UNNAMED AERIAL SYSTEM TO DETERMINE NITROGEN STATUS IN MAIZE

R.J.M. Melchiori, A.C. Kemerer, and S.M. Albarenque

Natural Resource and Abiotic Factors Department.

National Institute of Agricultural Technology (INTA). Paraná Experimental Station.

Entre Ríos, Argentina.

ABSTRACT

Maize field production shows spatial variability during vegetative crop growth that could be used to prescribe nitrogen variable rates. The use of portable sensors mounted on high-clearance applicators is well documented, however new UAS vehicle equipped with high resolution digital cameras could be used to determine crop spatial variability with the advantage of survey extensive field areas. To our knowledge, comparisons between vegetation indices obtained by a modified digital camera and GreenSeeker or hyperspectral measurements are unknown. The aims of this study were to compare vegetation indices (VI) obtained with a modified digital camera versus SPAD, VI obtained with a GreenSeeker and a hyperspectral sensor, and to study the relationship of VI with crop variables related to N status in maize. Selected treatments, ranged from 0 and 276 kgN ha^{-1}, were used to determine biomass, SPAD and sensors readings with a GreenSeeker and Ocean Optics USB 4000. The UAS was equipped with a digital camera modified by the extraction of the internal near-infrared blocking filter and the inclusion of a visible light-blocking filter. Crop measurements were made at V6 and V10 growth stages and photograph were obtained with two ground spatial resolution. Crop variables at V10 were related with VI determined with commercial sensors and with aerial photograph. The highest sensitivity to detect biomass and LAI changes was observed for VI calculated from an uncorrected high spatial resolution aerial photograph obtained with a modified RGB camera.

Keywords: maize, UAS, nitrogen status, vegetation index

INTRODUCTION

Spatial variability of crop yield and soil properties should be considered to improve crop productivity, profit, resource use efficiency and to minimize environmental impacts. Soil nitrogen (N) availability commonly has high spatio-temporal variability and great impact on crop productivity (Fiez et al., 1994, Batchelor et al., 2002). Therefore, management practices that consider N spatial variability, could improve N use efficiency (NUE) (Mulla and Schepers. 1997; Raun and Schepers. 2008; Mamo et al., 2003).

Nitrogen management practices should consider weather variability to decide N rates, especially in humid regions (Melkonian et al., 2005). Changing weather conditions during crop growing season affect soil N dynamic and so modify crop growth and variables such as biomass and LAI, and crop N status.

Remote sensing techniques allow determining vegetation indices (VI), related to crop variables and crop N status, which have been used to develop N prescription models (Raun et al 2005, Solari et al., 2008). In-season N management practices using on-the-go sensors could take into account how environmental conditions affect crop growth and could improve N fertilizer recommendations. On farm evaluations had shown that these practices could reduce N rates and improve profit (Scharf et al., 2011). However, these technologies still have some disadvantages, which may limit their spreading, such as the elevated price of components and longtime of setup.

In-season N management practices based on remote sensing may be performed also using VI obtained from high resolution satellite imagery or aerial photograph. Preliminary results have shown that VI obtained with aerial multispectral photograph was closely related to sensors mounted on applicator (Velez et al., 2012). Nevertheless, satellite images have restrictions related to revisit time, cloud interferences and fixed spatial resolution; whereas aerial photograph obtained with manned aircraft have high cost and more specialized requirements, such as a trained pilot and landing strips. Unmanned aerial systems (UAS) represent a practical and economic alternative to perform surveys of crops fields. A recent review of Zhang and Kovacks (2012) pointed out that applications of UAS in environmental studies are highly documented, but their applicability to help precision agriculture practitioners is even more a challenge. Portability, not requirement of a landing field; flexibility to decide the moment of flight according to a specific crop growth stages or to avoid cloud interferences; capability of fly at low altitude to obtain very high spatial resolution are among the UAS advantages in comparison to manned aircraft.

