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THE EFFECT OF CROP ROTATION, TILLAGE, RESIDUE MANAGEMENT AND N FERTILIZATION RATE ON WINTER WHEAT GROWTH AND DEVELOPMENT, EVALUATED WITH AN OPTICAL SENSOR

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ABSTRACT

Crop growth and development, as well as yield, are the result of the efficiency of the chosen agricultural management system within the boundaries of the agro-ecological environment. End of season yield results do not permit the evaluation of within season management interactions with the production environment and do not allow for full understanding of the management practice applied. Crop growth and development were measured during the 2017, 2018 and 2019 crop cycles with an optical handheld NDVI sensor for all plots of the different management treatments of a long-term (since 2015) sustainability trial. Cropping systems varying in (1) crop rotation [winter wheat (*Triticum aestivum* L.) after maize (*Zea mays* L.), winter wheat (*Triticum aestivum* L.) after sunflower (*Helianthus annuus* L.) and winter wheat (*Triticum aestivum* L.) after winter pea (*Pisum sativum* L.)], (2) tillage (chisel tillage vs. no tillage), (3) residue management (chopped vs. anchored) and (4) N fertilization rate (N_0, N_{50}, N_{100} and N_{150}) were compared. The NDVI handheld sensor was evaluated as a tool to monitor crop growth and development and was found to be an excellent tool for this purpose. The measurement with the handheld sensor was non-destructive and fast so that representative plot area could be measured easily and time efficiently. Crop rotation influnced early crop growth, with lower NDVI values for crops sown after maize and sunflower than crops after pea. The differences between the rotations diminished later in the growing season, and there was no advers effect on final yield. Fertilization rate significantly increased the NDVI values compared to non-fertilized plots. No tillage with residue retention, chopped or anchored, was characterized by a slower initial growth than chisel tillage practices, but this was compensated for by increased crop performance in the later stages. The results indicated that different rotation, tillage, residue management and N fertilization rate practices influence crop growth and development. It is important to monitor and understand crop growth under different management systems to select the right varieties and adjust timing and practice of input supply in each cropping system.

Keywords: crop rotation, no tillage, NDVI handheld sensor, residue management, N fertilization rate, crop growth and development.

INTRODUCTION

Spectral reflectance of a crop differs considerably in the near infrared region (λ=700-1300 nm) and in the visible red range (λ=550-700 nm) of the electromagnetic spectrum (Kumar and Silva, 1973). Plants generally have low reflectance in the blue and red portion of the spectrum, because of chlorophyll absorption, with a slightly higher reflectance in the green. Near infrared radiant energy is strongly reflected from the plant surface and the amount of reflectance is determined by the optical properties of the leaf tissues: their cellular structure and the air-cell wall-protoplasm-chloroplast interfaces (Kumar and Silva, 1973). These anatomical characteristics are affected by environmental factors such as soil moisture, nutrient status, soil salinity and leaf stage (Ma et al., 2001). The contrast between vegetation and soil is at a maximum in the red and near infrared region. Therefore, spectral reflectance data can be used to compute a variety of vegetation indices, which are well correlated with agronomic and biophysical plant parameters related to photosynthetic activity and plant productivity (Adamsen et al., 1999). The normalized difference vegetative index (NDVI) has been successfully used in

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predicting photosynthetic activity, because this vegetation index includes both near infrared and red light.

Crop growth and development as well are integrated evaluators that show the efficiency of the chosen agricultural management system within the boundaries of the agro-ecological environment. Any crop cultivar, that has been selected for the given agro-ecological zone, will act as an integrated evaluator of all environmental factors, thus showing how management influences and determines resource-use efficiency. Yields can be measured as an end of season static result of seasonal crop performance, but these results do not reflect the fluctuations of the crop`s performance throughout the season. In order to understand and evaluate cropping systems and to fine tune resource management, insight in crop performance over time is decisive.

The effect of management factors, such as crop rotation, tillage systems, crop residue management and N fertilization rate on crop development during the crop cycle has not been studied intensively yet. Therefore, crop performance was measured during the 2017, 2018 and 2019 crop cycles with an optical handheld NDVI sensor, in the different management treatments of a long-term sustainability trial, which was initiated in 2015 at NARDI Fundulea.

The objective of this long-term trial was to identify practices that would assure high and stable winter wheat yields in the target environment. The treatments combined different crop rotations (winter wheat after maize, winter wheat after sunflower and winter wheat after winter pea), tillage practices (zero tillage compared to chisel tillage), residue management (residue chopped and anchored), and N fertilization rate (0, 50, 100 and 150 kg a.i. ha^{-1}).

This study is intended to assess crop growth and development dynamics, as affected by the different rotation, tillage, residue management and N fertilization practices, throughout the growing season, to supplement normal postseason yield evaluation, and to evaluate the NDVI handheld sensor (GreenSeeker®Trimble Navigation Limited, Sunnyvale, CA) as a tool for crop monitoring.

MATERIAL AND METHODS

The experimental site

The measurements were carried out in a long-term polyfactorial experience within the multidisciplinary research platform based on conservation agriculture from NARDI Fundulea, situated at 44º27′45″ latitude and 26º31′35″ longitude, East of Romanian Danube Plain and East of Fundulea town. The soil is a cambic chernozem and has good chemical and physical conditions for farming. The major limitations are periodic droughts, periodical water excess, and wind and water erosion. The mean annual temperature is 10.9ºC (1960-2018) and the average annual rainfall is 587 mm y^{-1}, with approximately 417 mm, registered between October and June (234 mm falling in the cold season, between October and March, and 183 mm falling in the warm season, between April and June).

The cold season of the crop cycle 2016/2017 was characterised by a pluviometric regime almost similar to the long-term normal one, with the exception of December (Table 1). Starting with April, the precipitation regime became very abundant, way over the multi-annual means. In 2017/2018 fall, the precipitations exceeded the long term means in all months, except in December, so contributing well to the water supply of the deep soil levels for the next growing season. In April and the first half of May, the precipitation amounts were much lower than the multiannual means. In 2018/2019 cycle, the pluviometric regime in the cold season was amounted under the multi-annual average, however starting with April, it became very abundant. Essentially, the three experimental years were very variable as agro-meteorological conditions for testing the growth and development of winter wheat crop.

Table 1. Comparison of meteorological data during winter wheat growing cycles at Fundulea for 2016/2017, 2017/2018 and 2018/2019

Month	Temperature (ºC)			Rainfall (mm)		
	2016/2017	2017/2018	2018/2019	2016/2017	2017/2018	2018/2019
October	10.3	11.7	13.4	74.4	111.6	23.4
November	5.7	7.0	5.2	48.8	49.2	35.0
December	-0.3	3.6	0.1	0	27.8	43.0
January	-5.5	0.8	-1.2	35.4	36.0	53.8
February	-0.03	1.6	3.8	50.5	58.6	21.4
March	8.5	3.3	9.3	47.5	40.6	22.4
April	10.6	15.8	11.2	118.4	2.4	51.4
May	16.8	19.4	17.2	65.8	34.0	124.2
June	22.2	22.6	22.8	96.4	120.8	74.6
Total rainfall (mm)				537.2	481.0	449.2

Research information

The experimental design consisted of a randomized complete block, with split-split plot arrangement, and three replications. The big plots, representing crop rotation [winter wheat (W) after maize (M), winter wheat (W) after sunflower (S), and winter wheat (W) after winter pea (P)], were randomized each year, but the middle plots - with the tillage application [chisel tillage (C) and no tillage (N)], small plots - with crop residues [chopped (Ch) and anchored (A)], and very small plots - with nitrogen rates (N_0, N_{50}, N_{100} and N_{150}) were maintained in the same place each year.

Certified seed was planted with the twenty-four row TUME Nova Combi 3000 (Noka-Tume Oy, Turenky, Finland) seed drill with 12.5 cm row spacing with a rate of 500 viable grains per square meter. The size of plots was 24 m² at sowing and 16 m² at harvesting. Seeding took place on Nov. 01 in 2016, Oct. 17 in 2017 and Oct. 10 in 2018.

