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Research Article

Vegetation sensors as a tool for plant population identification and corn grain yield estimation[1]

André Luis Vian[2], Christian Bredemeier[2],
Maicon Andreo Drum[2], João Leonardo Fernandes Pires[3], Elizandro Fochesatto[4]

ABSTRACT

The estimated corn grain yield is dependent on plant density and should be monitored from the beginning of its development, especially between the phenological stages V3 and V10, since these stages are more responsive to management strategies. This study aimed to evaluate the efficiency of two methods [normalized difference vegetation index (NDVI) and plant occupation index (POI)] to estimate the density of corn plants, in order to identify the plant population in different phenological stages and corn grain yield. Two field experiments were conducted in two crop seasons and treatments consisted of four plant densities (4, 6, 8 and 10 plants m^{-2}). The NDVI measurements of the vegetative canopy were performed in the growth stages V4, V5, V6, V7, V8 and V9 (2014) and V3, V5, V6, V8, V9, V10 and V13 (2015/2016). For the POI, the measurements were performed in the stages V5, V6, V8 and V9, in both crop seasons. The different plant densities were efficient in generating variability in the NDVI and POI values throughout the corn crop development cycle, and both tools were efficient in identifying density variations. It was observed that these tools should be used between the V4 and V9 growth stages.

KEYWORDS: *Zea mays* L., normalized difference vegetation index, plant occupation index.

RESUMO

Sensores de vegetação como ferramenta para identificação de população de plantas e estimativa de produtividade de grãos de milho

A produtividade estimada de grãos do milho é dependente da densidade de plantas e deve ser monitorada desde o início de seu desenvolvimento, principalmente entre os estágios fenológicos V3 e V10, visto que são mais responsivos a estratégias de manejo. Objetivou-se avaliar a eficiência de dois métodos [índice de vegetação por diferença normalizada (NDVI) e índice de ocupação de plantas (POI)] para estimar a densidade de plantas de milho, a fim de identificar a população de plantas em diferentes estádios fenológicos e a produtividade de grãos de milho. Dois experimentos de campo foram conduzidos em duas safras agrícolas e os tratamentos consistiram em quatro densidades de plantas (4, 6, 8 e 10 plantas m^{-2}). As medições de NDVI do dossel vegetativo foram realizadas nos estágios de crescimento V4, V5, V6, V7, V8 e V9 (2014) e V3, V5, V6, V8, V9, V10 e V13 (2015/2016). Para o POI, as medições foram realizadas nos estádios V5, V6, V8 e V9, em ambas as safras. As diferentes densidades de plantas foram eficientes em gerar variabilidade nos valores de NDVI e POI ao longo do ciclo de desenvolvimento da cultura, e ambas as ferramentas foram eficientes para identificar as variações na densidade. Verificou-se que essas ferramentas devem ser utilizadas entre os estádios de crescimento V4 e V9.

PALAVRAS-CHAVE: *Zea mays* L., índice de vegetação por diferença normalizada, índice de ocupação de plantas.

INTRODUCTION

Plant density is an important variable to estimate corn grain yield, because of its direct influence on defining the number of ears per area (Kappes et al. 2011). In addition, it affects the distribution of leaf area, influencing the interception of solar radiation and maximizing the photosynthetic rate and the production of photoassimilates per plant (Santos et al. 2018). The optimal plant density for corn varies depending on soil type and fertility, soil organic matter content, water availability, solar radiation incidence, seed genotype, fertilization management and expected grain yield (Takasu et al. 2014, Vian et al. 2016).

