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RESEARCH ARTICLE

Normalized difference vegetation index analysis reveals increase of biomass production and stability during the conversion from conventional to organic farming

Lilia Serrano-Grijalva[1] | **Raúl Ochoa-Hueso**[1,2] | **G. F. (Ciska) Veen**[1] | **Irene Repeto-Deudero**[2] | **Sophie Q. Van Rijssel**[1] | **Guusje J. Koorneef**[3,4] | **Wim H. Van der Putten**[1,5]

[1]Department of Terrestrial Ecology, Netherlands Institute of Ecology (NIOO-KNAW), Wageningen, The Netherlands

[2]Department of Biology, IVAGRO, University of Cádiz, Campus de Excelencia Internacional Agroalimentario (ceiA3), Campus del Rio San Pedro, Puerto Real, Cádiz, Spain

[3]Soil Chemistry Group, Wageningen University and Research, Wageningen, The Netherlands

[4]Soil Biology Group, Wageningen University and Research, Wageningen, The Netherlands

[5]Laboratory of Nematology, Department Plant Sciences, Wageningen University (WUR), Wageningen, The Netherlands

Correspondence
Lilia Serrano-Grijalva, Department of Terrestrial Ecology, Netherlands Institute of Ecology (NIOO-KNAW), P.O. Box 50, Wageningen 6700 AB, The Netherlands.
Email: enzymessoft@gmail.com

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Abstract

Monitoring agriculture by remote sensing enables large-scale evaluation of biomass production across space and time. The normalized difference vegetation index (NDVI) is used as a proxy for green biomass. Here, we used satellite-derived NDVI of arable farms in the Netherlands to evaluate changes in biomass following conversion from conventional to organic farming. We compared NDVI and the stability of NDVI across 72 fields on sand and marine clay soils. Thirty-six of these fields had been converted into organic agriculture between 0 and 50 years ago (with 2017 as reference year), while the other 36 were paired control fields where conventional farming continued. We used high-resolution images from the Sentinel-2 satellite to obtain NDVI estimates across 5 years (January 2016–October 2020). Overall, NDVI did not differ between conventional and organic management during the time series, but NDVI stability was significantly higher under organic management. NDVI was lower under organic management in sandy, but not in clay, soils. Organic farms that had been converted less than ~19 years ago had lower NDVI than conventional farms. However, the difference diminished over time and eventually turned positive after ~19 years since the conversion. NDVI, averaged across the 5 years of study, was positively correlated to soil Olsen-P measured from soil samples collected in 2017. We conclude that NDVI in organic fields was more stable than in conventional fields, and that the lower biomass in the early years since the transition to organic agriculture can be overcome with time. Our study also indicates the role of soil P bioavailability for plant biomass production across the examined fields, and the benefit of combining remote sensing with on-site soil measurements to develop a more mechanistic understanding that may help us navigate the transition to a more sustainable type of agriculture.

KEYWORDS
NDVI, organic farming, Sentinel-2, transition of agriculture, yield stability

1 | INTRODUCTION

In intensive conventional farming systems, yield maximization may go at the expense of important components of soil biodiversity and their contribution to soil functioning (Matson et al., 1997; Tsiafouli et al., 2015; Walder et al., 2023; Wittwer et al., 2021). Organic agriculture has been proposed as a more sustainable alternative to current conventional agriculture, with potential benefits such as enhanced profitability and higher nutritional value, although it may produce lower yields (Reganold & Wachter, 2016; Seufert & Ramankutty, 2017; Walder et al., 2023). However, the effects on soil biodiversity and functioning of intensive agriculture may leave legacy effects in the soil that can slow down or even negate the transition to more sustainable farming systems (Mariotte et al., 2018). This could explain why the yield difference between organic and conventional agriculture appears to be strongest during the early years after the conversion from conventional to organic management (Schrama et al., 2018). If indeed land use conversion from conventional to organic needs time to adapt to a new fertilization and crop protection regime because of using organic amendments instead of artificial fertilizers, and biological plant protection instead of using synthetic chemicals, temporal biomass estimates may provide further insight into the time needed for developing organic farming soils.

While maximizing crop yield is a key goal in intensive agriculture, there is still considerable spatio-temporal variation in yield maxima (Tamburini et al., 2020). Counteracting temporal and spatial variability of yield is crucial for farmers and, currently, supplying fertilizers, artificial watering, and crop protection measures are important cornerstones of their management strategies. There is some evidence that organic and conventional farm management influence the temporal stability of crop yield differently, however, results point into opposite directions (Mäder et al., 2002; Schrama et al., 2018). This can be attributed to limited data, the small scale and short duration of studies, and the fact that most studies come from high-income countries (Seufert & Ramankutty, 2017). In a metanalysis comparing 193 studies from different countries, temporal yield stability in organic agriculture was lower than in conventionally managed lands, partly attributed to the different crop species planted and/or nutrient management regimes in both farming systems (Knapp & van der Heijden, 2018). In addition to meta-analyses, additional field studies are needed where data are collected in a systematic way. However, such an approach requires appropriate workflows for large-scale biomass data collection.

