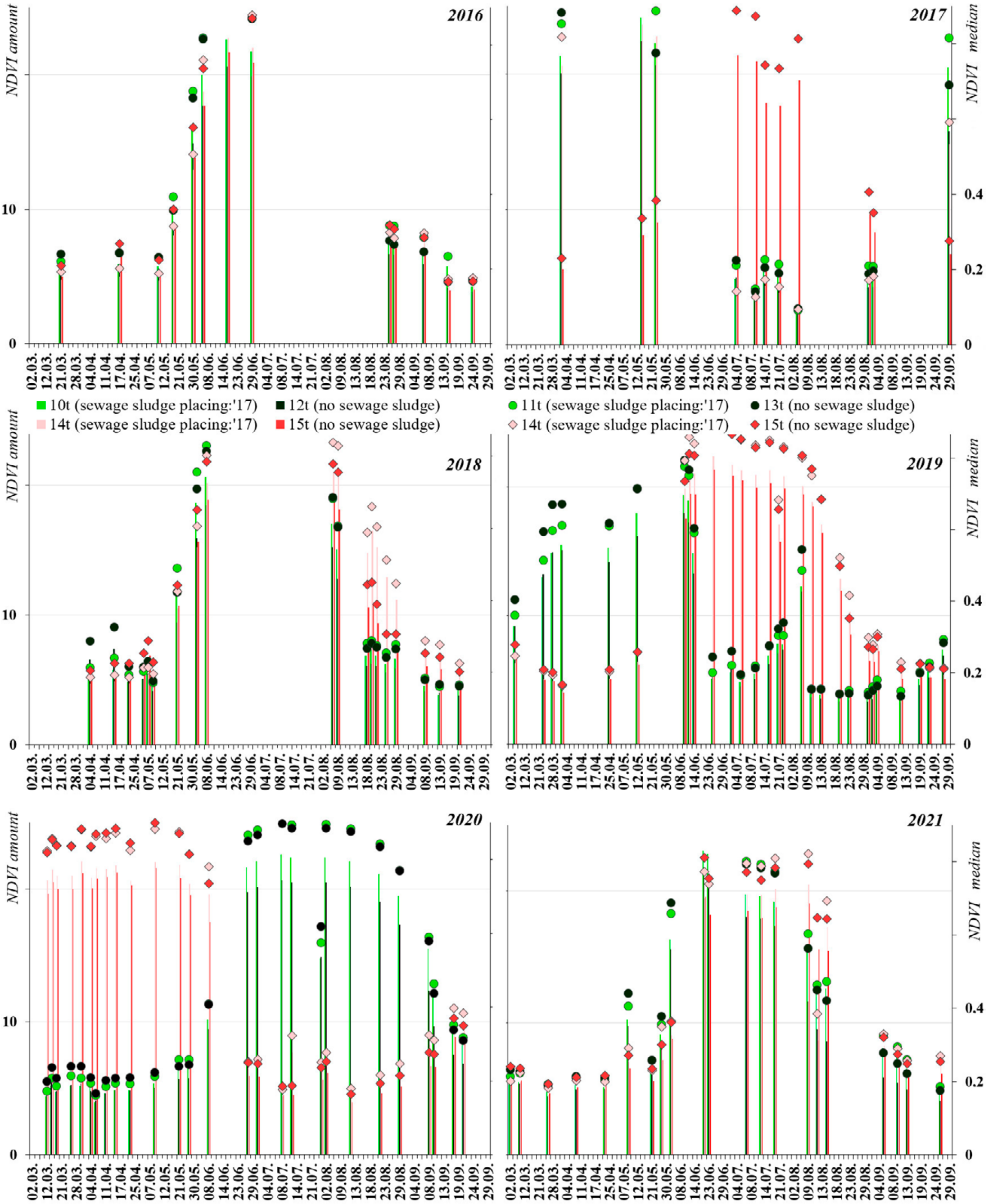

Figure 5. NDVI values of quadrates of Kardos study site between 2016 and 2021 (points: NDVI median, columns: NDVI total) (10t-11t and 14t: sewage sludge placing in 2017; 12t-13t and 15t: no sewage sludge)