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[2] Universidade Federal do Rio Grande do Sul, Faculdade de Agronomia, Departamento de Plantas de Lavoura, Porto Alegre, RS, Brasil. *E-mail/ORCID*: andre.vian@ufrgs.br/0000-0002-9781-1533; bredemeier@ufrgs.br/0000-0003-3006-6011; maicon.drum@ufrgs.br/0000-0001-7584-6498.
[3] Empresa Brasileira de Pesquisa Agropecuária (Embrapa Trigo), Passo Fundo, RS, Brasil. *E-mail/ORCID*: joao.pires@embrapa.br/0000-0002-9901-2030.
[4] Centro Universitário Vale do Iguaçu, União da Vitória, PR, Brasil. *E-mail/ORCID*: elizandrofochesatto@hotmail.com/0000-0003-0085-034X.

The corn yield forecast must be monitored and carried out from the beginning of its development, from the V3 to V10 growth stages (three to ten fully expanded leaves, respectively) (Ritchie et al. 1993), which are decisive phenological stages for the definition of yield, since the number of rows and ovules per ear are defined.

Tools such as remote sensing may be used to assist in monitoring the development of plants, their expected yield and the nutritional status, in relation to nitrogen (N) (Kaneko et al. 2010, Chioderoli et al. 2012, Vian et al. 2018a), by using vegetation sensors like the Greenseeker™ and RGB digital cameras. These sensors allow monitoring crops depending on the variation of the chlorophyll content in leaves and the canopy biomass (Muñoz-Huerta et al. 2013, Torres-Dorante et al. 2016, Padilla et al. 2018).

One of the most used vegetation indexes is the normalized difference vegetation index (NDVI), which can be used to identify the spatial variability of plant vigor and the canopy biomass through red and near-infrared reflectance of plants. Moreover, another alternative way of evaluating the plant canopy biomass is the plant occupation index (POI), which indicates the proportion occupied by green plant parts in a digital image that detects the reflectance of the visible spectrum (blue, green and red) and can be correlated with leaf area index, NDVI and canopy biomass.

The NDVI is one of the most used vegetation indices in agriculture and is related to canopy biomass and expected grain yield. However, due to its processing time and operation cost, new alternative and practical tools need to be implemented in the field, in order to understand the spatial variability of the plant development, enabling its correlation with spatially variable productive estimation in the field, allowing the adjustment of management practices, such as the application of inputs at a variable rate, reaching the maximum yield potential of each environment within a production area (Coelho et al. 2018).

This study aimed to evaluate the efficiency of the NDVI (determined by an active optical vegetation sensor) and POI (obtained by digital RGB imagery) for the identification of plant density variation at different phenological stages and their reflexes on corn production expectation.

MATERIAL AND METHODS

Two field experiments were carried out in the 2014 and 2015/2016 crop seasons, at the Universidade Federal do Rio Grande do Sul (Eldorado do Sul, Rio Grande do Sul state, Brazil). The experimental area is located in the physiographic region of the central depression of the Rio Grande do Sul state, at an average altitude of 46 m.

The climate in the region is subtropical with hot humid summer (Cfa type, according to the Köppen's classification) (Maluf 2000). The average annual rainfall is 1,440 mm and the average monthly air temperature varies between 14 and 25 ºC in the coldest and warmest months, respectively (Bergamaschi et al. 2003).

In both crop seasons, the hybrid 'Morgan 30A77 PW' was used. Treatments consisted of four plant populations (4, 6, 8 and 10 plants m^{-2}), arranged in a randomized block design, with four replications. In 2014, corn was sown on January 5 ("off-season"). Each plot was composed of four 3-m long rows spaced 0.5 m apart. In 2015/2016, sowing was carried out on September 15 ("first crop"), with each plot consisting of six 8-m long rows spaced 0.5 m apart. At 14 days after the plant emergence, the different plant populations were adjusted by manual thinning.

Fertilization was carried out at sowing using 15, 60 and 60 kg ha^{-1} of N, P_2O_5 and K_2O, respectively, in both crop seasons. The topdressing N fertilization consisted in the application of 235 kg ha^{-1} (SBCS 2016) at the V4 and V8 growth stages, estimating to produce 12,000 kg ha^{-1} of grains.