The use of satellites to monitor crops at large spatial scales is receiving increasing attention (Segarra et al., 2020). For example, the Sentinel-2 satellite generates high-resolution multispectral images at a 10 m × 10 m scale coupled with a frequent revisit rate (5–10 days). The high temporal resolution data improve accuracy by covering all different stages of crop development (Dhillon et al., 2023). This satellite data can be used to calculate vegetation indexes that, in turn, allow obtaining indirect measures of primary productivity and other vegetation parameters (Fieuzal et al., 2020; Toscano et al., 2019). One of these indices is the normalized difference vegetation index (NDVI: NIR − RED/NIR + RED). The NDVI is one of the most well known and commonly used indices in agriculture to describe the vegetative development of crops and to estimate yields. For example, Roznik et al. (2022) showed that using high-resolution satellite-derived NDVI measurements provided highly accurate crop yield estimations. Similarly, Panek et al. (2020) showed moderate to strong relationships (R^2 in the range between .35 and .81) between the NDVI and grain yield of winter wheat and triticale across three fields during two seasons. In another study in natural dryland ecosystems from the Patagonian steppes, Gaitán et al. (2013) found that NDVI was the best predictor of ecosystem-level attributes such as plant species richness and basal cover of vegetation, and that NDVI was significantly related to water infiltration and nutrient cycling indices.

In this study, we evaluated how NDVI changed over time during the transition from conventional to organic agriculture in two types of soils (marine clay and sandy soils) across the Netherlands. We used a chronosequence approach based on 72 arable farms, 36 of which had been converted from conventional to organic management between 0 and 50 years ago at the time of soil sampling (2017) (Koorneef et al., 2024; van Rijssel et al., 2022). In addition, we tested the temporal variation of NDVI during five successive growing seasons (2016–2020). This approach allowed us to compare the temporal stability of NDVI as a proxy for standing green biomass in both farming systems. We tested the following hypotheses: H1: NDVI will be higher in conventional farms, but these differences will diminish over time. H2: Organic farming will result in greater temporal stability of NDVI. H3: NDVI stability will increase during the transition from conventional to organic management. H4: NDVI will correlate positively with soil fertility, particularly soil organic matter (SOM) content and P bioavailability.

2 | MATERIALS AND METHODS

2.1 | Study sites

This study was conducted in 72 fields across the Netherlands on sandy and marine clay soils. Half of the fields were under conventional management, and the other half under organic management (Figure 1). We used a paired approach by, first, selecting organic fields of different conversion ages (between 0 and 50 years ago, taking 2017 as the reference year), and then, for each organic field, selecting a nearby conventional field to serve as a local control (van Rijssel et al., 2022). Mean annual temperatures ranged between 9.6 and 11.4°C across sites and precipitation is common throughout the year, averaging 800 to 975 mm annually. Our satellite evaluations were conducted between 2016 and 2020.

The Netherlands has agricultural landscapes with crops that are grown in rotation, and that vary in planting date, planting method, nutrient inputs (chemical fertilizers and/or liquid or solid manure) as well as different types of other management practices (e.g., till vs. no or reduced till) among farms. A minority of farms are under organic

FIGURE 1 Example of organic farm field paired with field from nearby conventional farm. Images were acquired from the Sentinel-2 satellite and processed in Google Earth Engine to obtain NDVI. Red polygon: conventional farm, blue polygon: organic farm. Green color represents greenness (NDVI). NDVI, normalized difference vegetation index.

management, so we needed to consider a substantial area in order to find fields of varying time since conversion from conventional to organic that had the same type of crop grown in the census year. In order to account for that spatial variation, for each organic field, we selected a conventional field with a comparable type of crop in 2017 to serve as a local paired control (van Rijssel et al., 2022). Further information on crops planted can be found in https://doi.org/10.5281/zenodo.7459213. We selected organic farms according to the SKAL certificate ("Stichting Keur Alternatief voortgebrachte Landbouwproducten"), a Dutch certification for organic farms based on the European legislation (www.skal.nl) (van Rijssel et al., 2022). A complete list of products allowed to combat pests and diseases under this certificate, based on the EU Regulation 2021/1165 of 15 July 2021, can be found here (https://eur-lex.europa.eu/legal-content/NL/TXT/?uri=CELEX:32021R1165).

Site selection was based on the following criteria: (1) *Soil type*: sites were situated on sandy or marine clay soils. (2) *Type of crop*: we selected sites that were predominantly cultivated with a monocotyledonous crop, preferably wheat (*Triticum aestivum*) or otherwise another cereal, a grass-clover mixture with *Trifolium* sp., or alfalfa (*Medicago sativa*). (3) *Rotation*: fields should have been under a crop rotation with tuber crops (e.g., potatoes, onions). (4) Soils should have been ploughed with an inversion plough at least once in the last 5 years before soil sampling in 2017 as inverting the soil can have a major effect on soil biota and structure.

2.2 | On-site soil characterization

We collected soil samples between June and July of 2017, which covers the peak growing season of the crops. In each field, we collected three subsamples separated by a minimum distance of 15 m. Soil samples were taken at 5 to 15 cm depth; the top 5 cm was excluded to avoid to the effects of variations in daily weather conditions (e.g., daily temperature, radiation received, frost, etc.). Soil was collected within the interior of fields to avoid the edge effect and tractor tracks. Once in the lab, soil samples were stored at 4°C until further processing. For each soil sample, we took a subsample to determine SOM content by loss-on-ignition. Samples were dried at 105°C and then placed in a muffle furnace for 8 h at 430°C. SOM content was calculated as the weight difference between samples heated at 105 and 430°C, respectively. Another subsample was used to determine pH by shaking 10 g dry weight equivalent fresh soil in 25 mL of demi water for 2 h at 250 rounds/min (Mettler Toledo). Bioavailability of phosphate was measured as Olsen-P following the methods described in Olsen (1954).

