The normalized difference vegetation index (NDVI) as a proxy of soil fertility under no-tillage: Features for different Chernozems and applied treatments in Russian forest-steppe region

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Abstract

Using the normalized difference vegetation index (NDVI) as a proxy for soil fertility would be highly useful for adapting no-tillage to specific environmental conditions and for monitoring soil quality. Therefore, our study aimed to evaluate the relationship between satellite-based NDVI (May-August 2022) and soil fertility under no-tillage in the forest-steppe of Russia, considering different Chernozems (Haplic and Luvic) and treatments (none / with microbial inoculation and irrigation). Among the soil fertility indices (0–10 cm), content of organic and inorganic C (SOC and C_{inorg}), total N, available P and K, SOC : N, pH, microbial biomass (MBC) and respiration were assessed. Overall, soil nutrient dependence of NDVI was found for Luvic Chernozem in both microbe-inoculated (SOC, N, K with $R^2 = 0.72 – 0.95$) and untreated sites (SOC, SOC:N with $R^2 = 0.58 – 0.66$). For Haplic Chernozem, only a negative relationship between NDVI and C_{inorg} was found ($R^2 = 0.47$) at an untreated site, which was eliminated by using irrigation with microbial inoculation. Thus, NDVI can be a robust tool for predicting soil nutrient levels for no-tilled Luvic Chernozem, but not for Haplic Chernozem. At the same time, applied treatments can significantly change the specifics of this relationship, which is important to consider in remote sensing of soil fertility.

Keywords: microbial inoculants, irrigation, Haplic / Luvic Chernozems, soil nutrient levels, microbial biomass, inorganic carbon.

Introduction

The normalized difference vegetation index (NDVI) is a widely used remote sensing spectral approach representing the difference between red (chlorophyll absorbed) and near-infrared (photosynthetically useless) image bands (Rouse, Haas, Schell, and Deering, 1974). Essentially, the index rising shows an increase in photosynthetically active biomass (Tucker, 1979; Goswami, Gamon, Vargas, and Tweedie, 2015; Barboza et al., 2023). Therefore, NDVI has been successfully applied to study the spatio-temporal variability of vegetation productivity and plant species distribution depending on various natural and anthropogenic factors (Pettorelli et al., 2005). Specifically, this indicator is actively used in agricultural practice to monitor crop growth, phenology and health (Rahman, Islam, and Rahman, 2004; Funk

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and Budde, 2009; Shafi et al., 2020), and to timely identify water and nutrient requirements (Cabrera-Bosquet et al., 2011; Prakasha, Somashekar, and Shivanand, 2020; Kimaro et al., 2023). In precision agriculture, NDVI remains the most frequently used vegetation index (Radočaj, Šiljeg, Marinović, and Jurišić, 2023). This has resulted in a well-developed commercial market for NDVI estimation for farmers based on satellite or drone imagery and handheld sensors (e.g., "GreenSeeker" and "Crop Circle"). Thus, NDVI is a widely recognized and readily available tool for rapidly assessing the spatial heterogeneity of vegetation productivity characteristics.

As plant productivity is largely related to soil fertility, NDVI is also a good predictor of the spatial distribution of nutrient availability and stocks (such as total/organic carbon, nitrogen, phosphorus and potassium) for different agricultural soils (Sumfleth and Duttmann, 2008; Whetton, Zhao, Shaddad, and Mouazen, 2017; Liu et al., 2018; Zhang et al., 2019) including arable Chernozems in some Russian regions (Gopp et al., 2017; Gopp and Savenkov, 2019; Suleymanov et al., 2021). This relationship could be useful in understanding the effectiveness of different agricultural practices in improving soil quality, including carbon stocks. The latter is particularly relevant for the implementation of the "4 per 1000" initiative (www.4p1000.org), which aims to develop carbon sequestration farming to mitigate climate change and improve food security (Chabbi et al., 2017). In this context, a no-till system that follows natural principles (i.e., no/minimal soil mechanical disturbance; continuous crop residue coverage; diverse crop rotation) can be promising (Ogle et al., 2019; Kan et al., 2022). According to a recent review by Kassam, Friedrich, and Derpsch (2019), no-till land accounts for about 180 million hectares worldwide (12.5% of the total global cropland), with an annual expansion of 10.5 million hectares. Despite this, Russian farmers remain extremely skeptical about this agricultural practice due to its complex and costly adaptation to different soil and climate conditions, as well as potential yield losses. Therefore, the no-till land in Russia is only 1.5–2 million hectares, located mainly in the forest-steppe and steppe regions with Chernozems (Cherkasov, Pykhtin, and Gostev, 2017; Turin, 2020). Thus, the applicability of remote sensing for predicting spatial changes in soil fertility indices under no-tillage can greatly facilitate (i) its adaptation to specific environmental conditions, (ii) monitoring soil quality, especially carbon stock dynamics, and (iii) the further expansion of this practice across Russia.