Nitrogen fertilization was performed by broadcasting on an uniform Phosphorous fertilization base, half of dose in early spring and the other half at 1st node growth stage. For weed control, appropriate and available herbicides were used, when was needed, and no disease or insect pest control was utilized.

Plots were harvested with Wintersteiger Delta (Wintersteiger AG, Ried, Austria) harvester on July 21 in 2017, July 16 in 2018 and July 31 in 2019. Results regarding grain yield are reported at the 14% standard moisture.

A GreenSeeker® Handheld Optical Sensor Unit (Trimble Navigation Limited, Sunnyvale, CA) was used to collect NDVI measurements. This device uses a patented technique to measure crop reflectance and to calculate NDVI. The unit senses a 0.25 (0.50) x 0,01 oval spot when held at a distance of approximately 0.6 to 1.2 m from the illuminated surface. The sensed dimensions remain approximately constant over the height range of the sensor. The sensor unit has self-contained illumination in both the red (650 ± 10 nm full width half magnitude (FWHM)) and near infra red (NIR) (770 ± 15 nm FWHM) bands. The device measures the fraction of the emitted light in the sensed area, which is returned to the sensor (reflectance). These fractions are used within the sensor to compute NDVI according to the following formula:

$$NDVI = (NIR-VIS) / (NIR+VIS)$$

where: NIR is the fraction of emitted NIR radiation returned from the sensed area (reflectance), VIS is the fraction of emitted visible red radiation returned from the sensed area (reflectance). The sensor takes readings at a very high rate (approximately 1000 measurements per second) and averages measurements between outputs. The sensor outputs NDVI at a rate of 10 readings per second. The sensor was passed over the crop at a height of approximately 0.6 m above the crop canopy and oriented so that the 0.25 m sensed width was perpendicular to the row and centred over the row. With advancing stage of growth, sensor height above the ground increased proportionally. Travel velocities were at a slow speed of approximately 1.0 ms^{-1}, permitting the sensor to accumulate multiple readings, and finally showing the mean of all readings on the whole plot length (8 m).

The experiment was analyzed using ANOVA for randomized complete block design, with factorial combination of rotation, tillage/seeding methods, crop residue management and N fertilization rate. The significant differences were separated by Duncan's new multiple range test. Significant differences were accepted at $p<0.05$ (Steel and Torrie, 1980).

RESULTS AND DISCUSSION

The average NDVI values were plotted against time for all treatments (crop rotation, tillage and residue management) of the three winter wheat crop cycles: 2017 [Figure 1 (a-d)], 2018 [Figure 2 (a-d)] and 2019 [Figure 3 (a-d)], for each nitrogen fertilization rate (N_0, N_{50}, N_{100} and N_{150}), applied on an uniform phosphorous fertilization base.

Generally, the NDVI values gradually increased with time until a maximum was reached, before starting to decrease. NDVI measurements provide a representation of a canopy expansion and senescence curve for winter wheat. The obtained plant growth and development curves (GDC) were characterized by 2 parameters: slope of the initial increase and maximum value of the GDC.

The GDC and their parameters obtained in 2017 for the variants under this study, within in the four conditions of nitrogen fertilization are presented in Figure 1 (a-d) and Table 2.

In 2017, in no-fertilization conditions (N_0), the GDC slopes were significantly influenced by soil tillage ($p<0.05$) and crop residue management ($p<0.001$), but the crop rotation had a non significant role ($p>0.05$) (Table 2). Considering the means, the steepest slopes were registered for the variants after M, significantly higher for N and Ch variants. The GDC slopes values were comprised between 0.003 and 0.011 values. The highest slopes were registered for the variants MNCh and SCCh (0.011), which were not significantly higher than the slopes of MNA (0.009), MCCh (0.008), PNCh (0.008) and PNA (0.008), but significantly higher than the slopes of the other variants (Table 2; Figure 1.a).

Table 2. Winter wheat growth and development curve (NDVI vs. days after sowing) slope and maximum for the 2017 crop cycle in the long-term trial NARDI Fundulea

N fertilization rate	N_0		N_{50}		N_{100}		N_{150}	
Treatment	Slope	Maximum	Slope	Maximum	Slope	Maximum	Slope	Maximum
MCCh	0.008 abc	0.683 C	0.006 a	0.850 A	0.007 a	0.867 A	0.004 a	0.863 AB
MCA	0.003 f	0.630 E	0.005 a	0.837 AB	0.005 ab	0.863 A	0.005 a	0.867 A
MNCh	0.011 a	0.633 DE	0.010 a	0.813 BC	0.008 a	0.850 AB	0.008 a	0.867 A
MNA	0.009 ab	0.687 BC	0.008 a	0.827 ABC	0.006 ab	0.843 ABC	0.005 a	0.870 A
SCCh	0.011 a	0.667 CD	0.007 a	0.807 BC	0.006 ab	0.803 D	0.006 a	0.847 AB
SNA	0.004 ef	0.650 CDE	0.003 a	0.800 C	0.006 ab	0.817 CD	0.005 a	0.850 AB
SNCh	0.007 bcd	0.657 CDE	0.007 a	0.807 BC	0.008 a	0.827 BCD	0.007 a	0.843 B
SNA	0.007 bcd	0.680 C	0.005 a	0.827 ABC	0.007 a	0.827 BCD	0.005 a	0.857 AB
PCCh	0.005 def	0.817 AB	0.003 a	0.850 A	0.007 a	0.843 ABC	0.005 a	0.840 B
PCA	0.006 cde	0.827 AB	0.004 a	0.863 A	0.004 b	0.843 ABC	0.006 a	0.853 AB
PNCh	0.008 abc	0.830 A	0.006 a	0.857 A	0.007 a	0.847 AB	0.007 a	0.860 AB
PNA	0.008 abc	0.827 AB	0.004 a	0.853 A	0.006 ab	0.853 AB	0.006 a	0.860 AB

Rotation	ns	**	ns	*	ns	**	ns	ns
Tillage	*	ns	ns	ns	ns	ns	ns	ns
Residue	**	ns	ns	ns	*	ns	ns	ns
Rotation x Tillage	ns	ns	ns	*	ns	*	ns	ns
Rotation x Residue	ns	ns	ns	ns	ns	ns	ns	ns
Tillage x Residue	*	*	ns	ns	ns	ns	ns	ns
Rotation x Tillage x Residue	ns	*	ns	ns	ns	ns	ns	ns

Management practice with the same letter are not significantly different for the indicated N fertilization rate ($p<0.05$).
* = $p<0.05$, ** = $p<0.01$, *** = $p<0.001$, ns = not significant.

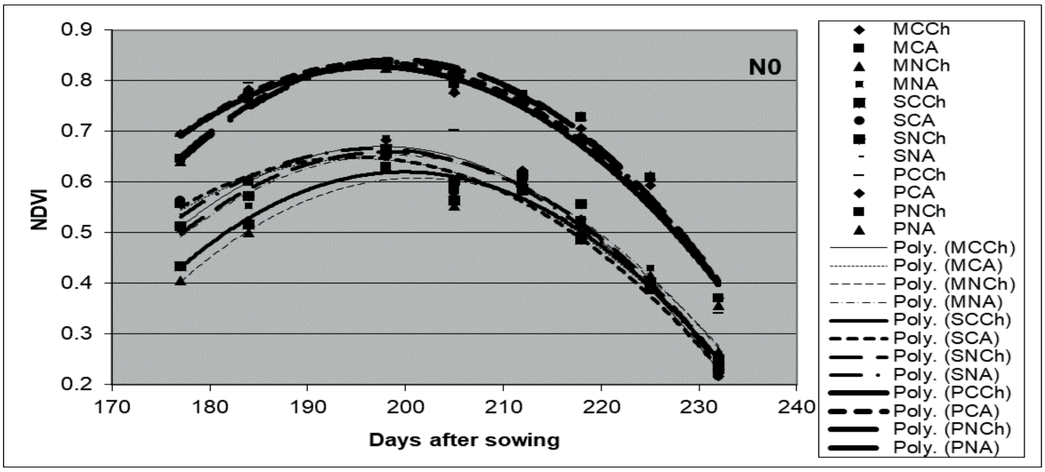

Figure 1.a. NDVI-based growth and development curve (NDVI vs. days after sowing) for 2017 winter wheat crop cycle in the long-term sustainability trial NARDI Fundulea. Crop sequence (first letter): M yearly rotation of wheat with maize, S yearly rotation of wheat with sunflower, P yearly rotation of wheat with pea. Tillage system (second letter): C chisel tillage, N no tillage. Residue management (third letter): Ch keep all residue chopped on the field. A keep all residue anchored on the field. Nitrogen rate: N_0 without fertilization