2.3 | Remote sensing data acquisition

We obtained measurements of NDVI for each farm as a proxy for green plant biomass (Abdi et al., 2021; Dedeoğlu et al., 2019). NDVI is the ratio between red and infrared wavelengths that are reflected by the plants, in this case by the different crops. This ratio is a measurement of primary productivity that is often highly correlated with crop yield. The combination of its normalized difference formulation and the use of the highest absorption and reflectance regions of chlorophyll makes it robust over a wide range of conditions (Gaitán et al., 2013; Rouse et al., 1974). NDVI ranges between −1 and 1. Negative values of NDVI (values approaching −1) correspond to water, while values closer to +1 indicate dense a green vegetation (e.g., tropical forest). Healthy vegetation primarily absorbs visible red light, while reflecting a substantial amount of near-infrared (NIR) light. In contrast, when vegetation is unhealthy or sparse, it shows lower reflectance values in the NIR band due to reduced chlorophyll content. These differences allow for the continuous, precise monitoring of green plants, such as on agricultural fields, worldwide (Defourny et al., 2019).

Each individual farm location and size were delimited using QGIS 3.20 (QGIS Development Gossau, Switzerland) based on its coordinates and given extent, using a Google Earth orthoimage with 0.30 cm resolution. The resulting polygons were imported to the Google Earth Engine platform (Gorelick et al., 2017). The Sentinel-2 mission produces high-resolution (10 meters/pixel) multispectral images coupled with a high revisit frequency (10 days at the equator, and 5 days under cloud-free conditions which results in 2–3 days at mid-latitudes). It provides valuable data for land cover change classification, atmospheric correction, and cloud/snow masks. We used cloud-free images (images with <20% of clouds). The code used to extract the NDVI data from Sentinel-2 imagery is available at: https://code.earthengine.google.com/e80e0767ae4e1f722e29c30d363ad8f1.

Given that Sentinel-2 was launched in mid-2015, we considered a 5-year period spanning from January 2016 to October 2020. We obtained all the available, cloud-free images, and data were later aggregated at different temporal scales for the different analyses. Lastly, the stability of NDVI was calculated as the inverse of the coefficient of variation by dividing the mean of NDVI during the study period by its standard deviation. We did not validate the NDVI obtained from remote sensors (i.e., Sentinel-2 satellite) with proximal platforms due to the large amount of work involved; however, previous studies have done so and have found a considerable level of agreement among the two, thus supporting our use of Sentinel-2 as our primary source of NDVI data (Panek et al., 2020; Roznik et al., 2022; Wagg et al., 2022).

2.4 | Statistical analysis

First, we used linear mixed effects models to evaluate the effect of management (i.e., conventional vs. organic), soil type (i.e., sand vs. clay), and date of observation on NDVI. In this analysis, NDVI observations were nested within fields (our replication unit), and fields within pairs to account for the repeated measures and paired design. We also used linear mixed effects models to evaluate the effect of management and soil type on NDVI stability. In this case, NDVI observations were nested within pairs to account for the paired design. For these analyses, we used the *lme* function from the *nlme* package in R.

We then used linear mixed effects models to evaluate whether the effect of management on NDVI and NDVI stability was dependent on time since conversion (based on 2017 as reference year). For this analysis, conventional fields were assigned the same age as their paired organic field. We specifically looked for significant interactions between management and time since conversion, which may be indicative of the existence of a transition period (i.e., responses of management are time-dependent). In this case, NDVI for each field was based on the average NDVI across the study period. Like in the previous analyses, we used the *lme* function from the *nlme* package in R and measurements were nested within pairs to account for the experimental design.

We also evaluated the relationship between NDVI and NDVI stability with geographical (latitude) and soil parameters (pH, SOM, and P bioavailability) measured in situ in 2017. These parameters were selected based on previous knowledge about their importance in driving plant productivity (Haverkort, 1990; Pagani & Mallarino, 2012; Ramaekers et al., 2010; Schjønning et al., 2018). For example, pH is one of the most important variables controlling nutrient availability and plant productivity. SOM and P bioavailability were considered as complementary aspects of fertility. On the one hand, organic matter can be considered as a proxy for overall long-term fertility, while soil P bioavailability (Olsen-P) can be considered as an indicator of short-term variability in a critical nutrient. Actually, soil P bioavailability has been recognized as one of the most important challenges to meet future food production goals (Elser, 2012). Other important variables were not considered either because they are highly correlated with organic C, like total N content, or because they are highly dynamic, like mineral N content, and, therefore, too transient in soils.

After this, we built a system-level model of hypothetical causal connections among management, soil type, geographical variables (latitude), soil properties, and NDVI and its temporal stability that could be tested using structural equation modelling, an approach that has been extensively used to evaluate the effects of changing agricultural management on soil and plant-related variables (Eisenhauer et al., 2015; Trivedi et al., 2017). In our model, we hypothesized that management, soil type, and geography would be the master variables controlling soil properties (pH) and fertility (SOM and Olsen P), and NDVI. We also predicted that soil properties and fertility would have a direct effect controlling NDVI. We also considered the effect of time since conversion to integrate the role of the transition period, and latitude to account for spatial effects. We decided to not include texture (e.g., sand or clay content) as this aspect was already intrinsically included in our model as soil type. When considering latitude, SOM, pH, and Olsen P simultaneously, the significant associations between latitude, SOM and pH with NDVI disappeared, and thus we decided to omit these variables from the final model. This structural equation modeling (SEM) allowed us to gain a more integrated and mechanistic system-level understanding of the effects of transitioning from conventional agriculture to organic agriculture on NDVI and its temporal stability. The model was considered robust when the *p*-value of the Fisher's *C* was greater than .05. We used a *d-sep* approach using the piecewiseSEM package in R (Lefcheck, 2016), which allows for nested experimental designs.