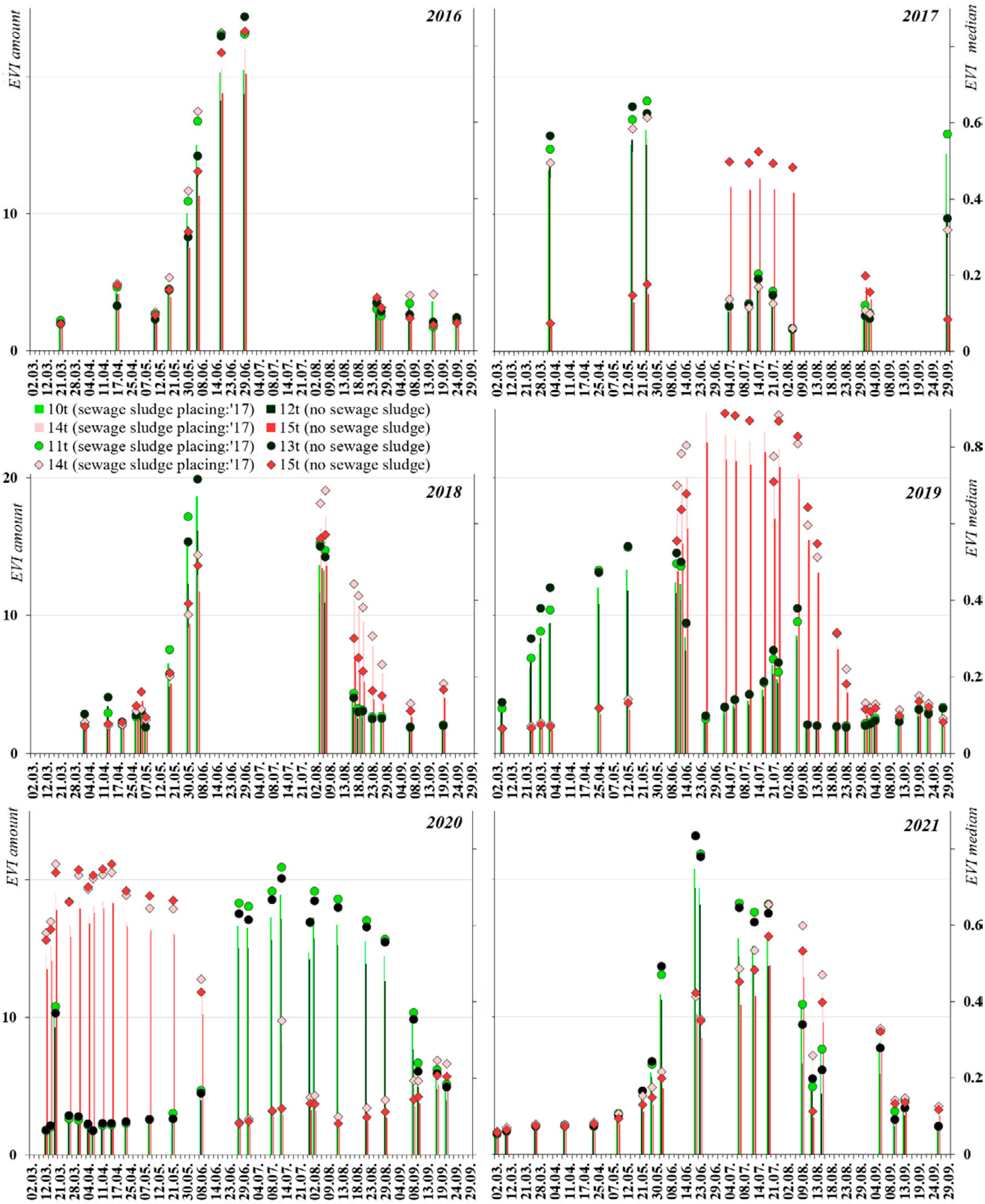

Figure 6. EVI values of quadrates of Kardos study site between 2016 and 2021 (points: EVI median, columns: EVI total) (10t-11t and 14t: sewage sludge placing in 2017; 12t-13t and 15t: no sewage sludge)