Current technologies of the UAS include flight planners, autopilots, special digital cameras and high-end software for stitching, mosaicking and processing aerial photographs. Select the most adequate configuration according to agronomic needs is an issue that affects the cost of the equipment required and has to be studied.

UAS are been used to perform field survey equipped with high resolution digital cameras (RGB). A high ground spatial resolution and a wide overlapping of photograms are procedures used to ameliorate geometric deformations of digital images and to obtain high quality ortho-rectificated mosaic or surface digital models (Gómez-Candón et al., 2014).

Precision agriculture UAS applications, such spatial analysis of crops vigor or N status, to prescribe variable rate could be performed using small multispectral cameras. However, a more economical alternative is the use of a modified high resolution digital camera (RGB) that would serve to obtain a VI together with a surface digital model. Lebourgeois et al. (2008) mentioned several limitations of modified cameras and suggest different process to correct the images. Nevertheless, image corrections not showed major improvement in the relationship between crops measurements and VI.

To our knowledge on-farm comparisons of VI obtained with modified digital cameras and commercial sensors are not documented. This study could contribute to a more appropriated use of UAS in PA applications, such as crop N status mapping.

The aims of this study were to compare VI indices obtained with a modified digital camera versus SPAD, VI obtained with a GreenSeeker and a hyperspectral sensor, and to study the relationship of VI with crop variables related to N status in maize.

MATERIALS AND METHODS

The study was conducted on a field located in INTA-Parana Experimental Station (Entre Ríos Province, Argentina; 31˚ 50' S; 60˚ 31' W; 110 a.s.l). Four contrasting N treatments (0, 69, 138, and 276 kg N ha^{-1}) from a long-term nitrogen fertilization experiment on maize were used to evaluate N response using crop growth variables and sensors readings. Experimental design was a RCBD with three replications. Crop seeding and weeds control were carried out using common farmer´s practices. Maize hybrid DK 7010 was sown at optimal date with 0.52 m row spacing, and a plant density of around 75.000 plants ha^{-1}.

Crop biomass was estimated allometrically from plant height and stem diameter as Vega and Sadras (2003), and leaf area index (LAI) according to Montgomery (1911). Sensors readings were made using a SPAD (Minolta Corp, Japan), Green Seeker (Ntech, Ukia, CA. USA) and a hyperspectral sensor USB 4000 (Ocean Optics Inc, FL, USA). Hyperspectral measurements were used to calculate normalized vegetation indices as (B1-B2)/(B1+B2).Where reflectance bands considered were: B1= 720 nm and B2 = 800 for $NDVI_{720}$; and B1= 550 nm and B2 = 800 for GNDVI.

All measurements were made at two crop growth stage, V6 and V10 (Ritchie and Hanway, 1986), on three tagged plants within an area of 0.5 m^{-2}, per plot. The central position of each measurement area was georreferenced using a GNSS R4 (Trimble Navigation Limited, Sunnyvale, CA, US) with a horizontal precision of about +/-2 cm. These georreferenced positions were used to identify the measurements areas as AOI (areas of interest) in photograph analysis.

An UAS system Gatewing X100 (Trimble Navigation Limited, Sunnyvale, CA, US.) was used to obtain aerial photograph. The system was programmed to carry out takeoff and landing in an autonomous manner. The flights over the experimental field were performed at V6 (22 November) and V10 (5 December) growth stage. Flights were performed around midday to get similar solar illumination and minimize shading between plants. Ground based spatial resolutions of 5 and 12.6 cm were obtained from two different flight heights (150 and 360 m). The flight plans to survey the field which includes the experiment were programmed to obtain 80% forward and side to side overlap. Ground control points were located in the field and georreferenced to ortho-rectificate the mosaic.