The normalized difference vegetation index (NDVI), plant occupation index (POI) and grain yield were evaluated. The NDVI was determined using the Greenseeker™ optical vegetation sensor (Trimble, Folsom, USA) by the relation $(\rho nir - \rho r)/(\rho nir + \rho r)$, where ρnir (770 nm) and ρr (680 nm) are the reflectances in the near-infrared and in the red bands, respectively (Rouse et al. 1974). The readings were taken with the equipment positioned on the crop sowing row, approximately 1.0 m above the canopy. In 2014, the readings were performed along the two central rows of the plot at six vegetative growth stages (V4, V5, V6, V7, V8 and V9), while the 2015/2016 readings were performed along four central rows at the growth stages V3, V5, V6, V8, V9, V10 and V13. The NDVI value of each plot was determined by the average of readings in each row. The growth stages were determined by using the Ritchie Scale (Ritchie et al. 1993), which considers the number of fully expanded leaves (leaves with visible leaf collar) in the plant.

The POI was determined at the growth stages V5, V6, V8 and V9 (only in 2015/2016) from digital RGB images (R: 650 nm; G: 550 nm; B: 450 nm) acquired with a camera Cyber-Shot A95 (Sony Corp, Japan), with resolution of five megapixels. The camera was positioned at 1.5 m above the canopy and the images were taken perpendicularly to the soil surface, in the central area of each plot (1.5 m^2), between 11:40 a.m. and 11:55 a.m. To process and analyze the images, the Siscob v. 1.0 software (Jorge & Silva 2009) was used. In each image, the percentage of pixels in each class of interest (plant, soil and straw) was determined. Therefore, it was necessary to determine the classes of patterns, as well as the patterns, for the construction of the image classifier from a supervised neural network (Jorge & Silva 2009). The POI refers to the percentage of "green" pixels (plant) in the image, ranging from zero (no green pixel) to 1 (100 % of green pixels).

The grain yield was quantified by harvesting two 2-m long rows (2.0 m^2) in 2014 and four 6-m long rows (12 m^2) in 2015/2016. Afterwards, the grain mass of each plot was weighed and corrected for a humidity of 130 g kg^{-1}, and the value extrapolated to kg ha^{-1}.

The NDVI, POI and grain yield data were subjected to analysis of variance (Anova) by the F test, for comparison between crop season and for each growth stage, using the statistical package SAS™. Subsequently, regression analyses were performed. A significance level of 5 % was considered for the parameters of grain yield and correlation. For the NDVI and POI parameters, the level of 1 % was considered. Correlation and determination coefficients among NDVI, POI, plant density and grain yield for each phenological stage were calculated.

RESULTS AND DISCUSSION

The identification of different corn plant densities was performed using the Greenseeker active optical sensor and the variations in the normalized difference vegetation index (NDVI) were related to the variation in plant population in both experiments (Figure 1). For all the phenological stages, the NDVI values increased linearly as the plant population increased. The coefficients of determination (R^2) between these two variables were high, ranging from 0.93 to 0.99 for the growth stages evaluated in 2014 (Figure 1A) and from 0.86 to 0.94 in 2015/2016 (Figure 1B), thus confirming the relation between the increase in plant biomass and soil coverage by the canopy provided by the increase in plant population and the NDVI value.

At the highest plant population (10 plants m^{-2}), the NDVI values were higher throughout the evaluated period, if compared to lower populations (Figures 1A and 1B). Thus, NDVI readings using an active optical sensor identified the treatments with the highest and lowest plant density. This response is mainly due to the lower amount of biomass in the shoots