There is a well-known problem of achieving effective weed control under no-tillage, which can be exacerbated by environmental policies aimed at reducing pesticide usage (Soane et al., 2012). Therefore, some farmers use various microbial inoculants to reduce dependence on pesticides as well as chemical fertilizers. At the same time, such biological treatments can alter the functioning of soil microbial communities and the resulting soil-plant-microbe interactions in unpredictable ways (Vázquez, César, Azcón, and Barea, 2000; Trabelsi and Mhamdi, 2013; Cassan and Diaz-Zorita, 2016). This, in turn, may be reflected in the relationship between crop productivity (NDVI) and soil nutrient variability. In this regard, our study aimed to investigate the predictive power of NDVI on the spatial variability of soil fertility indices (including nutrient levels and microbial activity) in no-till farming, considering the effects of different applied treatments on Haplic and Luvic Chernozems.

Materials and methods

Study sites and sampling design

The study was carried out at a private no-till farm of "Orlovka — Agro-Innovation Center" LLC located in the Samara region of Russia (53°49′N / 51°55′E). This area belongs to the forest-steppe with a warm-summer humid continental climate (Dfb according to the Köppen climate classification). The mean annual temperature is 4.7 °C, and the mean annual precipitation is 459 mm, of which 130 mm falls in the summer (1991–2020; data from the closest WMO weather station "28806 Buguruslan"). The history of agricultural use of the area goes back about a century (recorded since 1929). The current farm was preceded by another crop farm, JSC "Soviet Russia". Prior to no-till farming, conventional tillage (plowing to 23–25 cm) was used in this area. The dominant soil subtypes are Haplic and Luvic Chernozems, formed on brown clays and clay marls. The farm area (approx. 4,000 ha) is slightly undulating, with elevation ranging from 55 to 217 m a.s.l. (average 120 m a.s.l. according to Copernicus GLO-30 DEM). Currently, the farm crop rotation includes spring wheat, sunflower, soybean and flax.

In 2022, Haplic Chernozem (5-year no-till) and Luvic Chernozem (8-year no-till) sites were surveyed on the farm. Within each site, different treatments were considered: none / with microbial inoculation and irrigation for Haplic Chernozem; none / with microbial inoculation for Luvic Chernozem (Table 1). Non-irrigated and non-microbe-inoculated soils were hereafter referred to as "untreated" soils. In the study year, spring wheat and flax were cultivated on Haplic and Luvic Chernozem sites, respectively.

Microbial inoculants used for Haplic Chernozem were a fungal control agent (*Trichoderma harzianum* with 1×10^{10} UFC g^{-1} and 0.08 L ha^{-1}; Russian "AgroBioTechnology" LLC) and a straw-decomposing accelerator (combination of *Trichoderma, Bacillus, Actinomyces*, nitrogen-fixing and lactic acid bacteria with 1×10^{9} UFC g^{-1} and 2.5 L ha^{-1}; Russian "Scientific Research Institute Biopreparaty" LLC). Microbial treat-