The UAS was equipped with a digital camera (RICOH, GR Digital IV 10 Mp) modified by the extraction of the internal near-infrared blocking filter and the inclusion of a visible light-blocking filter. At V6 growth stage a Yellow-8 filter (Tiffen, Hauppauge, NY, US) was used, and at V10 growth stage an X-Nite 650 (LDP-LLC Max-Max, Carlstadt, NJ, US). Camera settings were shutter velocity of 1/2000, ISO sensitivity at 80, and F value of 4.

Aerial photograph were processed with the photogrammetry module from Trimble Business Center (Trimble Navigation Limited, Sunnyvale, CA, US) to obtain an ortho-rectificated mosaic. Normalized differences vegetation indices were calculated using Erdas Imaging 9.2 (Leica Geosystem Geospatial Imaging LLC). At V6 NDVI and GNDVI were calculated, and at V10 an index considering digital counts of bands 1 and 3 was calculated as: $I_{1\text{-}3} = (B_1 - B_3)/(B_1 + B_3)$. Data were extracted from the images using AOI of different dates and images (Figure 1).

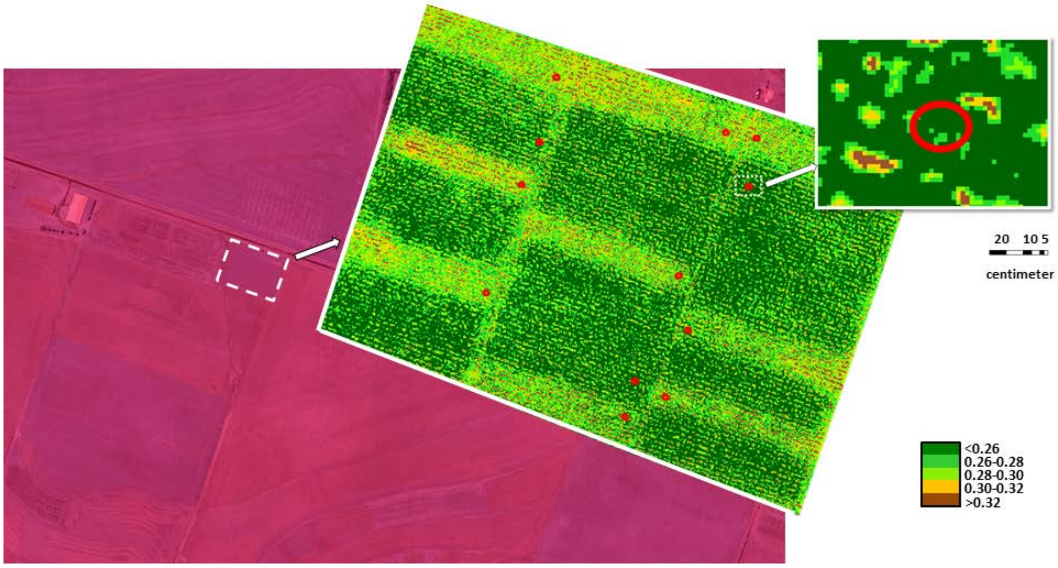


Figure 1. Image of ortho-rectificated mosaic obtained with a modified Ricoh GR IV camera at INTA Parana experimental field in a flight height of 150 m. R (b1):G(b2):B(b3). In front image of the normalized vegetation index calculated with bands 1 and 3 (I_{1-3} index). Insert (white pointed line) delimitate the nitrogen fertilizer experiment in maize at V10 growth stage. Red circles on experiment and detail are AOI (0.25 m^2) where crop variables and vegetation indices were measured.

The statistical analysis of the results including ANOVA, means comparisons by Tukey test (α= 0.05), simple correlations between variables, and linear regressions between crop variables and vegetation indices were performed with InfoStat v 1.1 (InfoStat, 2002). Additionally, vegetation indices sensitivity to crop variables was evaluated as Viña and Gitelson (2005).

RESULTS AND DISCUSSION

Nitrogen fertilizer not modified significantly, as expected, the growth variables evaluated (biomass and LAI) neither in V6 nor V10 growth stage, probably due to high plant to plant variability in the smalls selected AOI (Table 1). However, the measured variables range was wide enough to evaluate relationships between N status and vegetation indices.