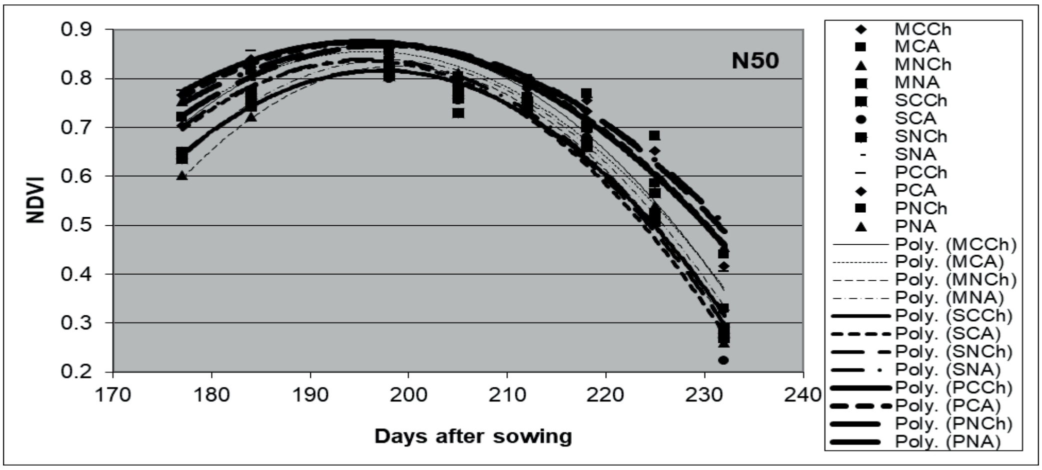

Figure 1.b. NDVI-based growth and development curve (NDVI vs. days after sowing) for 2017 winter wheat crop cycle in the long-term sustainability trial NARDI Fundulea. Crop sequence (first letter): M yearly rotation of wheat with maize, S yearly rotation of wheat with sunflower, P yearly rotation of wheat with pea. Tillage system (second letter): C chisel tillage, N no tillage. Residue management (third letter): Ch keep all residue chopped on the field. A keep all residue anchored on the field. Nitrogen rate: N_{50} - 50 kg N a.i. ha^{-1}

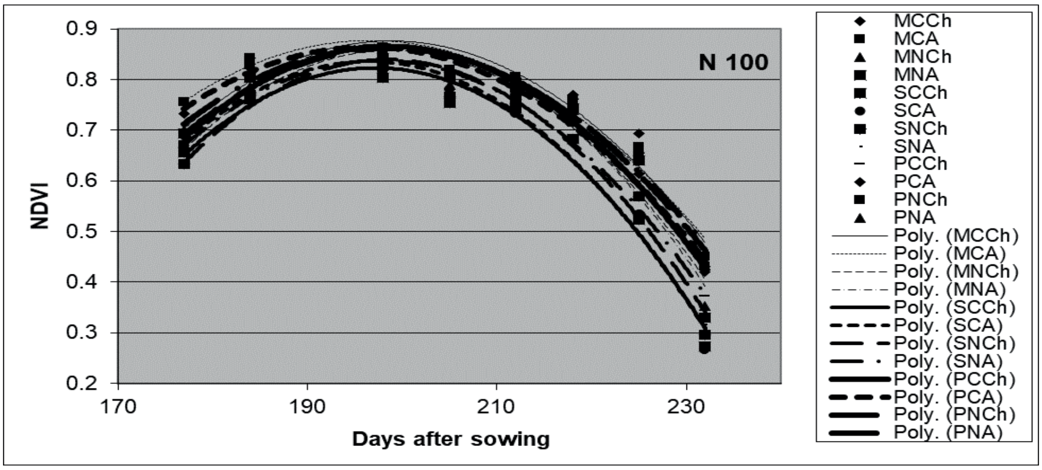

Figure 1.c. NDVI-based growth and development curve (NDVI vs. days after sowing) for 2017 winter wheat crop cycle in the long-term sustainability trial NARDI Fundulea. Crop sequence (first letter): M yearly rotation of wheat with maize, S yearly rotation of wheat with sunflower, P yearly rotation of wheat with pea. Tillage system (second letter): C chisel tillage, N no tillage. Residue management (third letter): Ch keep all residue chopped on the field. A keep all residue anchored on the field. Nitrogen rate: N_{100} - 100 kg N a.i. ha^{-1}

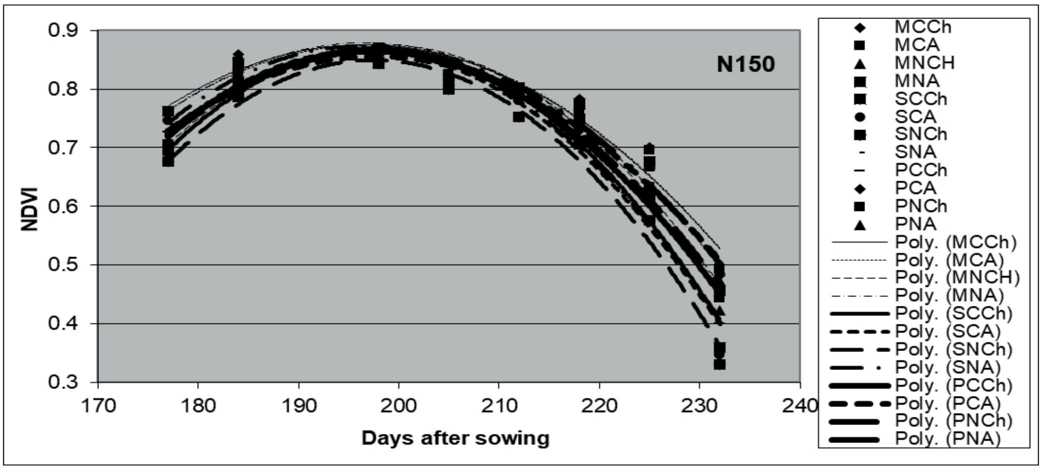

Figure 1.d. NDVI-based growth and development curve (NDVI vs. days after sowing) for 2017 winter wheat crop cycle in the long-term sustainability trial NARDI Fundulea. Crop sequence (first letter): M yearly rotation of wheat with maize, S yearly rotation of wheat with sunflower, P yearly rotation of wheat with pea. Tillage system (second letter): C chisel tillage, N no tillage. Residue management (third letter): Ch keep all residue chopped on the field. A keep all residue anchored on the field. Nitrogen rate: N_{150} - 150 kg N a.i. ha^{-1}

The GDC maximums were significantly influenced by crop rotation ($p<0.01$), the highest being after P in comparison with after M and S (Table 2). Soil tillage and crop residue management had a nons ignificant influence ($p>0.05$). The GDC maximum values ranged between 0.630 and 0.830, the greatest value PNCh (0.830) being not significantly higher than those of the variants PNA (0.827), PCA (0.827) and PCCh (0.817) (Table 2; Figure 1.a).