3 | RESULTS

3.1 | Comparison between organic and conventional on sand and clay through time

NDVI varied during the study period (i.e., 2016–2020; $F_{1,15,846}=8.47$; $p<.001$), with peaks generally found between May and July (Figures 2 and 3). NDVI was higher in sandy soils than in marine clay soils ($F_{1,70}=27.62$; $p<.001$; Figures 2 and 3). Overall, organic versus conventional management did not have a significant effect on NDVI ($F_{1,70}=1.16$; $p=.28$). However, we found a significant soil by management interaction ($F_{1,70}=6.54$; $p=.013$), which was associated with a significant effect of organic versus conventional management in sandy soils ($F_{1,24}=4.30$; $p=.049$), but not in marine clay soils ($F_{1,46}=0.71$; $p=.40$; Figure 3). In sandy soils, conventional fields had greater NDVI values than organic fields.

We also found a significant management by date of observation and soil type interaction on NDVI ($F_{1,15,846}=15.64$; $p<.001$), indicating that the effect of management on NDVI was date dependent, and that this effect varied depending on soil type (Figure 4). In sandy soils, the most negative effects of organic management on NDVI were seen between 2016 and 2018, while there were no significant effects in 2019–2020 (Figure 2). In marine clay soils, the date-dependent effect of management was, however, more variable, with periods of lower NDVI (e.g., early 2018 and early 2020) interspersed with periods of higher NDVI (e.g., early 2016) in organic fields (Figure 2).

NDVI was more stable in sandy soils than in marine clay soils ($F_{1,70}=26.33$; $p<.001$; Figures 2 and 3). The stability of NDVI did not change in response to management when all months were considered across the 2016–2020 period ($F_{1,70}=2.74$; $p=.10$). However, we found that, regardless of soil type, the NDVI of organic fields was more stable than the NDVI of conventional fields during the peak months of May, June, and July ($F_{1,70}=4.36$; $p=.04$) (Figure 2; Figure S1).

The effects of management on NDVI developed through time, as evidenced by a significant interaction between management and time since conversion ($F_{1,64}=4.87$; $p=.03$; Table 1; Figure 4). This effect was not dependent on soil type. The interaction indicated that, between years 0 and 18.5 since conversion, NDVI of organic fields was generally lower than the NDVI of conventional fields. However, after 18.5 years, the effects of organic management on NDVI turned to neutral and then positive when compared to conventional management. We did not find a significant management by time since conversion interaction in the case of the temporal stability of NDVI during the 5 years of observations ($F_{1,64}=1.60$; $p=.21$; Table 1; Figure 4).

3.2 | Relationships between NDVI and soil conditions

NDVI, averaged across the 5 years of study period, was positively associated with soil P bioavailability, organic matter content, and

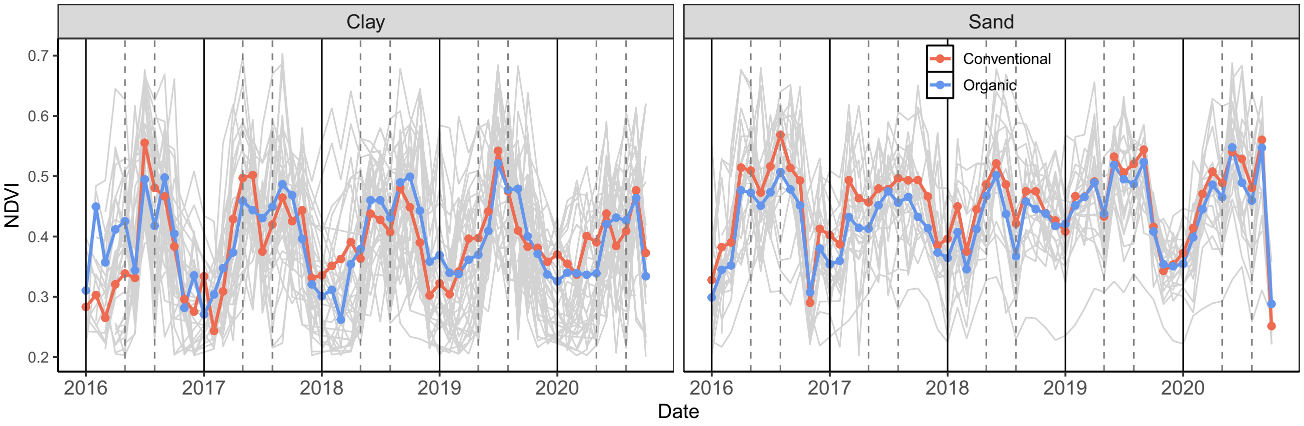

FIGURE 2 Mean NDVI of farms depending on management (conventional and organic) and soil type (marine clay and sand) across the time series (January 2016–October 2020). NDVI data were averaged by month to ease visualization. Grey lines represent individual fields. Red dashed lines indicate the period of May–July, considered as the peak growing season. NDVI, normalized difference vegetation index.