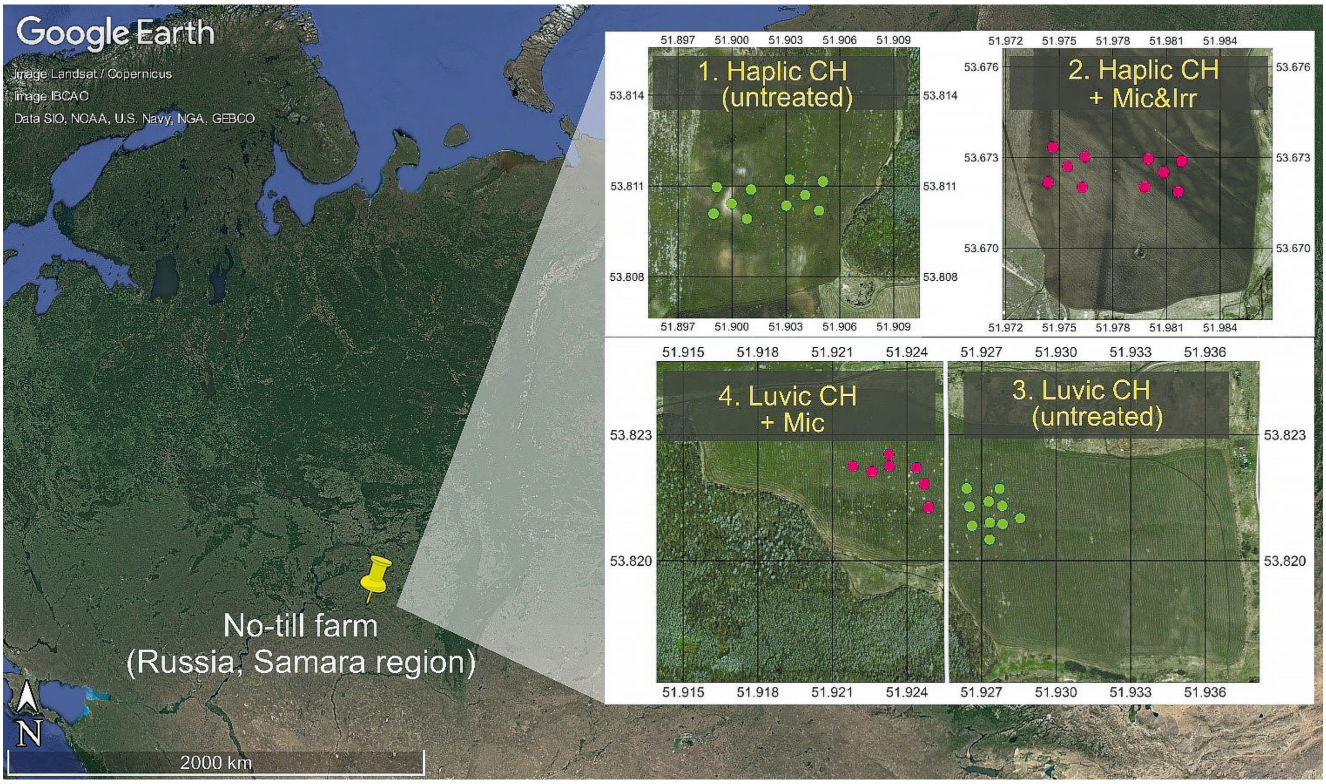

Fig. 1. Scheme of soil sampling for no-tilled Haplic and Luvic Chernozems (CH) on the untreated, microbe-inoculated (Mic) and irrigated (Irr) sites. Only 7 points are shown for "Luvic CH + Mic" site as the remaining coordinates are not available.

Table 1. Applied treatments and cultivated crops (2022) at Haplic and Luvic Chernozem (CH) sites under no-tillage

Site	Mic	Irr	HS (L ha^{-1})	NF (kg N ha^{-1})	Crop	S/H (dd.mm)
Haplic CH (untreated)	No	No	4	34	Wheat	09.05/30.08
Haplic CH + Mic&Irr	Yes	Yes	4	86	Wheat	08.05/22.08
Luvic CH (untreated)	No	No	No	34	Flax	03.06/11.09
Luvic CH + Mic	Yes	No	No	34	Flax	03.06/11.09

Notes: Mic, microbial inoculation; Irr, irrigation; HS, humic substances; NF, nitrogen fertilizers; S/H, sowing and harvesting dates.

ments were applied annually before sowing and after harvesting for five years (2018–2022). Irrigation was carried out using a center pivot system. In addition, nitrogen fertilizers (34–86 kg N ha^{-1} at sowing) and humic fertilizers (4 L ha^{-1} at heading stage) were applied to both Haplic Chernozem sites (the microbial / irrigation treated and the untreated). Pesticide treatments for wheat included herbicides (2,4-D 2-ethylhexyl ester + florasulam; tribenuron-methyl), fungicides (pyraclostrobin + epoxiconazole; propiconazole + tebuconazole) and insecticides (alpha-cypermethrin; thiamethoxam).