Crop N status evaluated by SPAD, Green Seeker and vegetation indices $NDVI_{720}$ and GNDVI were similar among rates at V6 (Table 2). SPAD showed significant differences between non-fertilized and the highest rate at V10. Green seeker measurements not showed a clear trend in relation to N rates. N276 was similar to N0 and N138 and significantly different of N69. $NDVI_{720}$ and GNDVI showed similar results with significant differences only for N276.

Although crop variables not showed differences due to N rates, sensors readings allow discriminate some differences, probably because these measures integrate biomass, LAI and greenness variations (Gitelson, 2004; Viña et al., 2004).

Table 1. Biomass and LAI measured at V6 and V10 growth stage in maize from different nitrogen fertilization rates at sowing (0, 69, 138 and 276 kg N ha^{-1}).

Variables	Growth stage	N0	N69	N138	N276
Biomass	**V6**	65.8a	63.3a	68.5a	93.9a
g pl^{-1}	**V10**	212a	212a	226a	395a
LAI	**V6**	0.73a	0.73a	0.75a	0.95a
m^2 m^{-2}	**V10**	2.04a	2.05a	2.05a	2.92a

Table 2. SPAD and Green Seeker readings in maize at V10 growth stage from different nitrogen fertilization rates at sowing. GS = NDVI from Green Seeker sensor; $NDVI_{720}$ and GNDVI = vegetation indices from measurement obtained with an Ocean Optic sensor USB 4000.

Variables	Growth stage	N0	N69	N138	N276
SPAD	**V6**	39.6a	42.0a	40.3[a]	40.6a
	V10	37.5a	39.2ab	38.9ab	53.1b
GS	**V6**	0.47a	0.52a	0.49[a]	0.50a
	V10	0.74ab	0.72a	0.76ab	0.82b
$NDVI_{720}$	**V6**	0.16a	0.17a	0.15[a]	0.21a
	V10	0.27a	0.26a	0.27[a]	0.45b
GNDVI	**V6**	0.44a	0.46a	0.42[a]	0.48a
	V10	0.57a	0.55a	0.57[a]	0.72b

Nitrogen rate was significantly correlated with crop variables, biomass and LAI, and was not correlated with any of the evaluated indices at V6 (Table 3). Biomass and LAI were correlated between them, and both with $NDVI_{720}$ and GNDVI. Green Seeker, SPAD, and vegetation indices obtained from aerial photographs were not correlated with crop variables and N. The lack of relation between the vegetation indices and the crop variables could be due to IR band saturation. The IR band saturation was confirmed looking at photographs histograms, despite of camera setting were performed as better as possible, considering focal distance F, shutter velocity, and ISO sensitivity. In order to avoid IR band saturation, at V10 flight another filter was evaluated.

The correlations between crop variables and vegetation indices were more closed at V10 than at V6 (Tables 3 and 4). This improvement in the relationships could be due to an increase of crop growth and N uptake between growth stages (Ritchie and Hanway, 1982).

At V10 all evaluated crop variables and sensors readings were significantly correlated (Table 4). Photograph at the highest spatial resolution used to calculate the I_{1-3} showed very high correlations with crop variables. The LAI at V10 was below 3, value indicated as a limit above which VI such as NDVI reaches a saturation level (Gilabert et al., 1996; Gitelson et al., 2004). Therefore all the evaluated indices showed a similar performance. Despite of the differences in size and shape of the field of view among the commercial sensors used, $NDVI_{720}$, GNDVI, SPAD, and GS, all the indices were alike correlated with the index I_{1-3} obtained at both ground spatial resolutions of aerial photograph (5 and 12.6 cm). Another studies report similar relationships between photograph derived VI and crop variables (Scharf and Lory, 2002; Flowers et al., 2003; Sripada et al., 2005).