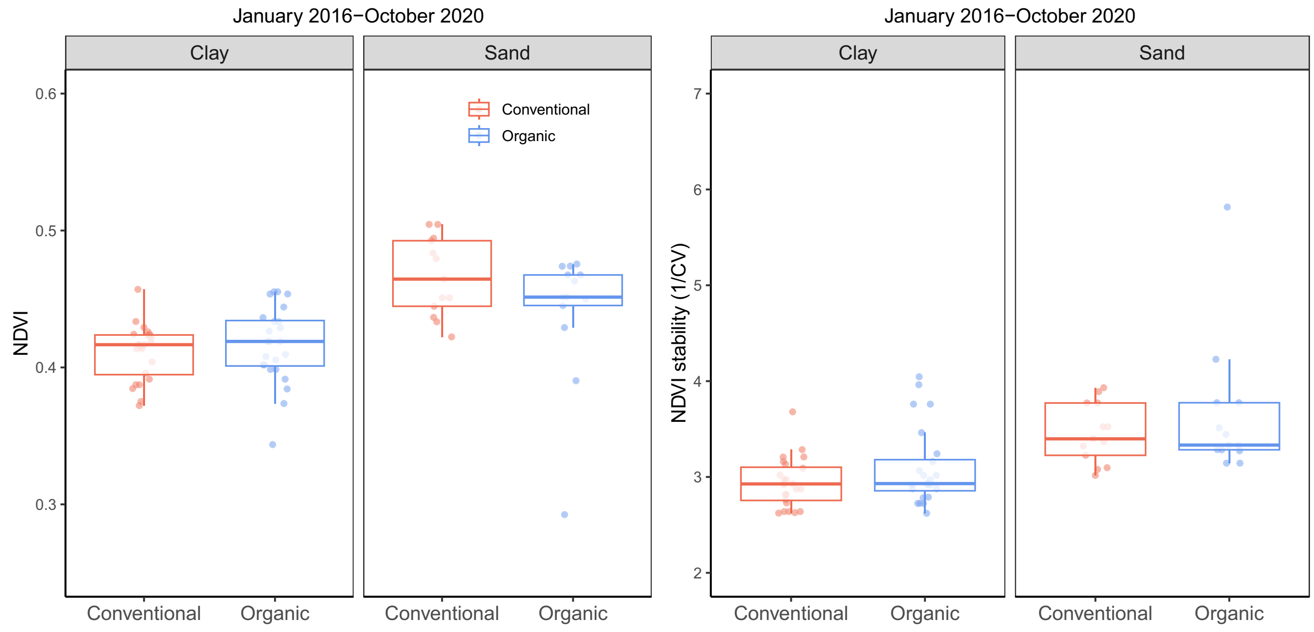

FIGURE 3 Boxplots of the effects of conventional and organic management, and soil type (marine clay and sand) on NDVI (left panel) averaged (based on individual observations) across the 5 years of study (2016–2020) and its temporal stability (right panel). Individual dots indicate fields. NDVI, normalized difference vegetation index.

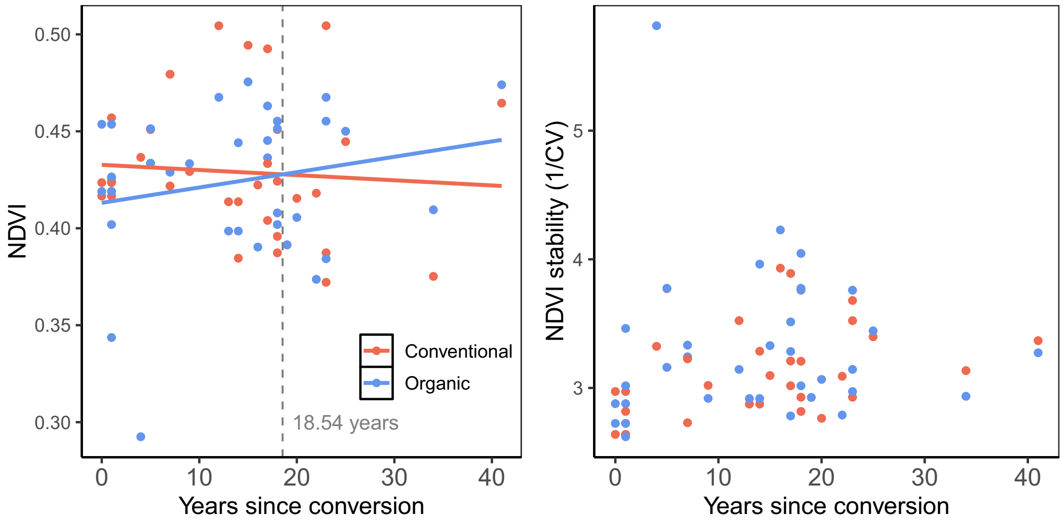

FIGURE 4 Effects of time since conversion on NDVI (left panel) and its temporal stability (right panel) depending on management. Regression lines associated with management indicate a significant management by time since conversion interaction. CV, coefficient of variation; NDVI, normalized difference vegetation index.

negatively with soil pH (Figures 5 and 6). However, its temporal stability showed a positive relationship with pH and a marginally significant negative relationship with soil P bioavailability (Figures 5 and 6). NDVI was also greater in northern than in the southern locations.

We integrated this information within a causal framework using SEM (Table S1; Figure 6). This analysis provided overall support for the lack of (negative) effects of organic agriculture on NDVI, for the important role of soil type in driving NDVI, and for a possible role of soil P bioavailability driving NDVI but not NDVI stability. Our SEM suggested that soil type may have had additional indirect effects on NDVI by controlling soil P bioavailability. Therefore, our results suggested that several soil factors may control NDVI simultaneously.

Our system-level SEM approach also supported that, when data were pooled across the 5 years of study period, time since conversion influenced NDVI. However, there was no evidence that the time since conversion influenced NDVI stability. In other words, the stability of NDVI remained relatively high under organic farming

TABLE 1 Effects of management (i.e., conventional vs. organic), soil type, and time since conversion on NDVI and its stability.

	numDF	denDF	NDVI		NDVI stability	
			F-value	*p*-Value	*F*-value	*p*-Value
Management	1	64	0.342	.561	2.243	.139
Soil type	1	64	26.546	**<.001**	40.392	**<.001**
Time since conversion	1	64	0.930	.338	0.034	.854
Management:soil type	1	64	5.594	**.021**	0.039	.844
Management:time since conversion	1	64	4.304	**.042**	1.810	.183
Soil type:time since conversion	1	64	8.412	**.005**	7.526	**.008**
Management:soil type:time since conversion	1	64	0.797	.375	0.408	.525

Note: Results are based on linear mixed models. Numbers in bold indicate $p < .05$.