The microbial inoculant for Luvic Chernozem was *Azospirillum* sp. (2×10^9 UFC g^{-1} and 0.5 L ha^{-1}; Russian "Ecos" LLC), which was used once (in 2022) during the budding phase to promote flax growth. Nitrogen fertilizers (34 kg N ha^{-1} at sowing) were applied to both Luvic Chernozem sites (the microbial treated and the untreated). Pesticide treatments for flax included only herbicides (dimethylamino + sodium + potassium salt mixture; clopyralid-olamine; clethodim).

In October 2022, soil samples were taken from the upper 0–10 cm layer at 10 spatially distributed points per site. Within the individual Haplic Chernozem site, the point locations were evenly distributed across two one-hectare squares (in the corners and in the center), somewhat approximating a grid sampling design (Fig. 1). Within the Luvic Chernozem site, the points were randomly distributed across ~2 ha sampling area with a minimum spacing of 30 m to match the spatial resolution of the Landsat 8–9 imagery. Totally, 40 freshly collected samples (4 fields × 10 sampling points) were transported to the laboratory for the immediate microbial and chemical testing.

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Soil analysis

The soil samples were sieved through a 2 mm mesh to exclude stones and roots. Then, one portion of the samples was air-dried and used for chemical analysis. The remaining portion of fresh soil samples was moistened up to 55–65 % water-holding capacity, pre-incubated at 25 °C for 72 hours (Jones, Verheijen, Reuter, and Jones, 2008), and then used for microbial analysis. Soil pH was measured in 1 *N* potassium chloride solution (soil : KCl solution = 1 : 2.5) using a pH-meter ("Ionometric converter I-500", Russia). Soil organic carbon (SOC) content was determined by the dichromate oxidation technique followed by colorimetry (FAO, 2019). Soil total carbon (C_{tot}) and nitrogen (N) were analyzed by the dry combustion method using a CHNS analyzer ("Vario EL III", Germany). Inorganic carbon (C_{inorg}) was calculated from the difference between C_{tot} and SOC. Available phosphorus (P) and potassium (K) contents were determined by soil extraction with dilute hydrochloric acid (0.2 *M* HCl) and then quantified with a photoelectric colorimeter/flame photometer. Microbial biomass carbon (MBC) was measured by the substrate-induced respiration method (Anderson and Domsch, 1978; ISO 1997). Basal respiration (BR) was measured as the rate of soil CO_2 release using gas chromatography ("KrystaLLyuks-4000 M", Russia) (ISO 2002). The MBC and BR values were determined under optimum hydrothermal conditions for the microorganisms: 22 °C and 55–65 % water holding capacity.

NDVI calculation

Landsat 8–9 satellite imagery of the study area with a spatial resolution of 30 m were derived from USGS EarthExplorer (https://earthexplorer.usgs.gov/). Only cloud-free remote imagery from May to October 2022 were selected, including 14 dates (dd.mm): 07.05; 08.05; 24.05; 25.06; 02.07; 10.07; 11.07; 18.07; 11.08; 12.08; 19.08; 20.08; 28.08, 13.09. Pre-processing of the image dataset included radiometric calibration and atmospheric correction (Vermote, Roger, Franch, and Skakun, 2018). NDVI was calculated by the equation (Rouse, Haas, Schell, and Deering, 1974):

$$NDVI = \frac{(NIR - R)}{(NIR + R)},$$

where NIR is near-infrared reflection; R is visible red reflection. The NIR band for Landsat 8–9 imagery is 851–879 nm, and the R band is 636–673 nm.

Statistical analysis

The spatial variability of the soil fertility indices was quantified by the coefficient of variation (CV, %), which is the ratio of the standard deviation to the mean. The significance of differences between two independent groups (untreated and treated sites) was tested using the Welch's t-test. Simple linear regression was used to test the significance of NDVI in predicting the spatial variability of soil fertility indices for each Chernozem site individually. Prior to the statistical analysis, the variable distribution was checked with the Shapiro-Wilk normality test. Box-Cox transformation was performed for variables with non-normal distribution. Statistical analysis and results visualization were carried out in the R software system (version 4.1.2) (RStudio Team, 2023).

Results

Spatial variability of soil fertility indices

The main difference between the studied Chernozems (CH) was pH value, which was higher for Haplic CH (slightly alkaline) than for Luvic CH (neutral) (Table 2). Within each soil subtype, the elevation and some soil properties varied significantly between the untreated and the treated sites. For Haplic CH, the microbe-inoculated and irrigated site was located about 130 m lower than the untreated site and had higher SOC, P and, conversely, lower C_{inorg}. Moreover, the spatial variability of most soil properties (except P and K contents) in the treated site was 1.5–3.0 times lower than at the untreated one. In the case of Luvic CH, the microbe-inoculated site was located 5 m higher than the untreated site and had lower pH, P, K and MBC and BR. At the same time, the spatial variability of soil properties was mainly the same at both Luvic CH sites.