In conditions of fertilization with 50 kg N a.i. ha^{-1} (N_{50}), the GDC slopes were non-significantly influenced by all factors under this study (Table 2). The GDC slopes showed values between 0.003 and 0.010. The steepest slope was registered for the variant MNCh (0.010), but its value was not significantly positive when it is compared to the other variants (Table 2; Figure 1.b). The GDC maximums were significantly influenced by crop rotation ($p<0.05$). In mean, after P were recorded maximums significant higher than after S, but the respective values were non significant for after M (Table 2). Soil tillage and crop residue management did not influence significantly the GDC maximums ($p>0.05$), showing values between 0.800 and 0.863. The highest maximum, registered for the variant PCA (0.863), did not differ significantly from those of the variants PNCh (0.857), PNA (0.853), PCCh (0.850) and MCCh (0.850) (Table 2; Figure 1.b).

The GDC slopes of the variant N_{100} fertilization were significantly influenced by the crop residue management ($p<0.05$). On average, the slope of after Ch variant was significant steeper than that after A (Table 2). The GDC slope values were comprised between 0.004 and 0.008. The smallest value 0.004, recorded for PCA variant, was significantly lower than those calculated for MNCh (0.008), SNCh (0.008), MCCh (0.007), SNA (0.007), PCCh (0.007) and PNCh (0.007) (Table 2; Figure 1.c). The GDC maximums were significantly influenced by crop rotation ($p<0.01$), in mean, after M variant registering maximums significantly higher than after S variant, but non significant than after P variant (Table 2). Soil tillage and crop residue management did not have a significant influence on GDC maximums ($p>0.05$). The values of GDC maximums ranged between 0.803 and 0.867. The highest values were recorded for the variants MCCh (0.867) and MCA (0.863), which were significantly higher than those of the variants SNCh (0.827), SNA (0.827), SCA (0.817) and SCCh (0.803) (Table 2; Figure 1.c).

In the conditions of 150 kg N a.i. ha^{-1} (N_{150}) fertilization, the GDC slopes were not significantly influenced by any factor under this study ($p>0.05$) (Table 2). The GDC slopes values were comprised between 0.004 and 0.008. The steepest slope was registered for the MNCh variant (0.008), but it was not significantly higher than the values of the other variants (Table 2; Figure 1.d). GDC maximums were not influenced significantly ($p>0.05$) by any factors of this research (Table 2). The values of GDC maximums were comprised between 0.840 and 0.870. The highest values were recorded for the variants MNA (0.870), MNCh (0.867) and MCA (0.867), which were significantly higher than those of PCCh (0.840) and SNCh (0.843) variants (Table 2; Figure 1.d).

The GDC and their parameters of the variants under study, obtained in 2018, are presented in Figure 2 (a-d) and Table 3.

In no fertilization conditions (N_0), the GDC slopes were not significantly influenced by crop rotation, soil tillage or crop residue management ($p>0.05$) (Table 3). The GDC slopes had values between 0.002 and 0.006. The highest slopes were registered for the variants MNA and SNCh (0.006), which were significantly greater than those of MNCh and PCCh (0.002) (Table 3; Figure 2.a). GDC maximums were significantly influenced by crop rotation ($p<0.001$), the variant after P showing maximums significant higher than M and S (Table 3). Soil tillage and crop residue management did not have a significant influence ($p>0.05$). The GDC maximums showed values between 0.407 and 0.707. The highest value (0.707) was recorded for the variants PCCh and PCA, but it was non significantly greater than those of PNA (0.697) and PNCh (0.673) (Table 3; Figure 2.a).

Table 3. Winter wheat growth and development curve (NDVI vs. days after sowing) slope and maximum for the 2018 crop cycle in the long-term trial NARDI Fundulea

N fertilization rate	N_0		N_{50}		N_{100}		N_{150}	
Treatment	Slope	Maximum	Slope	Maximum	Slope	Maximum	Slope	Maximum
MCCh	0.003 ab	0.407 D	0.004 abc	0.477 D	0.005ab	0.637 C	0.003 bc	0.633 EF
MCA	0.003 ab	0.420 D	0.004 abc	0.473 D	0.005 ab	0.643 C	0.004 ab	0.670 CDEF
MNCh	0.002 b	0.407 D	0.003 bc	0.500 D	0.004 b	0.643 C	0.003 bc	0.617 F
MNA	0.006 a	0.467 CD	0.003 bc	0.477 D	0.006 a	0.710 AB	0.003 bc	0.650 DEF
SCCh	0.005 ab	0.593 B	0.004 abc	0.587 C	0.003 bc	0.660 BC	0.003 bc	0.710 BCD
SCA	0.003 ab	0.573 B	0.005 ab	0.607 C	0.003 bc	0.677 BC	0.003 bc	0.723 ABC
SNCh	0.006 a	0.503 C	0.006 a	0.633 BC	0.003 bc	0.653 BC	0.005 a	0.680 CDE
SNA	0.004 ab	0.503 C	0.004 abc	0.580 C	0.004 b	0.647 C	0.003 bc	0.700 BCD
PCCH	0.002 b	0.707 A	0.002 c	0.740 A	0.003 bc	0.743 A	0.002cd	0.760 AB

PCA	0.003 ab	0.707 A	0.003 bc	0.710 A	0.002 cd	0.753 A	0.002 cd	0.753 AB
PNCh	0.003 ab	0.673 A	0.003 bc	0.720 A	0.001 d	0.760 A	0.001 d	0.747 AB
PNA	0.002 b	0.697 A	0.002 c	0.690 AB	0.001 d	0.753 A	0.002 cd	0.773 A
Rotation	ns	***	ns	*	**	**	ns	*
Tillage	ns	ns	ns	ns	ns	ns	ns	ns
Residue	ns	ns	ns	ns	ns	ns	ns	ns
Rotation x Tillage	ns	ns	ns	ns	ns	ns	ns	ns
Rotation x Residue	ns	ns	ns	ns	ns	ns	ns	ns
Tillage x Residue	ns	ns	ns	ns	ns	ns	ns	ns
Rotation x Tillage x Residue	ns	ns	ns	ns	ns	ns	ns	ns

Management practice with the same letter are not significantly different for the indicated N fertilization rate (p<0.0
* = p<0.05, ** = p<0.01, *** = p<0.001, ns = not significant.

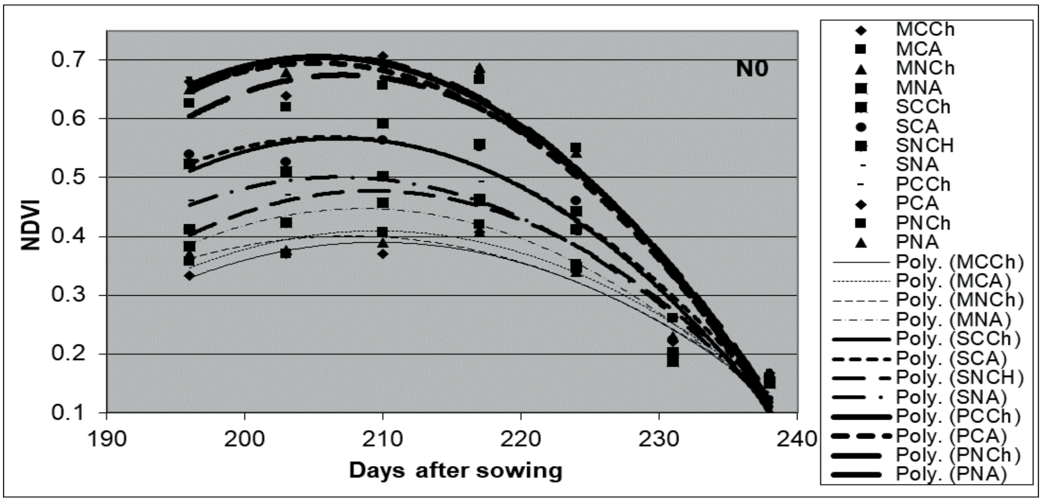

Figure 2.a. NDVI-based growth and development curve (NDVI vs. days after sowing) for the 2018 winter wheat crop cycle in the long-term trial NARDI Fundulea. Crop sequence (first letter): M yearly rotation of wheat with maize, S yearly rotation of wheat with sunflower, P yearly rotation of wheat with pea. Tillage system (second letter): C chisel tillage, N no tillage. Residue management (third letter): Ch keep all residue chopped on the field. A keep all residue anchored on the field. Nitrogen rate: N_0 without fertilization