Abbreviation: NDVI, normalized difference vegetation index.

regardless of time since conversion. Our SEM approach also indicated a greater NDVI stability under organic farming.

4 | DISCUSSION

In this study, we evaluated changes in NDVI and its temporal stability for 5 years (2016–2020) across 36 Dutch fields that were converted from conventional to organic management, and their paired conventional fields. We found that in fields that were converted more recently, particularly on sandy soils, NDVI was lower under organic than under conventional management. However, as time passed, this reduction diminished and was eventually reverted, indicating the potential of organic soils to sustain biomass production at levels that are equal to conventionally managed soils. These results may also indicate a learning curve for farmers when transitioning to organic farming. If NDVI can be used as a satellite-derived proxy of biomass, and when the biomass measured as NDVI correlates with yield, our results indicate the importance of supporting farmers during these critical early years of transition to organic farming. Our SEM analysis also suggests the important role of soil properties in driving productivity, particularly soil P bioavailability. This suggests opportunities to link on-site collected data with satellite imagery when understanding the transition from conventional to organic agriculture. Finally, we also demonstrated that organic farming results in more stable NDVI during the peak season, which is frequently considered as an advantage for farmers, particularly during stressful years, for example, due to extreme weather conditions (de Vries et al., 2012).

4.1 | NDVI performance between 2016 and 2020

In agreement with our predictions, NDVI varied greatly during the study period regardless of management and soil type. This variability can be partly attributed to the presence of bare soil after cash crops were harvested (Abdi et al., 2021), to different crops planted, as well as to seasonal and interannual climatic variability. The fact that organic systems showed greater stability is similar to results by Schrama et al. (2018) from a long-term farming field trial on one single experimental farm with limited spatial replication. The increased temporal stability on that organic farming system was suggested to be related to improved soil conditions (Schrama et al., 2018). In addition, the greater stability in organic systems may be associated with the tendency of organic farms to use cover crops more widely.

In contrast to the overall effects of management on NDVI stability, we did not find overall significant effects of organic versus conventional management on NDVI across the study period. This is in contrast to other studies showing negative effects of organic management on yield (Knapp & van der Heijden, 2018; Seufert & Ramankutty, 2017). The lack of effects may be attributed to the fact that our study spanned a wide range of locations under contrasting soil conditions and across a representative time period, which may compensate potential site-level effects. This is supported by the fact that we found a significant negative effect of organic management on NDVI when sandy soils were analyzed separately. Our results suggest the importance of considering soil type when planning transitioning from conventional to organic agriculture for a more informed decision and to establish realistic expectations.

4.2 | Changes in NDVI during conversion

In support of our hypothesis, organic fields generally showed lower NDVI during the early years after conversion, but then this difference disappeared around approximately 19 years since conversion, after which the effects of organic farming on NDVI turned positive. This effect occurred regardless of soil type, indicating a more general phenomenon. In organic systems, productivity might have been enhanced through the years by multiple actions taken by farmers, including: (i) the use of different organic amendments, such as compost, that increase SOM content (Hartmann et al., 2015; Lotter et al., 2003); (ii) a greater proportion of time during which the soil is covered (including by cash crops, cover crops, forage leys or mulching), thus providing habitat for soil microorganisms (Garland et al., 2021); (iii) the use of multispecies cover crops (Chu et al., 2017); (iv) the implementation of more diverse crop rotations (Barbieri et al., 2017); (v) and changes in