Table 2. Elevation and soil properties (0–10 cm) for no-till Haplic and Luvic Chernozems (CH) on untreated, microbe-inoculated (Mic) and irrigated (Irr) sites

Property	Haplic CH (untreated)	Haplic CH + Mic&Irr	Luvic CH (untreated)	Luvic CH + Mic
Elevation (m a. s. l.)	198 (1)	64 (4)***	151 (1)	156 (1)***
pH_{KCl}	6.8 (6)	6.9 (3)	5.6 (4)	5.3 (3)**
C_{inorg} (%)	1.06 (84)	0.42 (57)*	0.39 (36)	0.37 (41)
SOC (%)	3.75 (24)	4.42 (8)*	4.52 (6)	4.52 (5)
N (%)	0.34 (27)	0.39 (9)	0.37 (5)	0.38 (5)
SOC:N	11.3 (9)	11.5 (6)	12.2 (4)	12.1 (3)
P (mg kg^{-1})	95 (30)	151 (28)***	104 (26)	69 (23)**
K (mg kg^{-1})	218 (27)	183 (24)	235 (12)	163 (23)**
MBC (μg g^{-1})	708 (53)	833 (23)	916 (34)	560 (26)**
BR (μg C g^{-1} h^{-1})	0.39 (55)	0.45 (23)	0.62 (45)	0.42 (40)*

Notes: SOC, soil organic carbon; C_{inorg}, inorganic carbon; N, total nitrogen; P, available phosphorus; K, available potassium; MBC, microbial biomass carbon; BR, basal respiration.

Data are mean values with coefficient of variation (%) in parentheses (*n* = 10; *p ≤ 0.05, **0.01, ***0.001 for Welch's t-test).

Changes in NDVI values

Regardless of the soil subtypes and applied treatments, the NDVI values changed similarly throughout the observed growing season (Fig. 2). The index was low at the beginning and the end of the season, with a peak in the middle (0.60–0.87 in June-July). As expected, using additional ameliorative treatments significantly increased crop productivity and consequently NDVI. In the case of Haplic CH with wheat, the NDVI means for the growing season were 0.49 and 0.58 for the untreated and the microbe-inoculated + irrigated sites, respectively ($p < 0.001$ for Welch's t-test). For Luvic CH with flax, the means were 0.48 and 0.52 for the untreated and the microbe-inoculated sites, respectively ($p < 0.001$ for Welch's t-test).

Relationship between NDVI and soil fertility indices

Simple linear regression has shown different drivers of NDVI variability depending on the soil subtypes and the applied treatments (Fig. 3). For the untreated Haplic CH, the spatial variability of NDVI averaged over the growing season (May-August) was determined by C_{inorg} content (negative relationship; $R^2 = 0.47$). However, for the microbe-inoculated and irrigated Haplic CH, NDVI was positively associated with elevation ($R^2 = 0.78$) and negatively associated with MBC ($R^2 = 0.80$). In the case of Luvic CH, the mean NDVI variability (June-August) at the untreated site was determined by SOC and SOC : N values (positive relationships; $R^2 = 0.66$ and 0.58, respectively). Applying microbial inoculation for Luvic CH only increased the dependence of NDVI on SOC ($R^2 = 0.73$), as well as other nutrients — N and K (positive relationships; $R^2 = 0.95$ and 0.72, respectively).

Discussion

NDVI-nutrient relationship: different soil subtypes and agricultural treatments

This study did not show a general trend between spatial changes in NDVI and soil fertility indices for different soil subtypes and applied treatments. In particular, SOC