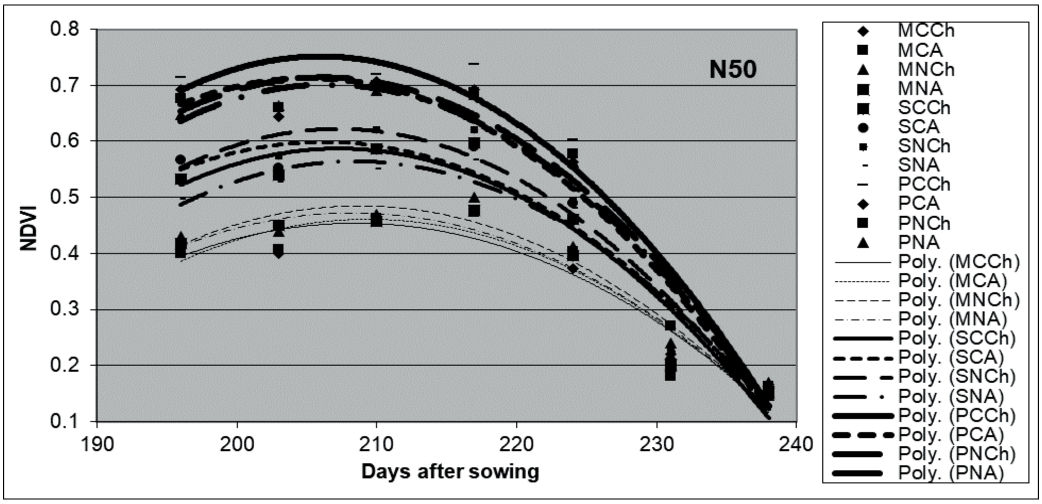

Figure 2.b. NDVI-based growth and development curve (NDVI vs. days after sowing) for the 2018 winter wheat crop cycle in the long-term trial NARDI Fundulea. Crop sequence (first letter): M yearly rotation of wheat with maize, S yearly rotation of wheat with sunflower, P yearly rotation of wheat with pea. Tillage system (second letter): C chisel tillage, N no tillage. Residue management (third letter): Ch keep all residue chopped on the field. A keep all residue anchored on the field. Nitrogen rate: N_{50} - 50 kg N a.i. ha^{-1}

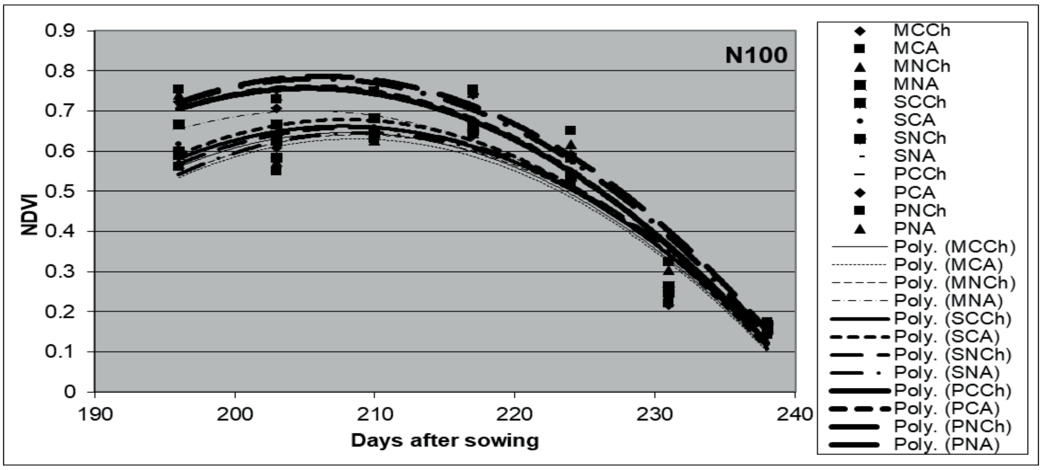

Figure 2.c. NDVI-based growth and development curve (NDVI vs. days after sowing) for the 2018 winter wheat crop cycle in the long-term trial NARDI Fundulea. Crop sequence (first letter): M yearly rotation of wheat with maize, S yearly rotation of wheat with sunflower, P yearly rotation of wheat with pea. Tillage system (second letter): C chisel tillage, N no tillage. Residue management (third letter): Ch keep all residue chopped on the field. A keep all residue anchored on the field. Nitrogen rate: N_{100} - 100 kg N a.i. ha⁻¹

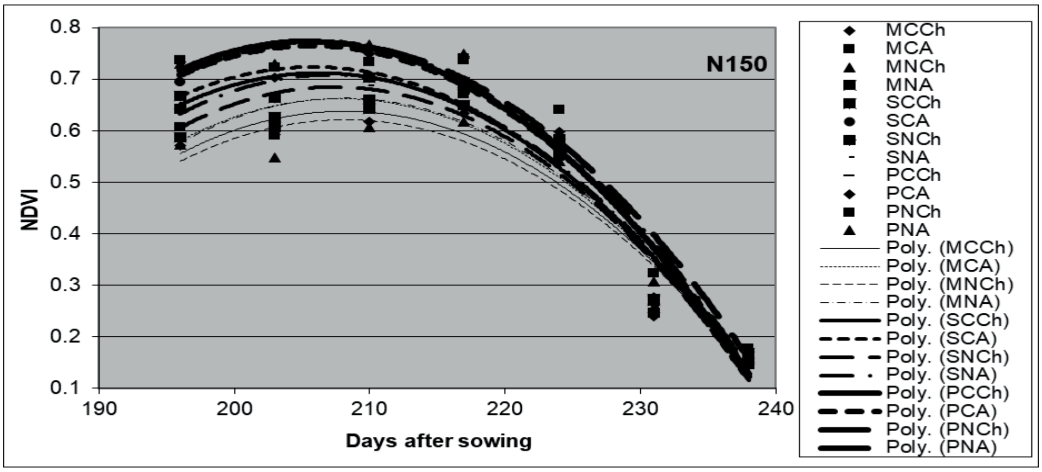

Figure 2.d. NDVI-based growth and development curve (NDVI vs. days after sowing) for the 2018 winter wheat crop cycle in the long-term trial NARDI Fundulea. Crop sequence (first letter): M yearly rotation of wheat with maize, S yearly rotation of wheat with sunflower, P yearly rotation of wheat with pea. Tillage system (second letter): C chisel tillage, N no tillage. Residue management (third letter): Ch keep all residue chopped on the field. A keep all residue anchored on the field. Nitrogen rate: N_{150} - 150 kg N a.i. ha⁻¹

In 50 kg N a.i. ha⁻¹ (N_{50}) fertilization conditions, the GDC slopes were non significantly affected by the factors under this study (Table 3). For the GDC slopes were recorded values comprised between 0.002 and 0.006. The steepest slope was registered for the variant SNCh (0.006), which was significantly higher than those of PCCh and PNA (0.002) (Table 3; Figure 2.b). GDC maximums were significantly influenced by crop rotation ($p<0.05$). In mean, after P were recorded significantly higher maximums than P, but non significant than S (Table 3). Soil tillage and crop residue management did not have a significant influence on GDC maximums ($p>0.05$). The values of GDC maximums ranged between 0.580 and 0.740. The highest maximum was registered at the variant PCCh (0.740), but it was not significantly higher than all the other variants: PNCh (0.720), PCA (0.710) and PNA (0.690) (Table 3; Figure 2.b).