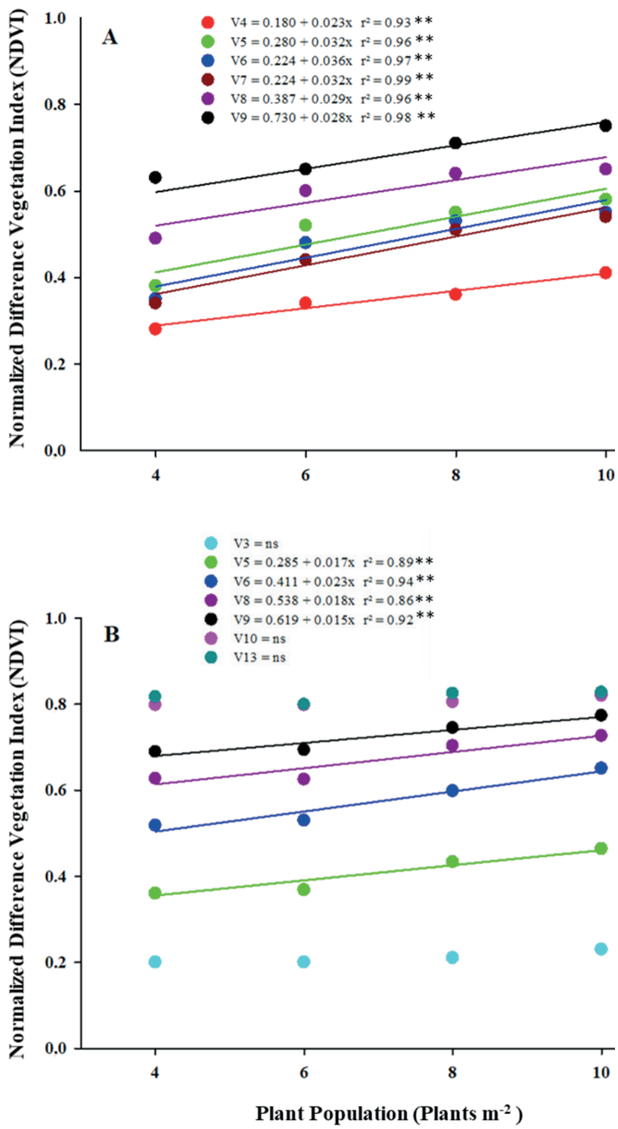

Figure 1. Normalized difference vegetation index, as a function of corn plant population, at different phenological stages, in 2014 (A) and 2015/2016 (B). ns: not significant; ** significant at 1 % of probability.

at the initial stages of development, in treatments with lower plant densities (4-6 plants m^{-2}), whereas the increase in NDVI values with increasing plant populations may be related to the greater accumulation of shoot biomass. The greater the accumulation of photosynthetically active biomass, the greater is the reflectance of radiation in the near-infrared band (NIR), and the lower is the reflectance in the red band, resulting in an increase in the NDVI value (Smith et al. 2017).

The plant populations were differentiated by NDVI readings between the phenological stages V4 and V9 (Figure 2A). In the phenological stages before V3 and after V9, the NDVI measured by the Greenseeker sensor reduced its sensitivity, resulting in difficulties in differentiating plant populations, since, in the early growth stages, there is little ground cover by plants, resulting in a low amount of biomass in the sensor reading area. In phenological stages after V9, due to the high accumulation of shoot biomass and maximum coverage of the soil surface by the canopy, there is a saturation of this vegetation index. From the V9 stage onwards, a high amount of biomass occurs at all plant densities (high leaf area index) and the inter-row spaces are almost or completely covered by the canopy, resulting in the saturation of NDVI values (Santos et al. 2014, Vian et al. 2018b).