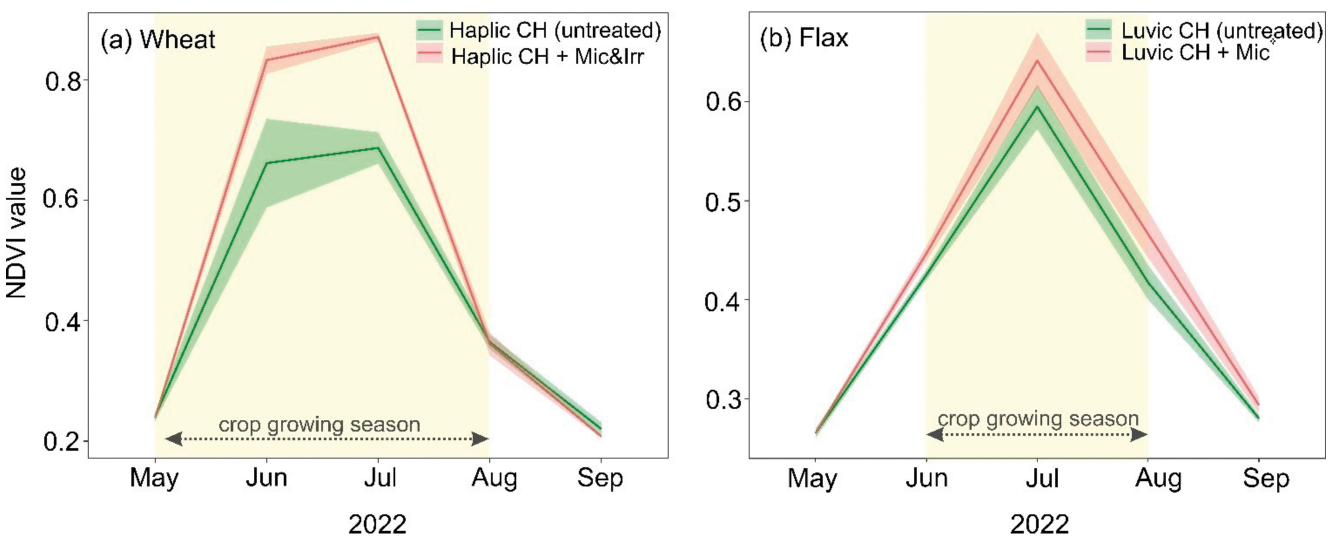

Fig. 2. Temporal dynamics of monthly average normalized difference vegetation index (NDVI) for wheat at Haplic Chernozem (a) and flax at Luvic Chernozem (b) under no-tillage of untreated, microbe-inoculated (Mic) and irrigated (Irr) sites. Line shows the mean with 95 % confidence interval (n = 10 and †n = 7).

NDVI_mean (growing season)	elev	pH	C_{inorg}	SOC	N	SOC:N	P	K	MBC	BR	Site:
	0.02	0.16	***0.47****	0.26	0.31	0.37	0.14	0.42	0.20	0.08	Haplic CH (untreated)
	0.78**	0.06	0.05	0.09	0.19	0.07	0.02	0.03	***0.80*****	0.33	Haplic CH + Mic&Irr
	0.32	0.03	0.25	***0.66*****	0.13	***0.58*****	0.11	0.02	0.02	0.01	Luvic CH (untreated)
	0.19	0.03	0.01	***0.73*****	***0.95*****	0.09	0.19	***0.72****	0.18	0.48	Luvic CH + Mic

negative relationship | positive relationship R^2
1.0 0.5 0 0.5 1.0

Fig. 3. Heatmap showing coefficient of determination (R^2) of linear regression between normalized difference vegetation index (NDVI) averaged over the growing season, elevation (elev) and Chernozem properties (CH; 0–10 cm) under no-tillage of untreated, microbe-inoculated (Mic) and irrigated (Irr) sites (*p ≤ 0.05, **0.01, ***0.001; n = 10 and †n = 7).

content played a more important role in determining NDVI variability for Luvic CH than for Haplic CH. This can be related to the fact that SOC provides a slow and continuous supply of essential nutrients to plants, reducing their leaching along both the soil profile and slope (Wander, 2004). The latter could be particularly relevant for Luvic CH, as evidenced by higher levels of labile P and K at the lower site than at the upper site (Table 2). Moreover, inoculation with *Azospirillum*, well-known as a plant growth promoter, only increased the nutrient dependence of NDVI (Fig. 3). *Azospirillum*'s ability to biologically fix N and produce phytohormones can improve nutrient use efficiency in crops (Cassan and Diaz-Zorita, 2016; Zeffa et al., 2019).