Within the N_{100} fertilization variant, the GDC slopes were significantly affected by crop rotation ($p<0.01$). On average, after M were registered slopes significantly higher than those of S and P (Table 3). The GDC slopes showed values comprised between 0.001 and 0.006. The smallest values were recorded for the variants PNCh and PNA (0.001), which were significantly smaller than all the other variants, with the exception of PCA (0.002) (Table 3; Figure 2.c).

The GDC maximums were significantly influenced by crop rotation ($p<0.01$), on average, after M being registered maximums significantly higher than S, but not significantly different from the P (Table 3). Soil tillage and crop residue management did not influence significantly the GDC maximums ($p>0.05$).

The values of GDC maximums were comprised between 0.637 and 0.760. The highest maximum was calculated for the variant PNCh (0.760), but it was not significantly greater than those of the variants PNA (0.753), PCA (0.753), PCCh (0.743) and MNA (0.710) (Table 3; Figure 2.c).

In the conditions of fertilization with 150 kg N a.i. ha^{-1} (N_{150}), the GDC slopes were not significantly affected by the factors under this study (Table 3). The GDC slopes showed values between 0.001 and 0.005. The steepest slope had the variant SNCh (0.005), which was significantly greater than the slopes of the other variants, with the exception of MCA (0.004) (Table 3; Figure 2.d). The GDC maximums were significantly influenced by crop rotation ($p<0.05$), in mean, after P being recorded maximums significantly higher than M, they were not significantly different from S (Table 3). Soil tillage and crop residue management had not a significant influence on the GDC maximums ($p>0.05$). Their values ranged between 0.617 and 0.773. The highest maximum, recorded for variant PNA (0.773), was not significantly greater than those of PCCh (0.760), PCA (0.753), PNCh (0.747) and SCA (0.723) (Table 3; Figure 2.d).

The GDC's and their parameters for the variants evaluated in 2019, within the four rates of nitrogen fertilization are presented in Figure 3 (a-d) and Table 4.

In 2019, in no N fertilization conditions (N_0), the GDC slopes were significantly influenced ($p<0.05$) by crop rotation. Soil tillage and crop residue management had a non significant influence ($p>0.05$) (Table 4). In mean, after P were registered the steepest slopes. Their values were comprised between 0.005 and 0.010. The highest slope was calculated for the variant PCA (0.010), which was significantly greater than the slopes of all the other variants (Table 4; Figure 3.a). The GDC maximums were non significantly affected by all factors under this study ($p>0.05$) (Table 4). The values of GDC maximums ranged between 0.517 and 0.770. The highest maxim values were recorded for the variants PCA (0.770), PCCh (0.760), PNCh and PNA (0.740), which were significantly higher than those of all the other variants (Table 4; Figure 3.a).

In the case of 50 kg N a.i. ha^{-1} (N_{50}) fertilization, the GDC slopes were significantly influenced ($p<0.01$) by crop rotation and crop residue management ($p<0.001$), soil tillage having a non significant influence ($p>0.05$) (Table 4). In mean, after S, were registered higher GDC slopes, significantly greater being those of N and A variants. In this case, the GDC slope values were comprised between 0.009 and 0.012. Variant SNA showed the steepest slope, with a value of 0.012, which was significantly higher than those of the other variants (Table 4; Figure 3.b).

Table 4. Winter wheat growth and development curve (NDVI vs. days after sowing) slope and maximum for the 2019 crop cycle in the long-term trial NARDI Fundulea

N fertilization rate	N_0		N_{50}		N_{100}		N_{150}	
Treatment	Slope	Maximum	Slope	Maximum	Slope	Maximum	Slope	Maximum
MCCh	0.004 g	0.517 C	0.009 d	0.733 C	0.012 b	0.830 B	0.013 a	0.847 A
MCA	0.005 f	0.560 C	0.010 c	0.793 AB	0.011 c	0.847 AB	0.012 b	0.857 A
MNCh	0.004 g	0.520 C	0.009 d	0.740 C	0.010 d	0.833 B	0.013 a	0.853 A
MNA	0.004 g	0.543 C	0.010 c	0.770 BC	0.010 d	0.837 AB	0.013 a	0.847 A
SCCh	0.006 e	0.660 B	0.011 b	0.797 AB	0.012 b	0.840 AB	0.012 b	0.853 A
SCA	0.006 e	0.667 B	0.010 c	0.807 AB	0.013 a	0.840 AB	0.013 a	0.850 A

SNCh	0.007 d	0.640 B	0.010 c	0.793 AB	0.012 b	0.830 B	0.013 a	0.860 A
SNA	0.006 e	0.623 B	0.012 a	0.800 AB	0.012 b	0.850 AB	0.013 a	0.860 A
PCCh	0.008 c	0.760 A	0.009 c	0.833 A	0.010 c	0.847 AB	0.009 d	0.847 A
PCA	0.010 a	0.770 A	0.010 c	0.833 A	0.010 c	0.843 AB	0.010 c	0.823 A
PNCh	0.009 b	0.740 A	0.010 c	0.810 AB	0.013 a	0.860 A	0.013 a	0.867 A
PNA	0.008 c	0.740 A	0.011 b	0.830 A	0.012 b	0.860A	0.010 c	0.847 A
Rotation	*	ns	**	**	*	ns	*	ns
Tillage	ns	ns	ns	ns	ns	ns	**	ns
Residue	ns	ns	***	*	ns	ns	ns	ns
Rotation x Tillage	ns	ns	ns	ns	**	ns	ns	ns
Rotation x Residue	ns	ns	*	ns	*	ns	*	ns
Tillage x Residue	**	ns	***	ns	ns	ns	***	ns
Rotation x Tillage x Residue	*	ns	**	ns	**	ns	***	ns

Management practice with the same letter are not significantly different for the indicated N fertilization (p<0.05).
* = p<0.05, ** = p<0.01, *** = p<0.001, ns = not significant.

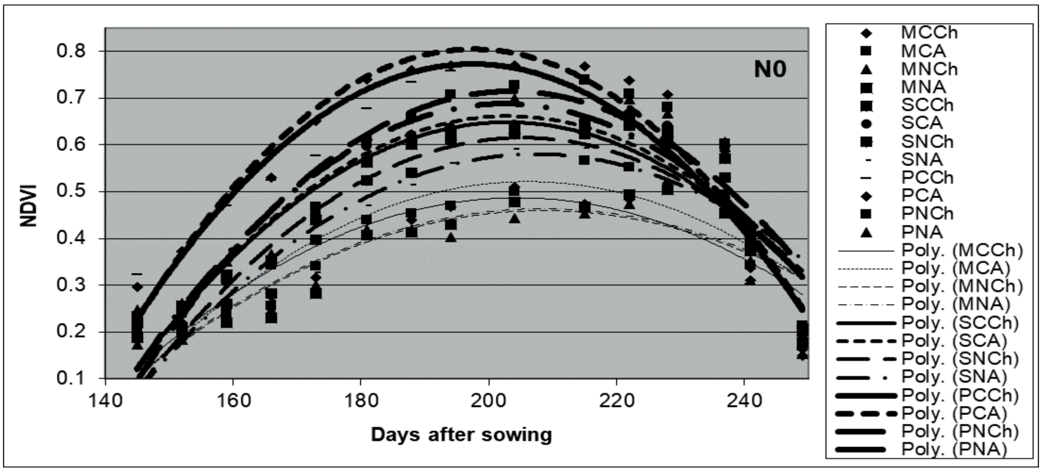

Figure 3.a. NDVI-based growth and development curve (NDVI vs. days after sowing) for the 2019 winter wheat crop cycle in the long-term trial NARDI Fundulea. Crop sequence (first letter): M yearly rotation of wheat with maize, S yearly rotation of wheat with sunflower, P yearly rotation of wheat with pea. Tillage system (second letter): C chisel tillage, N no tillage. Residue management (third letter): Ch keep all residue chopped on the field. A keep all residue anchored on the field. Nitrogen rate: N_0 without fertilization