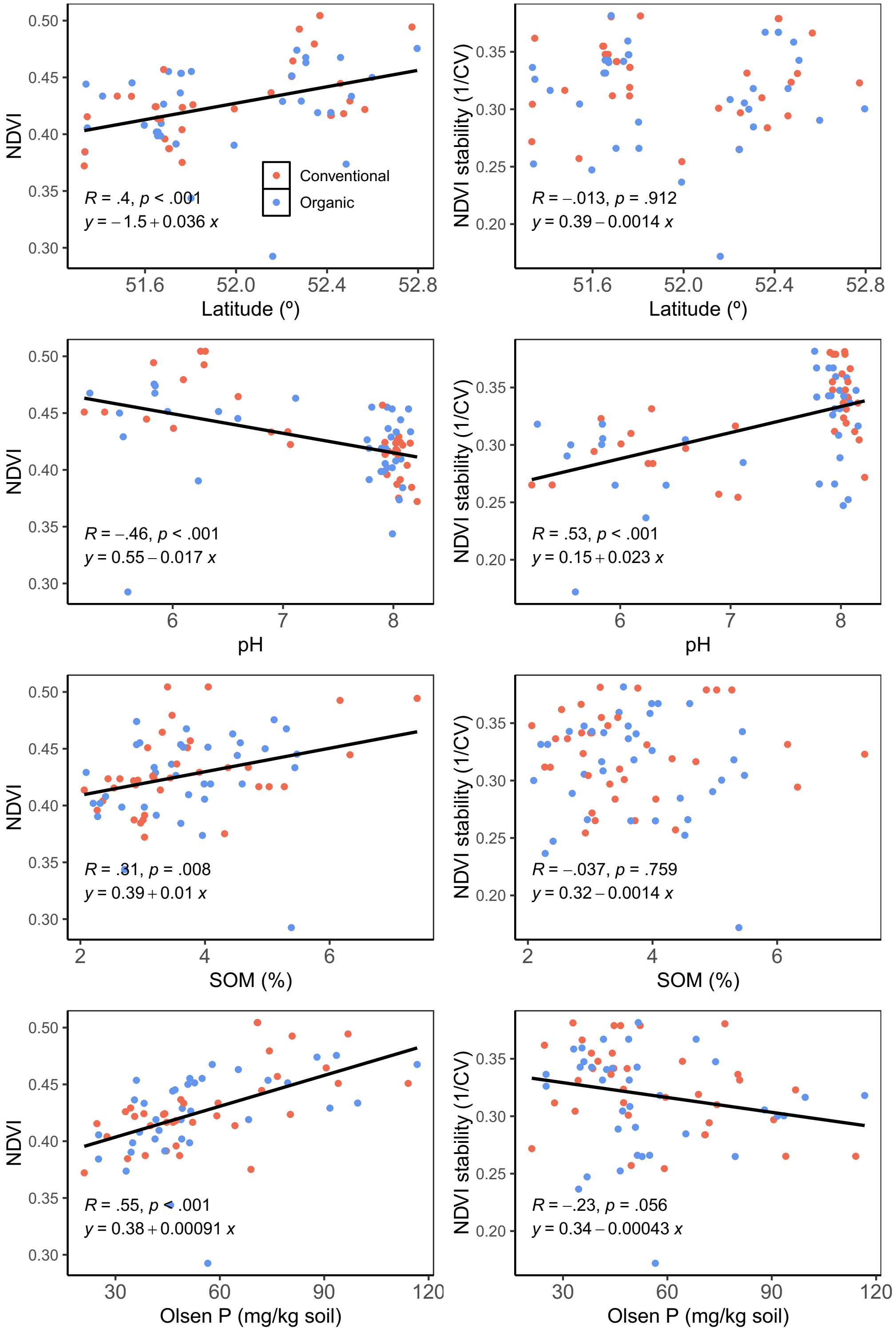

FIGURE 5 Relationships between latitude and soil properties, and NDVI (left panel) and its temporal stability (right panel). Regression lines indicate significant associations. Red dots = conventional management, blue dots = organic management. NDVI, normalized difference vegetation index.

the cash crops planted. For example, in one study, up to one third of difference in production between organic and conventional systems could be explained by the type of crops planted (Barbieri et al., 2019). Our results using NDVI across 72 farms are also similar to Schrama et al. (2018), who found that yields under organic farming were initially lower, but that they approached those of conventional systems after 10–13 years since conversion, while requiring lower nitrogen inputs and leaching less nitrogen to the ground water.

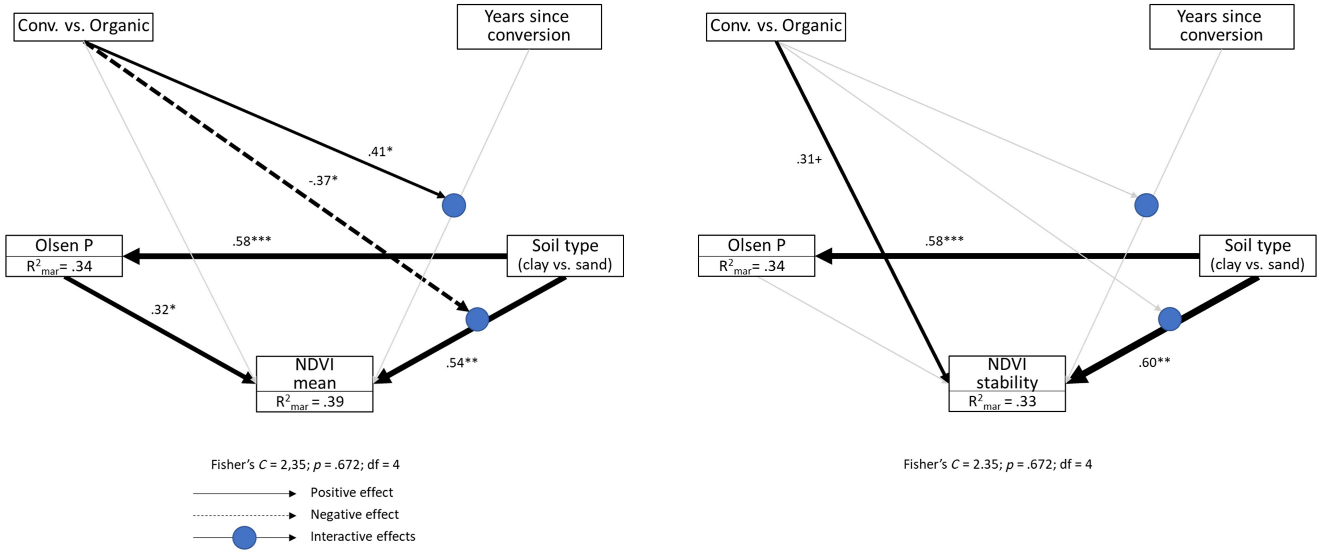

FIGURE 6 Structural equation models depicting predicted mechanistic links among management, soil type and properties, and NDVI (averaged across the study period) and its temporal stability. Black and grey lines indicate significant ($p < .1$) and non-significant effects, respectively. Solid arrows indicate positive links, while dashed arrows indicate negative ones. df = degrees of freedom. $^{+}p < .1$; $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$. All the coefficients can be found in Table S1. NDVI, normalized difference vegetation index.