Lebourgeois et al. (2008) recommend perform detailed correction of the images obtained with a RGB modified camera to monitor crop variables. However, the VI obtained without any correction performed satisfactorily. According the results, the direct use of photograph to calculate VI could be suggested as a useful and simple procedure to evaluate crop conditions and as a tool to prescribe nitrogen variable rate.

Table 3. Crop variables and sensor readings correlations at V6 in maize. GS = NDVI from Green Seeker sensor; $NDVI_{720}$ and GNDVI = vegetation indices from measurement obtained with an Ocean Optic sensor USB 4000; I_{1-3} = normalized difference vegetation index using Bands 1 and 3 of aerial photographs obtained with a modified Ricoh digital camera (model RG), equipped with a high band pass filter (XNite665)

	N	**SPAD**	**Biomass**	**LAI**	**GS**	**$NVDI_{720}$**	**GNDVI**	**$NDVI^{\#}$**	**$GNDVI^{\#}$**	**NDVI***
SPAD	0.04									
Biomass	$0.71^{\dagger}$	0.20								
LAI	$0.65^{\dagger}$	0.19	$0.96^{\dagger\dagger\dagger}$							
GS	0.12	0.45	0.31	0.26						
NVDI720	0.38	-0.09	$0.74^{\dagger}$	$0.73^{\dagger}$	0.23					
GNDVI	0.24	-0.21	$0.59^{\dagger}$	$0.61^{\dagger}$	0.13	$0.97^{\dagger\dagger\dagger}$				
$NVDI^{\#}$	-0.26	-0.09	-0.15	-0.04	0.32	-0.20	-0.19			
$GNDVI^{\#}$	0.18	0.11	0.33	0.42	$0.66^{\dagger}$	0.29	0.18	$0.58^{\dagger}$		
NDVI*	-0.54	-0.13	-0.57	-0.48	0.18	-0.46	-0.39	$0.87^{\dagger\dagger\dagger}$	0.40	
GNDVI*	-0.25	0.07	-0.25	-0.16	0.55	-0.10	-0.12	0.58	0.81	$0.69^{\dagger}$

$^{\#}$ 5 cm ground based spatial resolution. * 12.6 cm ground based spatial resolution; $^{\dagger, \dagger\dagger, \dagger\dagger\dagger}$ Significant at 0.05, 0.01 and 0.001 level, respectively.

Table 4. Crop variables and sensor readings correlations at V10 in maize. GS = NDVI from Green Seeker sensor; $NDVI_{720}$ and GNDVI = vegetation indices from measurement obtained with an Ocean Optic sensor USB 4000; I_{1-3} = normalized difference vegetation index using Bands 1 and 3 of aerial photographs obtained with a modified Ricoh digital camera (model RG), equipped with a high band pass filter (XNite665)

	N	**SPAD**	**Biomass**	**IAF**	**GS**	**$NDVI_{720}$**	**GNDVI**	**$I_{1-3}^{\#}$**
SPAD	$0.78^{\dagger\dagger\dagger}$							
Biomass	$0.76^{\dagger\dagger}$	$0.88^{\dagger\dagger\dagger}$						
IAF	$0.59^{\dagger}$	$0.78^{\dagger\dagger\dagger}$	$0.93^{\dagger\dagger\dagger}$					
GS	$0.72^{\dagger}$	$0.72^{\dagger}$	$0.89^{\dagger\dagger\dagger}$	$0.76^{\dagger\dagger\dagger}$				
$NVDI_{720}$	$0.81^{\dagger\dagger\dagger}$	$0.94^{\dagger\dagger\dagger}$	$0.89^{\dagger\dagger\dagger}$	$0.81^{\dagger\dagger\dagger}$	$0.74^{\dagger}$			
GNDVI	$0.79^{\dagger\dagger\dagger}$	$0.94^{\dagger\dagger\dagger}$	$0.86^{\dagger\dagger\dagger}$	$0.77^{\dagger\dagger\dagger}$	$0.71^{\dagger}$	$0.99^{\dagger\dagger\dagger}$		
$I_{1-3}^{\#}$	$-0.83^{\dagger\dagger\dagger}$	$-0.89^{\dagger\dagger\dagger}$	$-0.92^{\dagger\dagger\dagger}$	$-0.90^{\dagger\dagger\dagger}$	$-0.78^{\dagger\dagger\dagger}$	$-0.92^{\dagger\dagger\dagger}$	$-0.89^{\dagger\dagger\dagger}$	
I_{1-3}*	$-0.74^{\dagger}$	$-0.89^{\dagger\dagger\dagger}$	$-0.76^{\dagger\dagger\dagger}$	$-0.64^{\dagger}$	$-0.57^{\dagger}$	$-0.94^{\dagger\dagger\dagger}$	$-0.94^{\dagger\dagger\dagger}$	0.79