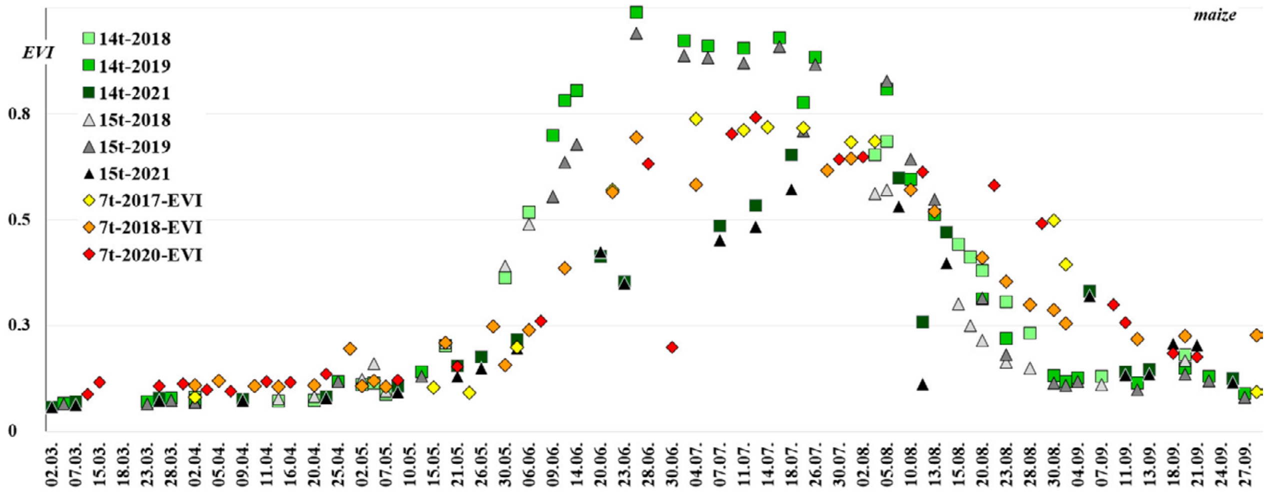

Figure 7. Effect of sewage sludge deposition based on maize Sentinel-2 EVI values on the example of 14t quadrat by comparing 15t, 7t control areas

The spring EVI and NDVI data for 14t 2018 are still in line with 15t quadrat, but before the harvest, the area treated in the previous year shows continuous VI values of at least 0.1 higher throughout August. NDVI value of the treated area is higher, even exceeding the untreated 15t maize production by up to 0.2. In 2019, the difference between 14t-15t can now be tracked throughout the year. The EVI difference in June-July is consistently between 0.05-0.15 in favour of 14t and the two curves only level out towards the end of July. This difference in 2019 is not present at all in the NDVI, the values of the two quadrates are actually the same. The 2019 14t maize EVI values are the highest index values for the whole study period, with average values above 0.8 from the second half of June and above 0.9 in July. This is a striking phenomenon, as the NDVI is otherwise known as a higher index prone to saturation (Huete et al., 2002). In 2021, we basically get different VI's, which is also due to the moderately droughty summer semester and the rainless June (2 mm of precipitation fell at the drought monitoring station). The NDVI curve matches the values observed in previous years, but shows the lowest biomass production in both the growth and maturation phases in the period 2018-2021; between May and August, with biomass production typically 10-40% lower than in previous years. There is no typical NDVI difference between the 14t and 15t areas, but rather the untreated area has the higher index value. EVI shows the difference in a more sensitive way when comparing; the values for June 2021 are only half of those for the same period in previous years, with the difference closing in August, probably also due to the late harvest in 2021. Even the summer peak is almost 30% lower than in 2019. The EVI of the 14t treated area in 2021 is slightly, but typically higher (+10-12%) than the untreated 15t sample area. The EVI values for maize in the 15t control area in 2017 - also droughty - are similarly only 55-60% of the 2019 data.

There is no typical change in the Újkígyós maize fields (6t-7t); the 2017 and 2018 VI values before planting coincide almost perfectly with the 2020 data after planting. Compared to the very high EVI values of 14t, lower values of between 0.56 and 0.73 were also found here. In the case of maize, a comparative evaluation of the EVI values for the 14t quadrat suggests that sewage sludge disposal may have played a role in the evolution of biomass, while such a relationship was not observed in the Újkígyós area.

The impact of placement on winter wheat production at Újkígyós could be assessed on the basis of data of 1t-4t for 2018 and 2020. As a control, the 9t-10t could only be compared indirectly with the VI for 2019 and 2021. Our observations show that the VI values for different years are either the same or possibly even higher in the control areas. As a control for the 2019 crop of 10t-11t of Kardos, we used the previous values of the same quadrates from 2017 and the data of 12t-13t from 2017 and 2019, free of placement. The VI values in the different quadrates are the same in the different years, and despite the treatment, the values in May-June 2017 are higher. It can be concluded that for this crop, the effect of sewage sludge placement is not noticeable.