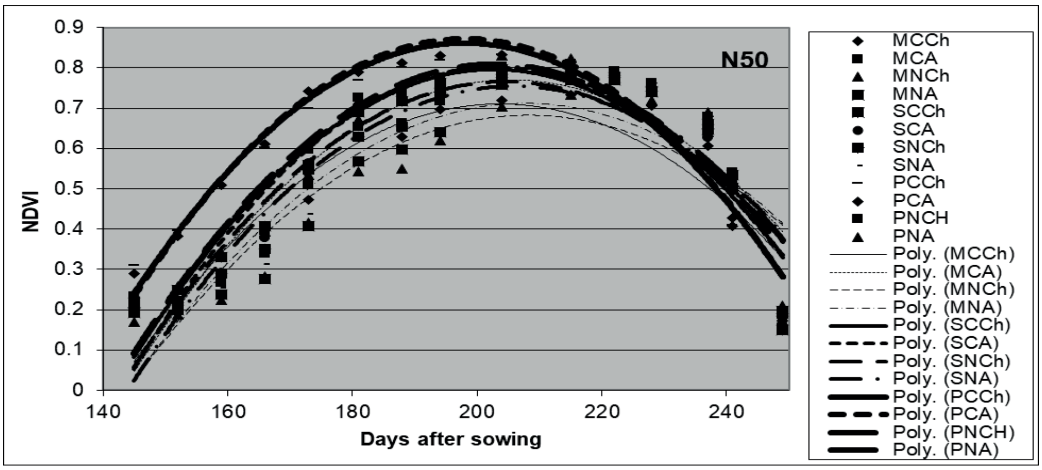

Figure 3.b. NDVI-based growth and development curve (NDVI vs. days after sowing) for the 2019 winter wheat crop cycle in the long-term trial NARDI Fundulea. Crop sequence (first letter): M yearly rotation of wheat with maize, S yearly rotation of wheat with sunflower, P yearly rotation of wheat with pea. Tillage system (second letter): C chisel tillage, N no tillage. Residue management (third letter): Ch keep all residue chopped on the field. A keep all residue anchored on the field. Nitrogen rate: N_{50} - 50 kg N a.i. ha^{-1}

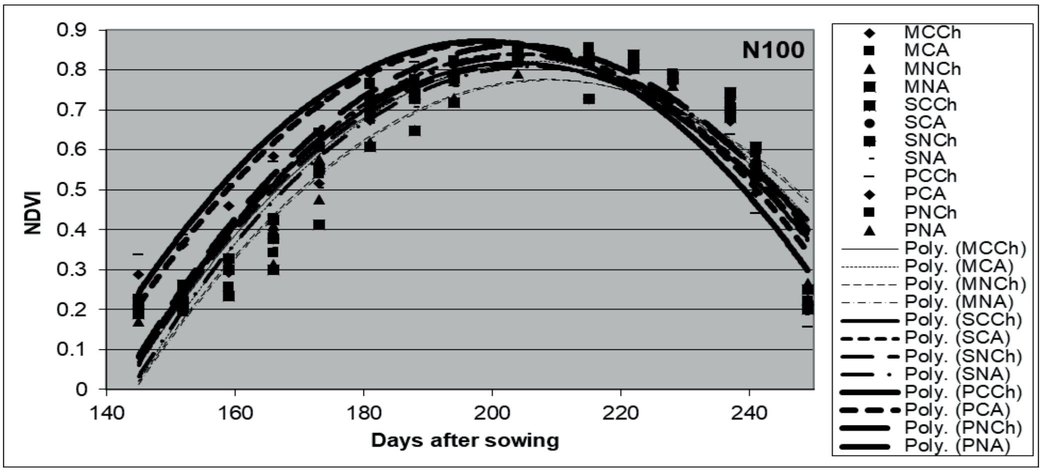

Figure 3.c. NDVI-based growth and development curve (NDVI vs. days after sowing) for the 2019 winter wheat crop cycle in the long-term trial NARDI Fundulea. Crop sequence (first letter): M yearly rotation of wheat with maize, S yearly rotation of wheat with sunflower, P yearly rotation of wheat with pea. Tillage system (second letter): C chisel tillage, N no tillage. Residue management (third letter): Ch keep all residue chopped on the field. A keep all residue anchored on the field. Nitrogen rate: N_{100} - 100 kg N a.i. ha^{-1}

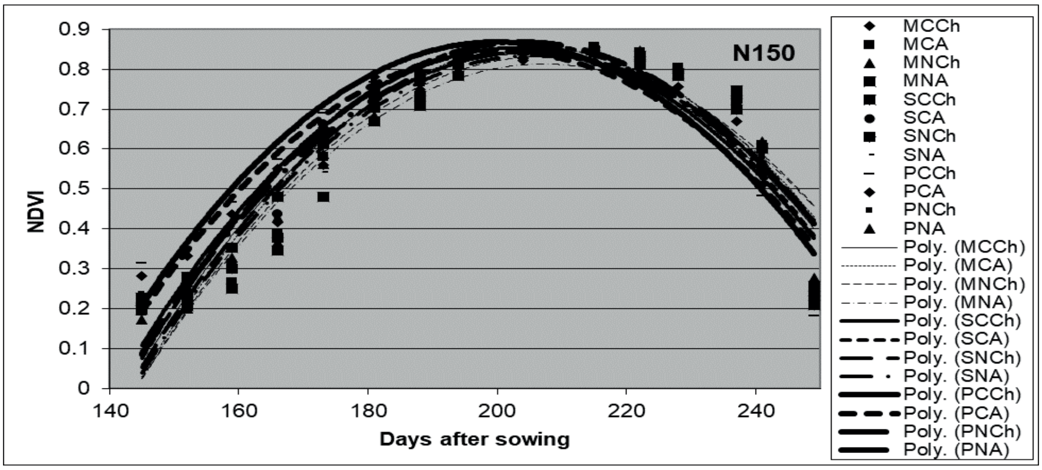

Figure 3.d. NDVI-based growth and development curve (NDVI vs. days after sowing) for the 2019 winter wheat crop cycle in the long-term trial NARDI Fundulea. Crop sequence (first letter): M yearly rotation of wheat with maize, S yearly rotation of wheat with sunflower, P yearly rotation of wheat with pea. Tillage system (second letter): C chisel tillage, N no tillage. Residue management (third letter): Ch keep all residue chopped on the field. A keep all residue anchored on the field. Nitrogen rate: N_{150} - 150 kg N a.i. ha^{-1}

The GDC maximums were significantly influenced by crop rotation ($p<0.01$) and crop residue management ($p<0.01$), soil tillage having a non significant influence ($p>0.05$) (Table 4). In mean, after P, were registered higher GDC slopes, significantly for C and A variants. The values of GDC maxims were comprized between 0.733 and 0.833. The highest maxim value (0.833) was recorded for the variants PCCh and PCA, which was significatly higher than the maxim values of the variants MNA (0.770), MNCh (0.740) and MCCh (0.733) (Table 4; Figure 3.b).

The GDC slopes within the N_{100} variant were significantly affected by crop rotation ($p<0.05$). On average, after S, significantly higher slopes were registered than in the case of M and P (Table 4). The GDC slopes showed values between 0.010 and 0.013. The steepest slopes were registered for the variants SCA and PNCh (with a value of 0.013), which were significantly higher than those of all the other variants (Table 4; Figure 3.c). The GDC maximums, with values between 0.830 and 0.860, were not influenced significantly by any factor of this study ($p>0.05$) (Table 4).

The highest maximum (0.860) was recorded for the variants PNCh and PNA, being significantly greater than those of the variants MCCh and SNCh (0.830) and MNCh (0.833) (Table 4; Figure 3.c).