$^{\#}$ 5 cm ground based spatial resolution. * 12.6 cm ground based spatial resolution. $^{\dagger, \dagger\dagger, \dagger\dagger\dagger}$ Significant at 0.05, 0.01 and 0.001 level, respectively.

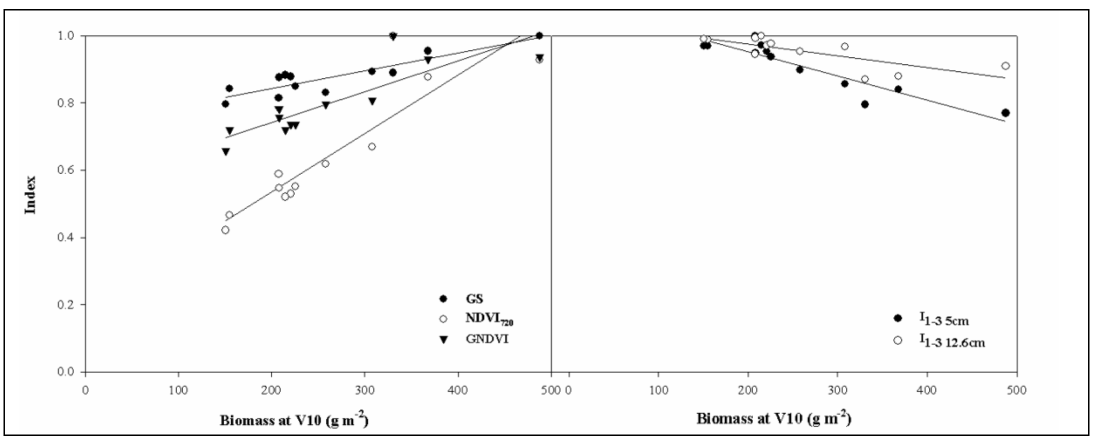
Table 5. Crop variables measured at V10 in maize and vegetation indices relationships. GS = NDVI from Green Seeker sensor, $NDVI_{720}$ and GNDVI = vegetation indices from measurement obtained with an Ocean Optic sensor USB 4000, I_{1-3} = normalized difference vegetation index using Bands 1 and 3 of aerial photographs obtained with a modified Ricoh digital camera (model RG), equipped with a high band pass filter (XNite665)

Independent variable	Dependent variable	Intercept	Slope	r^2	P value	RMSE	Sensitivity
LAI (cm^2 cm^{-2})	GS	0.62	0.06	0.58	<0.01	0.033	0.55
	NVDI 720	0.03	0.13	0.65	<0.01	0.057	0.44
	GNDVI	0.37	0.10	0.59	<0.01	0.053	0.53
	I_{1-3} #	0.36	-0.04	0.81	<0.001	0.010	0.26
	I_{1-3} *	0.28	-0.01	0.41	<0.05	0.009	0.95
Biomass (g m^{-2})	GS	0.64	4.6 E-04	0.79	<0.001	0.024	51.4
	NVDI 720	0.09	8.4 E-04	0.80	<0.001	0.044	51.9
	GNDVI	0.42	6.9 E-04	0.73	<0.001	0.042	61.5
	I_{1-3} #	0.34	-2.2E-04	0.85	<0.005	0.010	43.4
	I_{1-3} *	0.28	-9.1E-05	0.57	<0.001	0.008	87.9

[#] 5 cm ground based spatial resolution. * 12.6 cm ground based spatial resolution.