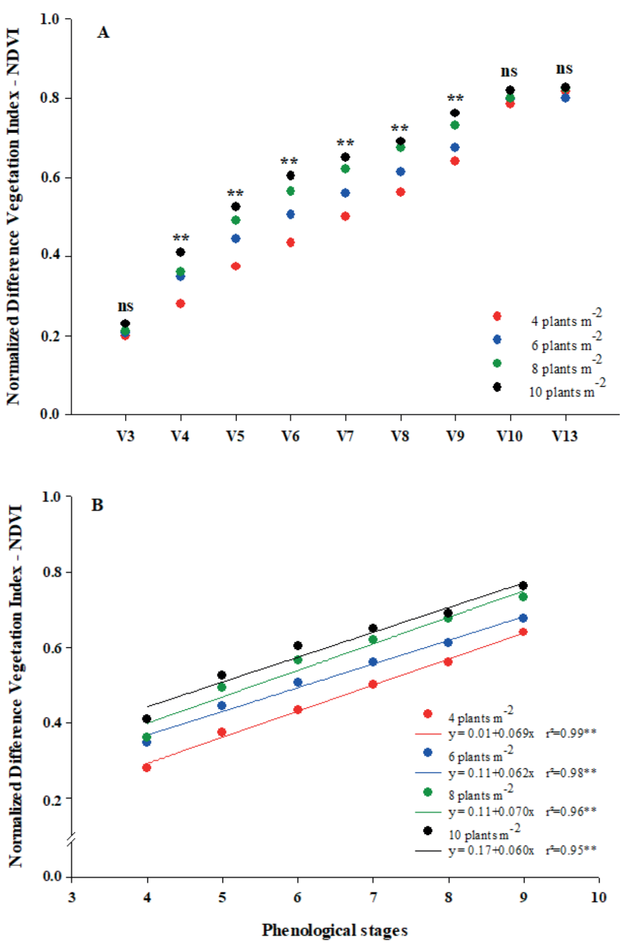

Figure 2. Mean normalized difference vegetation index of both crop seasons, as a function of corn plant population, at all evaluated phenological stages (A) and between V4 and V9 (B). ns: not significant: ** significant at 1 % of probability.

At growth stages after V9, the difference between NDVI absolute values is smaller for each population density, and no differentiation among plant populations can be done with confidence (Figure 2A). Studies on barley showed saturation of NDVI values between 0.84 and 0.87 (Coelho et al. 2018). Padilla et al. (2018) reported that NDVI readings were efficient in identifying different plant populations in corn (4, 5, 7, 8 and 10 plants m^{-2}) only up to the V6 growth stage (six fully expanded leaves). After this stage, a saturation of the NDVI value was identified.

Figure 2B shows the significant relationships between the different growth stages and NDVI values. The data corroborate those of Wang et al. (2016), Alvino et al. (2020) and Venancio et al. (2020), to which the behavior of the NDVI obtained via satellite images throughout the development cycle of maize was evaluated. These authors found a rapid increase in NDVI values at the beginning of the cycle, thus confirming the results found between the stages V4 and V9.

It was also observed that, with the increase in the population density (8 and 10 plants m^{-2}), there was a greater response in the NDVI values, due to the increase in biomass by area and soil coverage by the crop. In lower densities, the NDVI values are lower, when compared to the higher densities. This characteristic follows the same pattern throughout the crop development cycle.

The grain yield was also affected by plant population (Figure 3). In 2014, there was an increase in grain yield up to the population of 7.7 plants m^{-2}, with a maximum yield of 10,616 kg ha^{-1}. In 2015/2016, on the other hand, the increase in grain yield occurred up to the density of 8.7 plants m^{-2}, with a maximum yield of 10,680 kg ha^{-1} (Figure 3). This higher grain yield obtained with a lower plant population in the second year is associated with the fact that there

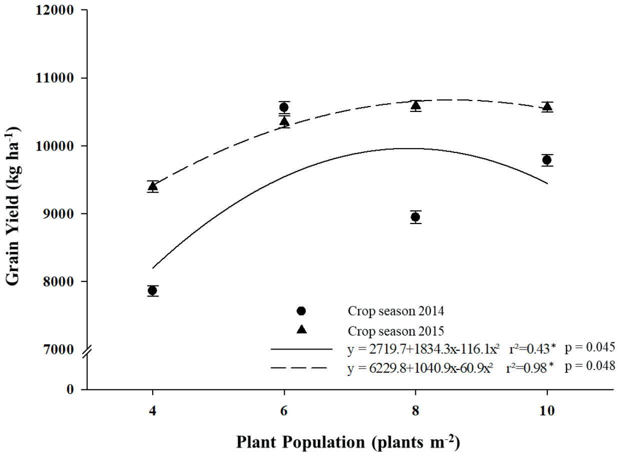

Figure 3. Corn grain yield, as a function of plant population, in two crop seasons. * Significant at 5 % of probability. Bars represent the standard error of the mean.