4.3 | NDVI and NDVI stability and their relationship with soil properties

As initially predicted, NDVI was highly associated with soil properties measured on-site. We found positive relationships between NDVI and soil P bioavailability, measured as Olsen P, and SOM content, and a negative relationship with soil pH. However, the role of SOM and pH in driving NDVI disappeared when integrated within the framework of SEM, indicating that the positive effects of P may be more linked to its role as a limiting nutrient. The stability of NDVI was, in contrast, not affected by soil parameters, particularly when considered within the mechanistic framework of SEM. Our results, therefore, suggest the important role of soil P bioavailability in driving crop biomass, which is in agreement with other studies demonstrating the limiting role of this element for plant production (Peñuelas & Sardans, 2022; Vitousek et al., 2009). For example, Whetton et al. (2017) used a nonparametric modelling approach to demonstrate that soil P, together with K, was one of the main drivers of NDVI across a 18 ha wheat field in the UK. Actually, it has been suggested that P will become increasingly important for agriculture (Bai et al., 2023; Zou et al., 2022), particularly as mineral reserves become globally depleted and crops rely increasingly more on the local soil bioavailability of P, either naturally contained in minerals or as part of organic matter (Cooper et al., 2011; Cordell et al., 2009; Zou et al., 2022). In our study, greater soil P bioavailability was higher in slightly acidic and neutral soils (i.e., in our sandy soils) as compared with alkaline soils, which is also in agreement with previous evidence linking soil P bioavailability and pH (Sorn-Srivichai et al., 1984). Our results thus suggest that, in addition to shifting to organic management, an additional alternative for farmers to increase their long-term yields may involve increasing soil P solubilization by the addition of P-solubilizing rhizobacteria (De Zutter et al., 2022; Dinesh et al., 2022; Pereira & Castro, 2014), inoculating with mycorrhizal fungi (Köhl et al., 2016), or by promoting practices that lower the pH in naturally alkaline soils. Such practices may include the addition of organic amendments (Rolando et al., 2023), which is also compatible with organic farming.

Despite these findings, in our study, we did not have on-site validations in terms of grains, vegetables, or fruits produced. Moreover, we did not consider other parameters during the transition from conventional to organic agriculture such as the quality of crops, including their nutritional quality. However, this is admittedly an important aspect that cannot be evaluated based on remote sensing techniques and that would require on-site evaluations. In addition, we did not focus on a single type of crop because, due to the heterogeneity of agricultural landscapes, this was not possible. For example, while we considered monocot-dominated crops, there were different species and cultivars, as well as grass-leguminous mixtures involved in our study during the field campaign in 2017. When analyzing NDVI, we were able to consider a time series of 5 years, which allowed us to cover a typically narrow rotation cycle in all fields, thus including effects of a wider variety of crop species. While fallowing is not a regular practice in Dutch farms, we did not have information regarding differences in terms on possible fallowing, which might have accounted for undetected cumulative differences in crop yields between managements. Moreover, we used a space-for-time substitution approach when evaluating the time needed to revert the negative effects of transitioning to organic agriculture, for which we necessarily attributed the same conversion age to conventional and organic fields. However, the data collected may not be enough to study the relationship among parameters over time in a single farm. Additionally, as the farms are located in the Netherlands with relatively similar annual temperatures and precipitation (although there are gradients from coast to inland and from south to north, which is why we took the approach of pairing organic fields with nearby conventional fields), other factors such as climate and soil type may need to be considered when these relationships are studied across wider regions. Despite these limitations, the present study provides novel insights into changed productivity during the transition from conventional to organic agricultural management.

5 | CONCLUSION

We showed that, opposite to widespread claims, long-term organic management resulted in comparable NDVI values (used as a proxy of green biomass, in turn used as a proxy of yield) across 36 farms that were converted from conventional to organic agriculture. In our comparison, each organic field was paired with a nearby conventional field. In this comparison, conversion to organic agriculture increased NDVI stability during the growing season. Moreover, we found that, despite negative effects of organic management on NDVI early after the conversion, organic management may even result in consistently greater NDVI than conventional management, and thus perhaps yields, once the transition period of almost two decades has been overcome. Our analyses suggested that the legacy effects of conventional farming on organic soils may involve a transition of ~19 years under conditions of agriculture in The Netherlands, and thus the potential of organic soils to sustain biomass production at levels that are equal to conventionally managed soils. We also showed that NDVI was highly dependent on soil type, which appeared to be partly attributed to between-site variations in soil P bioavailability. The strong link between NDVI and soil properties like Olsen P indicates the potential of combining satellite-derived data with on-site collected information to drive the informed transition of agriculture towards enhanced sustainability. This type of system-level knowledge may help farmers develop a science-based predictive framework during the sustainable transition towards a more sustainable agriculture. Moreover, the strong association between NDVI and soil P also suggests the importance of developing nature-based strategies that naturally enhance the bioavailability, and the internal recycling, of this critical element. However, this will only be possible when soils have sufficiently high total P levels, either as part of organic matter or in the form of minerals. Finally, our results point out that the conversion from conventional to organic agriculture may be a long-term process easily taking almost two decades, provided that obtaining the same yield levels as in conventional farms would be the only benchmark for comparison.

AUTHOR CONTRIBUTIONS

Lilia Serrano-Grijalva: Conceptualization; formal analysis; methodology; visualization; writing – original draft; writing – review and editing. **Raúl Ochoa-Hueso:** Conceptualization; formal analysis; methodology; visualization; writing – original draft; writing – review and editing. **G. F. (Ciska) Veen:** Investigation; writing – review and editing. **Irene Repeto-Deudero:** Formal analysis; methodology; visualization; writing – review and editing. **Sophie Q. Van Rijssel:** Investigation; methodology; writing – review and editing. **Guusje J. Koorneef:** Investigation; methodology; writing – review and editing. **Wim H. Van der Putten:** Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are available in Zenodo: https://doi.org/10.5281/zenodo.7459213. All figure and map outputs are included in S1.

ORCID

Lilia Serrano-Grijalva https://orcid.org/0000-0002-2530-4719
Raúl Ochoa-Hueso https://orcid.org/0000-0002-1839-6926

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SUPPORTING INFORMATION

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