In the conditions of 150 kg N a.i. ha^{-1} (N_{150}) fertilization, the GDC slopes were significantly affected by crop rotation ($p<0.05$) and soil tillage ($p<0.01$), but crop residue management had not significant influence ($p>0.05$) (Table 4). After M and S the slope values were significantly higher than those of P. On average, within N, significantly higher slopes were recorded than in the C case (Table 4). The GDC slopes showed values between 0.009 and 0.013. The smallest slope was calculated for the variant PCCh (0.009), which was significantly lower than the slopes registered for all the other variants (Table 4; Figure 3.d). The GDC maximums showed values comprised between 0.823 and 0.867 (Table 4; Figure 3.d). They were not influenced significantly by any of the factors of this study ($p>0.05$) (Table 4).

The average NDVI values were plotted against time for all treatments. All NDVI values gradually increased along the growing season until a maximum was reached before crop senescence induced a decrease [Figures 1(a-d), 2(a-d) and 3(a-d)]. The NDVI increased when the canopy started to close and started decreasing during grain filling. Scotford and Miller (2004) found similar results for winter wheat and Mandal et al. (2003) for wheat grown after transplanted rice. The onset of the decrease in NDVI values was different between years. Drought stress earlier in the season results in quicker ripening of the crop and this was reflected in NDVI-based growth and development curves. Therefore, the NDVI started decreasing the earliest in 2017 (dry period days 198-205) and earlier in 2019 (dry period days 204-215) than in 2018 (dry period days 217-224).

Crop rotations influenced early crop growth with higher NDVI values for crops sown after pea than crops after maize or sunflower [Figures 1(a-d), 2(a-d) and 3(a-d)]. Significantly greater NDVI values were registered each year after pea, especially within the variants unfertilized and N_{50} fertilization (Tables 2, 3, and 4). The differences among crop rotations did diminish later in the growing season, and there was no adverse effect on final yield (Table 5).

Table 5. Effect of crop rotation, tillage, crop residue management and N fertilization rate on winter wheat yields (t ha^{-1} at 14% H_2O) for 2017, 2018 and 2019 yields, in the long-term sustainability trial, NARDI Fundulea

Year	2017				2018				2019			
Manage. practice	N_0	N_{50}	N_{100}	N_{150}	N_0	N_{50}	N_{100}	N_{150}	N_0	N_{50}	N_{100}	N_{150}
MCCh	3.43b	6.05c	7.20a	6.70b	2.42f	3.47bf	4.72de	5.18c	2.82bc	4.77ab	4.85a	5.65a
MCA	3.27b	6.20bc	7.12a	6.85b	2.32f	3.00f	4.32de	5.34c	2.96bc	3.86b	5.25a	5.89a
MNCh	3.09b	5.85cd	7.01a	7.12b	2.33f	3.44ef	4.09e	5.02c	3.12abc	4.59ab	5.00a	5.07a
MNA	3.33b	6.09bc	7.06a	7.57a	2.66f	3.50def	5.09cde	5.47bc	2.75c	4.41ab	4.62a	5.03a
SCCh	3.19b	4.99d	5.85b	6.62b	4.11cde	4.44cde	5.31bcd	5.44c	3.37abc	5.06ab	5.15a	5.90a
SCA	3.09b	5.62cd	5.77b	6.65b	4.24bcd	4.52bcd	5.33bcd	5.72abc	3.60abc	4.69ab	4.71a	5.08a
SNCh	3.38b	5.72cd	6.55ab	6.48b	3.09ef	4.68bcd	5.14cde	5.36c	3.47abc	4.85ab	4.99a	6.11a
SNA	3.67b	5.82cd	6.58ab	7.12b	3.52def	4.32cde	5.16cde	5.72abc	3.56abc	4.00ab	4.54a	4.70a
PCCh	6.49a	7.44a	7.22a	7.17b	5.89a	5.94a	6.36ab	6.20abc	4.93a	5.04ab	6.16a	6.21a
PCA	6.15a	7.28a	6.98a	6.90b	5.23abc	5.43abc	6.19abc	6.00abc	3.79abc	5.78a	6.10a	6.11a
PNCh	6.04a	6.83ab	7.16a	7.28b	5.34ab	5.43abc	6.66a	6.81a	4.62ab	5.46ab	5.68a	6.10a
PNA	6.38a	7.05ab	7.19a	7.25b	5.25abc	5.62ab	6.07abc	6.60ab	3.68abc	5.09ab	5.96a	6.36a

Management practices with the same letter are not significantly different for the indicated period and N rate ($p<0.05$).

Higher yields by crops grown on legume stubble may be due to increased soil mineralization (Birch and Dougall, 1967). Generally, plant residues with an N content of less 1.2-1.3% (C/N ratio of about 30) will immobilize soil N (and fertilizer N, if present), however, if the percent N is more than 1.8-2.0 (C/N ratio about 20) considerable mineralization occurs (Jenkinson, 1981). So, decomposition of maize and sunflower residue has the potential to lower soil N availability, due to its high C/N ratio which induces N immobilization, in comparison with the decomposition of pea residue which is expected to increase the soil N availability due to its reduced C/N ratio, inducing considerably the mineralization, plus adding the fixed N in nodulated roots.

N fertilization influenced significantly the NDVI values in all three years of experimentation, being greater in 2017 and 2019 than in 2018, when water supply from precipitations in the warm season was much lower (Tables 2, 3, and 4).

Fertilization rate significantly increased the NDVI values compared to non fertilized plots [Figures 1(a-d), 2(a-d) and 3(a-d)].

Tillage systems and residue management had an insignificant influence on NDVI values in all three experimental years; however, chisel tillage resulted in faster growth compared to no tillage, with residue retention chopped or anchored, at the beginning of the season. Reports on differences in crop growth under different tillage practices are scarce, but some reports were found that coincide with our findings. Raimbault and Vyn (1991) and Vyn and Raimbault (1993) reported that zero tillage resulted in slower plant growth compared to conventional tillage system. However, McMaster et al. (2002) found faster, more uniform and greater seedling emergence in zero tillage than in conventional tillage in 4 out of 6 years in the Central Great Plains, due to more favourable soil water levels in the seeding zone under no tillage.

Rather than the retention of crop residue as such, the combination of crop residue retention and tillage will induce a change in the nitrogen cycle and as such the timing of N release (Govaerts et al., 2006). The change in N-cycling could partly explain why the NDVI-based crop growth and development curves of chisel tillage take off more quickly in comparison with the other treatments, i.e. more inorganic N is initially available for the growing crop. It is important, however, to note that the slower take off in growth with no tillage compared to chisel tillage is compensated for later in the season. Moreover, when looking at final yield (Table 5), treatments with higher yields generally achieved their NDVI maximum later in the growing period. This indicates that treatments with an initially slower growth may have an advantage. It seems that no tillage with residue retention induces a more timely and efficient use of available crop growth resources.

The results described above indicate that for a given cultivar, different tillage, crop rotation, residue management and N fertilization practices influence crop growth and development. Therefore, it could be hypothesized that different agronomic practices call for different plant types and thus for specific breeding processes in order to obtain the full potential of newly created soil and crop growth environment by the selected management practices.

CONCLUSIONS

The measurement with the handheld sensor was non-destructive, and fast (output is generated at a rate of 10 measurements per second) so that a representative plot area could be measured easily and time-efficiently. The NDVI handheld sensor is therefore an interesting tool to monitor efficiently and in real time crop growth and development under different management systems.

Crop rotation influenced early crop growth, with lower NDVI values for crops sown after maize and sunflower than crops after pea. The differences among crop rotation influences diminished later in the growing season, and there was no adverse effect on final yield. Fertilization rate significantly increased the NDVI values compared to non fertilized plots. No tillage with residue retention, choped or anchored, was characterized by a slower initial growth than chisel tillage practices, but this was compensated for by increased crop performance in the later stages. The results indicated that different rotation, tillage, residue management and N fertilization rate practices influence crop growth and development. It is important to monitor and understand crop growth under different management systems to select the right varieties and adjust timing and practice of input supply.

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