was a water deficit period of approximately 15 days, coinciding with the flowering and grain filling stages. Therefore, when using larger plant populations in an environment without irrigation, the grain yield decreases, if compared to lower plant densities, due to the increased competition between plants for water, nutrients and solar radiation throughout the cycle (Sangoi et al. 2010), even with sowing at the recommended time for this region.

Table 1 shows the correlation coefficients between the NDVI values evaluated between the growth stages V3 and V13 and grain yield. In 2014, there was a significant correlation between the two variables at all evaluated phenological stages. At the V8 stage (eight fully expanded leaves),

Table 1. Pearson's linear correlation coefficient between the normalized difference vegetation index (NDVI) evaluated at different phenological stages and corn grain yield.

Phenological stage[1]	NDVI *vs*. Grain yield	
	2014	2015/2016
V3	-[1]	0.23^{ns}
V4	0.43**	-
V5	0.59**	-0.33^{ns}
V6	0.55**	-0.48^{ns}
V7	0.50**	-
V8	0.65**	-0.47^{ns}
V9	0.49**	-0.46^{ns}
V10	-	0.19^{ns}
V13	-	-0.32^{ns}

[1] Not evaluated; ** significant at 5 % of probability.

the best correlation coefficient (r = 0.65) between the variables was observed (Table 1). Thus, it is possible to differently manage each zone of different yield potentials within a field defined by the plant population, such as targeting different doses of topdressing nitrogen fertilization according to population and yield potential. However, depending on environmental and management conditions, there may be a lack of representativeness of grain yield by NDVI, as shown by the data for the 2015/2016 experiment (Table 1).

The grain yield was significantly correlated with the NDVI values assessed by the Greenseeker sensor (Table 1) only in 2014. In 2015/2016, on the other hand, there was no significant correlation between these variables. This may be explained by the vigorous vegetative growth at the initial development in all plant populations, as can be seen by the NDVI values, which were influenced by the large rainfall volumes (an *El Niño* year). At the flowering stage, however, there was a reduction in the grain yield potential, especially at the higher plant populations, due to the water deficit that occurred between the flowering and grain filling stages.

The variation in plant population was reflected in variations on the NDVI values, as well as on POI (Figure 4). At lower plant populations, there are more "empty" spaces, when compared to higher ones. Thus, there is a tendency that a maximum soil coverage occurs from the stages V9 to V10,

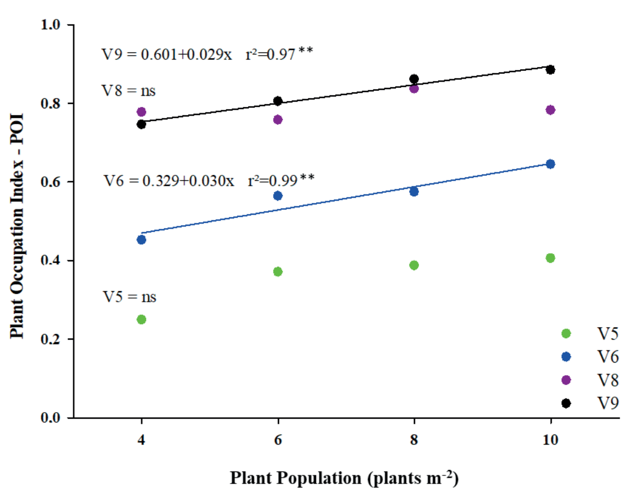

Figure 4. Plant occupation index for corn, as a function of plant population, at different phenological stages, in 2015/2016. ns: not significant; ** significant at 1 % of probability.

reaching approximately 0.9 of POI, that is, close to a maximum vegetative development and almost maximum soil coverage by the canopy. The plant populations (4-10 plants m^{-2}) presented an increase in soil coverage, within each evaluated phenological stage, of 15 % in V5, 19 % in V6 and 17 % in V9, that is, reduction of "empty" spaces with increasing plant developmental stage (Figure 4).