For the evaluation of sunflower, the VI values for 2018 and 2021 for the 10t-11t in Kardos study area were used, with the control values for the same years being the 12t-13t and the 10t-13t for 2016. The similar small April values compared to 2016 increased very intensively in May 2018 – producing a nearly 3-fold increase in VI during one week – and by the beginning of June the EVI value was 0.08 higher in the area of sludge disposal (Figure 8.), a difference that is also – to a lesser extent – characteristic of the NDVI. The

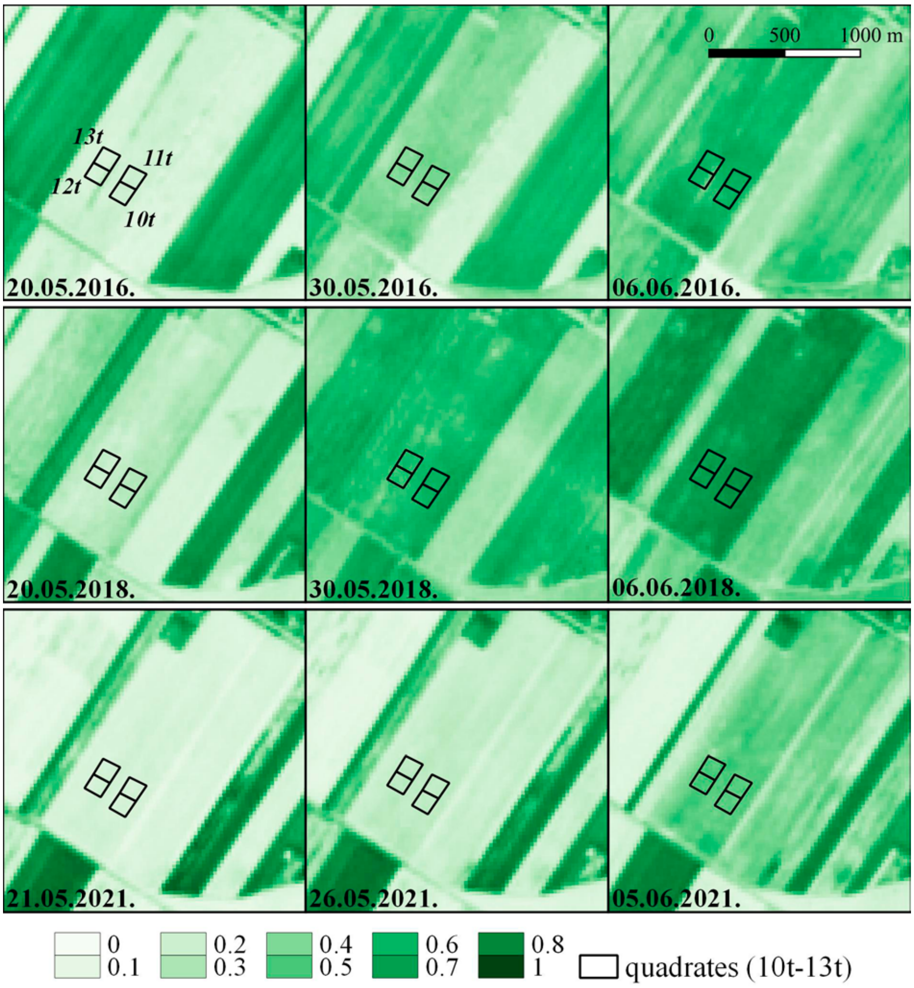

Figure 8. Short-term impact of sewage sludge disposal in 2017 on sunflower yield based on Sentinel-2 EVI data

drought in 2021 seems to have set back yields and we get EVI values similar to 2016 in the first half of the year. NDVI is less sensitive, with no typical difference between years. The VI difference between treated and untreated areas during drought can be seen. In August and September, EVI and NDVI values were 1.2-1.5 times and 1.2-1.3 times higher in the 10t-11t compared to the control area, indicating improved soil water management characteristics.

The more constant NDVI value, which also characterise the quadrat despite the drought, may indicate more favourable soil water management. At Újkígyós we were able to compare 2016 and 2021 data, but only at different quadrates; 9t-10t versus 1t-4t. No difference was observed, but given the drought situation, it could be here also a sign of better water management, so the application of the sludge in 2017 could have played a role, given the climatic parameters.