At the same time, for the slightly alkaline and non-irrigated Haplic CH, NDVI was negatively associated with C_{inorg} content, which largely determines the availability of some macro- and micronutrients to plants (such as P, K, Fe and Zn) (Wahba, Labib, and Zaghloul, 2019). As a result, crops grown on calcareous soils (rich in C_{inorg}) have reduced levels of chlorophyll, endogenous growth promoters (auxins, gibberellins and cytokinins) and subsequent crop productivity (Shukry, Khattab, and EL-Bassiouny, 2007). However, irrigation can mitigate the inhibitory effect of excess C_{inorg} on plant growth and development (Shukry, Khattab, and EL-Bassiouny, 2007; Wahba, Labib, and Zaghloul, 2019) due to its leaching from the upper soil horizon (Khokhlova, Arlashina, and Kovalevskaya, 1997; de Soto et al., 2017). This effect was also consistent with our results: the C_{inorg} in the irrigated Haplic CH was half that of the non-irrigated one (Table 2). Interestingly, there was a strong negative relationship between NDVI and MBC in the microbe-inoculated and irrigated Haplic CH, which could be explained by plant-microbe competition for the nutrients under developing abundant monocrop biomass (Kuzyakov, 2002). In addition, a strong positive relationship between NDVI and elevation variability for irrigated Haplic CH was found (Fig. 3). A possible explanation for the sensitivity of NDVI to topography under irrigation could be related to the uneven spatial redistribution of water across the field, leading to unfavorable excess moisture in lower areas. This indicative ability of NDVI in assessing irrigation efficiency has been often used to develop irrigation management strategies (Hunsaker et al., 2007; Poudel, Stephen, and Ahmad, 2021; Yousaf et al., 2021).

Prospects of using NDVI as a proxy of Chernozem's fertility

NDVI, along with the soil type and some climatic and topographic variables, is one of the most informative and widely used predictors in the digital mapping of SOC content and stocks (Gopp et al., 2023). Regarding the Chernozem zone in Russia, a significant positive relationship between NDVI and SOC content in the plow layers (0–10/0–30 cm layers) was shown for the Novosibirsk region ($R^2 = 0.52$; Gopp et al., 2017) and for the Republic of Bashkortostan ($R^2 = 0.46$; Suleymanov et al., 2021). However, other studies conducted in the Novosibirsk region found no such relationship (Gopp et al., 2019a; 2019b). Similarly ambiguous results have been observed in relation to predicting other Chernozems fertility indices (e.g., N and P levels) (Gopp et al., 2017; Gopp and Savenkov, 2019), which is generally consistent with our results (Fig. 3). Such differences in the predictive ability of NDVI for understanding the spatial distribution of soil properties can be explained by the interaction of different factors: relief characteristics and the development of erosion processes (Gopp et al., 2017; Gopp and Savenkov, 2019), meteorological conditions in a particular year (Whetton, Zhao, Shaddad, and Mouazen, 2017), variability range of soil property and individual limiting factors (Verhulst et al., 2009), time series of used satellite imagery (Zhang et al., 2019), applied agricultural treatments and so on. Identifying clear patterns of relationships between remote sensing data and soil properties for the Chernozem zone under different agro-ecological conditions requires further investigation. Moreover, the collection of additional data is necessary for the development of more accurate soil modelling and digital mapping, which is particularly relevant for the vast territory of Russia (Suleymanov, Arrouays, and Savin, 2024).

Conclusion

This study examined the predictive power of NDVI in understanding the spatial variability of soil fertility under no-tillage with different soil subtypes (Haplic and Luvic Chernozems) and treatments (microbial inoculation, irrigation). In general, SOC was a more important factor in NDVI variability for Luvic Chernozem (CH) than for Haplic CH, regardless of applied treatments. The application of microbial inoculation (*Azospirillum* sp.) in Luvic CH only increased nutrient dependence of NDVI, especially for N and K. For Haplic CH, NDVI was negatively associated with C_{inorg}, which was eliminated by using irrigation. Additionally, irrigation and microbial inoculation (*Trichoderma, Bacillus, Actinomyces*, etc.) in Haplic CH induced the highest NDVI among all studied sites, which was negatively correlated with MBC due to possible microbial-plant competition. Thus, our results demonstrate the ambiguity of using easily accessible NDVI as a proxy for spatial variability in soil fertility under no-tillage with different soils and treatments. Generally, this index can be a more reliable tool for understanding the spatial variability of soil fertility in the case of no-tilled Luvic CH than in the case of Haplic CH. At the same time, applied treatments can significantly change the specifics of this relationship, which is important to consider in remote sensing of soil fertility.

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