In both experiments, it was possible to observe that, from the V10 growth stage, a canopy closure takes place, reducing the variability of NDVI values for the different plant populations evaluated. Therefore, the recommendation to use the active canopy sensor Greenseeker and the NDVI to estimate variability in corn plant population and grain yield potential is for the subperiod between the V4 and V9 growth stages, since the sensor is able to identify the variation between plant populations and estimate different grain yield potentials (Risso et al. 2012, Padilla et al. 2018).

At the initial development stages (V4 to V9), most of the productive potential is defined, and, consequently, there is the greatest demand for nitrogen for the definition of high grain yield potential. Thus, the estimation of plant population and grain production in well-managed fields, in which high grain yields are sought, is necessary for increasing the response and efficiency of the N topdressing fertilization by means of variable rate application. The identification of the variability on plant population and productive potential allows the application of different nitrogen doses in areas with different grain yield potentials within the field.

The coefficient of determination for the relationship between NDVI and POI values, using the data of the V6 and V9 growth stages, was high ($r^2 = 0.91$) (Figure 5). Thus, the NDVI and POI are good tools to analyze the spatial variability of the crop within a field and to estimate the grain yield from the readings throughout the development cycle of corn. With the evolution of the crop development stages, there is an increase in shoot biomass and, in consequence, an increase in the NDVI and POI values (Figure 5), evidencing the potential of these tools to assess varying crop conditions within a field and to estimate the crop grain production.

This response corroborates a study where the use of proximal digital images was compared with the NDVI value obtained by satellite images in soybean and corn crops, obtaining $r^2 = 0.80$ (Sakamoto et al.

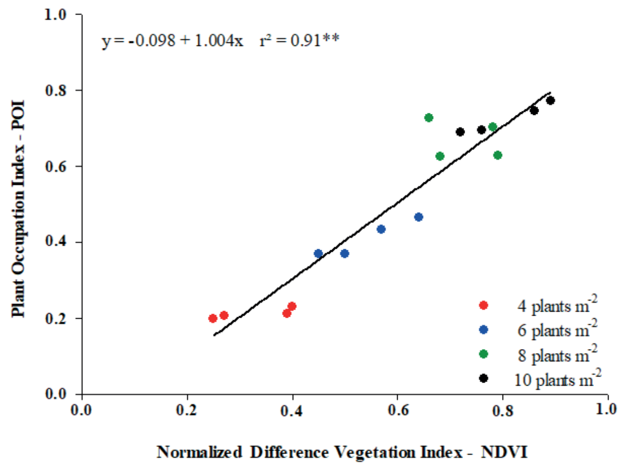

Figure 5. Normalized difference vegetation index and plant occupation index of the corn crop in the 2015/2016 crop season, at the phenological stages V6 and V9. ** Significant at 1 % of probability.

2012). A similar result was reported for cotton and corn crops (Alganci et al. 2014).

CONCLUSIONS

1. The different plant populations generated variability in the normalized difference vegetation index (NDVI) and plant occupation index (POI) values along the vegetative period of corn, with the lowest values of these indexes being related to lower plant populations;
2. The NDVI evaluated by an active optical canopy sensor and the POI are efficient in identifying variations in plant population and in estimating corn grain yield between the V4 and V9 growth stages;
3. The NDVI and POI indexes have a good correlation with each other and may be used to identify variations in corn plant population within a field.

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