The effect of treatment on colza production could only be studied in Újkígyós, comparing quadrates of different areas. The control values for the 1t-4t after sewage sludge placing (2019) were taken from the 6t-7t of 2016. In 2019, due to the approximately 1 month later greening and harvesting time, the VI values are of limited comparability. The peak of VI values in 2016 are higher, especially for EVI, and there is no difference in the run of the data, so the sewage sludge has no consequences for colza produce. The differences between August and September already indicate the next year's crop; in 2017 maize while in 2020 it is winter wheat.

The heterogeneity of the different crops is also well patterned spatially by quadrates. The columns in Figure 9. show the recording of nearly the same days of each month of each summer semester, plotted against the rows for each year. As in the diagrams, the spatial homogeneity of the VI generally shows homogeneity within quadrates, but also in such small sample areas, sampling with larger variance occurs; e.g. on 06.06.2018 and 05.06.2021. In particular, the remote sensing survey in June and August revealed the alluvial form which bisects the area from North-East to South, the curvature of which is determined by the soil conditions and the biomass product, causing differences in yields within a single plot. The VI values of the 2t, 3t, and 10t quadrates are influenced by the different physical nature of the soil resulting differences in water management. In the time series, the drought year 2021 is strikingly distinct from similar periods in other years, with perhaps only March 2017 indicating a more drought-like character. Looking at satellite imagery data from early June 2021, there are several years with lower VI categories, e.g. 04.06.2017.

Using PlanetScope imagery in 2020

Our Sentinel-2 EVI and NDVI results were verified using the method of comparison with satellite data with higher geometric and different spectral resolution. When using Planet and Sentinel-2 data taken on the same days in 2020, we typically observe a larger difference between the two sensors in the case of EVI. The standard deviation of the annual data is smaller for Planet, and for all three crops studied (Figure 10). The S-2 VI value is higher (up to +0.1) in the greening and ripening stage, while the Planet index is higher in the pre-harvest and post-harvest stages. According to the S-2 based results, the Planet VI mid-summer peaks are in decreasing order: oil radish, maize, winter wheat. The 21 common dates were compared for all crops in the different quadrates.

The value ranges of determination coefficient suggest a close relationship, especially for NDVI; $0.685 < R^2_{EVI} < 0.867$, and $0.8137 < R^2_{NDVI} < 0.921$. The higher NDVI coefficient is the result of saturation (typical of the index), as the difference between the Planet and S2 NDVI values of the soil or sparsely vegetated surface is often greater than 0.2. In the case of EVI, the relationship is consistent for both dense and sparse vegetation. On a crop-by-crop basis, we found greater similarity between the EVI for maize and the NDVI for winter wheat, while looking the two indices together most balanced was for oil radish. Based on the coefficients of determination, Sentinel-2 data with high temporal resolution and on homogeneous surface coverage of sufficient quality can be used for agricultural monitoring at the parcel level.

Conclusion

To observe the short-term effects of sewage sludge disposal, we planned a six-year, high-resolution monitoring study in continuously cultivated agricultural parcels, often covered with different crops from year to year. In 14 quadrates of 50 m x 50 m, Sentinel-2 satellite imagery-based data collection was applied at the highest temporal and spatial resolution. A database of 140 cloud-free images, supplemented with PlanetScope images was evaluated with vegetation indices (EVI, NDVI) to assess photosynthetic activity and biomass production changes in space and time during the summer semester.

Spectral index-based differences in the vegetation cycle can be used to determine the diversity of plant species produced in the area, and differences in land cover. Similar to the analyses of soil and shorter-term field vegetation monitoring (Ladányi et al., 2020; Kovács & Ladányi, 2021) prior to our studies, we could not detect a generally significant relationship between areas affected and unaffected by sludge placement, through statistical differences measured by EVI and NDVI. Among the four crops studied, the biomass products of sunflower and maize show index differences, which can be evaluated as the effect of sludge application within 1-4 years: more intensive greening, typically higher index values, and vegetation development not affected by drought. In the case of colza and winter wheat, the available data do not show a similar pattern, and in several cases the vegetation index values before the placement are higher. The spatial heterogeneity of the parcels, which is well represented by the quadrates, was not altered by the disposal of sewage sludge during the period studied.

The combination of two different vegetation indices is useful. In addition to the general advantages of the EVI, the accuracy of the assessment of the dense vegetation period, its sensitivity, and applicability in comparative analysis can be highlighted, while the NDVI can be a good complementary data in the dynamics of sparse vegetation, and in the differentiation of vegetation types. Interesting, that the difference between NDVI and EVI is smaller in areas treated with sewage sludge. As expected, in a study requiring a high spatial resolution, the Planet data are generally in close statistical correlation with the Sentinel-based index values and confirm the results of the assessment. Due to their temporal and spatial detail, they can also be presented as separate data, but only from 2017 onwards.

Despite the change in management, the objective of detecting significant differences justifies the continuation of monitoring and the inclusion of data from current years in further analysis, which will also help to narrow down the data gap periods; the extension of Planet data over time and space is already in progress.

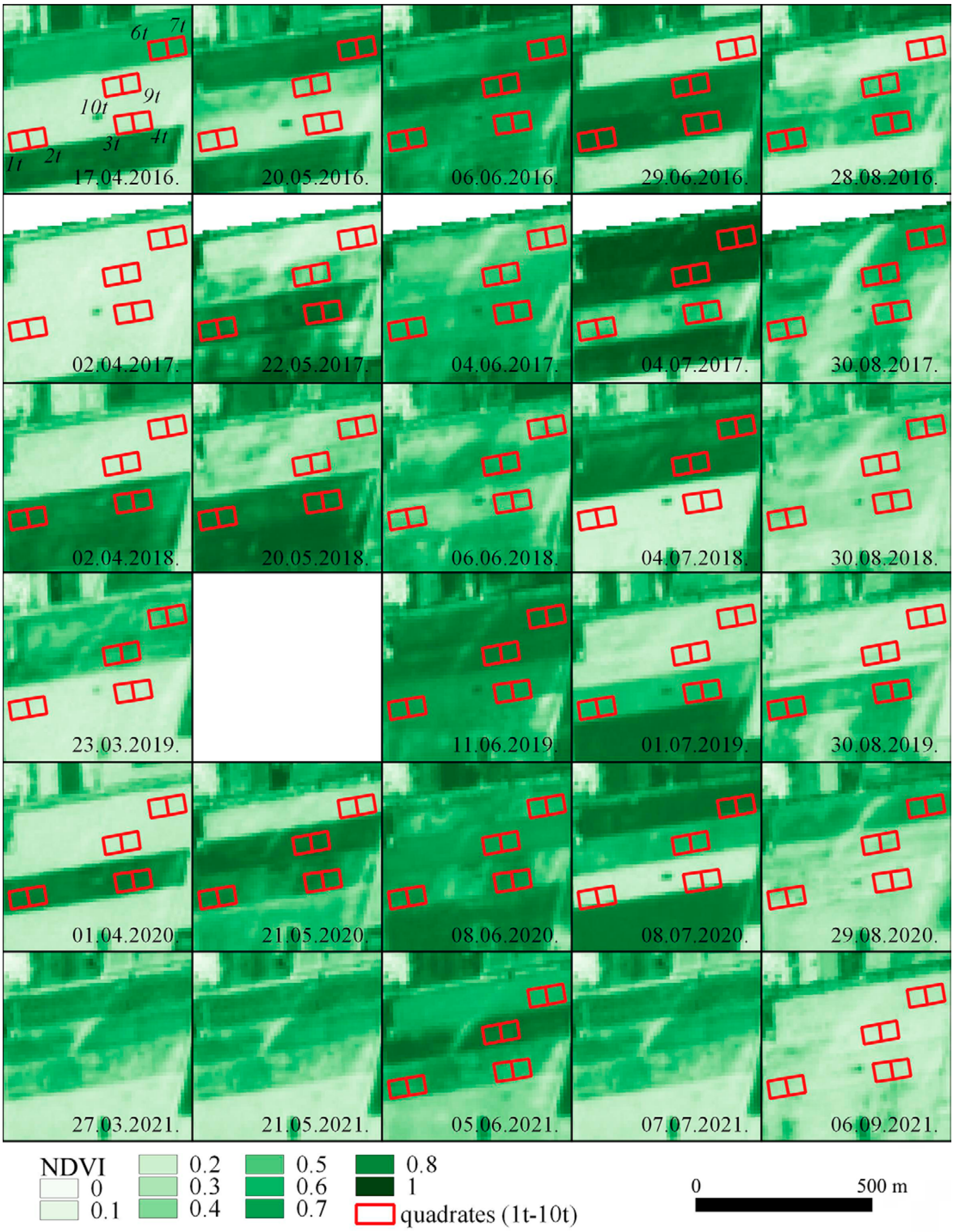

Figure 9. Spatial distribution of agricultural biomass production in the same summer periods of different years based on Sentinel-2 EVI in Újkígyós sample area between 2016–2021 (May 2019: lack of data)

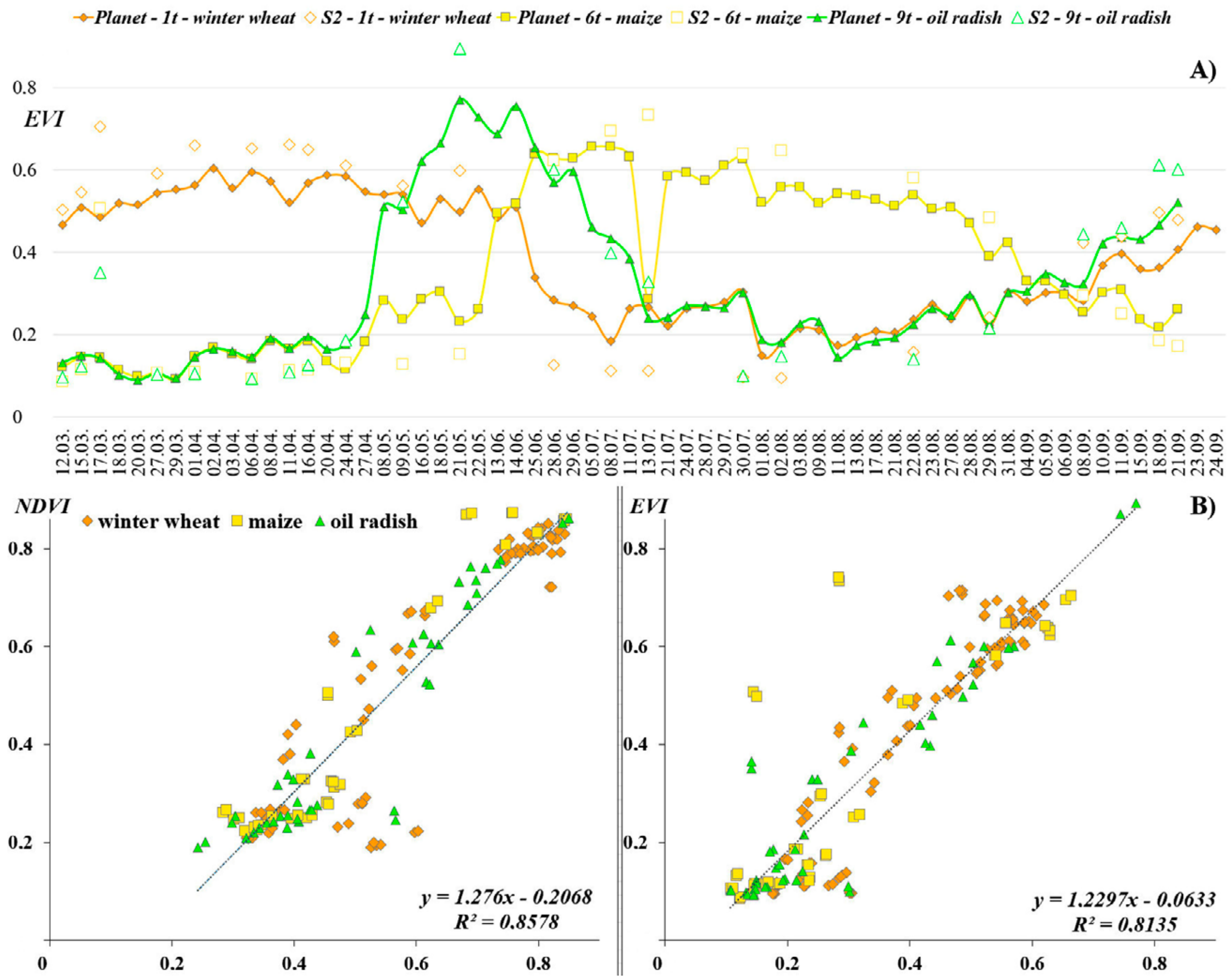

Figure 10. EVI time series of Planet and Sentinel-2 satellites for different crops in summer 2020 (A), and linear regression analysis based on EVI and NDVI for this period (B)

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