Vegetation indices were more closely related with biomass than LAI at V10, except I_{1-3} which showed a close relationship with both variables when was calculated from high ground spatial resolution photograph (5 cm pixel size) (Table 5). All indices were related with biomass and LAI showing different regression slopes. A high slope increases the capability to detect changes in crops condition, but an adequate index additionally requires a closed fit of the regression. Viña and Gitelson (2005) proposed a sensitivity index, calculated as a ratio between RMSE and the regression models slope. The best sensitivity was determined for I_{1-3} at 5 cm ground spatial resolution (Table 5), mainly due to very close fits of the relationships between I_{1-3} with biomass and LAI.

In order to compare the indices in an easily manner, a normalization procedure calculated as ratio with the maximum value was applied (Figure 2). The relationships between crop variables and VI obtained using commercial sensors showed higher slopes than photograph index. Nevertheless, their sensitivity was lower due to a less fit. The results obtained at two flight heights showed a striking difference in the I_{1-3} performance, the higher the photograph resolution the higher the sensitivity. The selected areas used (AOI) were small (0.25 m^2), however the spectral signatures obtained depending on different proportion of plant and soil coverage and the pixel size. High resolution photograph allow obtaining a major proportion of pure pixels of soil and vegetation within each AOI, therefore a wide range of values of VI was determined.



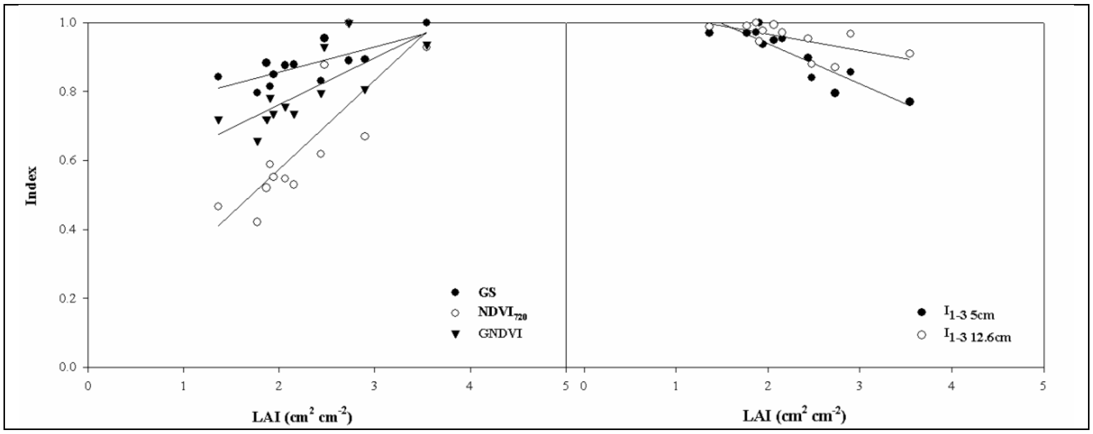


Figure 2. Relationship between maize aboveground biomass and LAI at V10, and vegetation indices obtained with different devices: GS = NDVI from Green Seeker sensor, $NDVI_{720}$ and GNDVI = vegetation indices from measurement obtained with an Ocean Optic sensor USB 4000, I_{1-3} (5cm), and I_{1-3} (12.6cm) = normalized difference vegetation index using Bands 1 and 3 of aerial photographs obtained with a modified Ricoh digital camera (model RG), equipped with a high band pass filter (XNite665)

High resolution digital cameras are common and suggested as an advantage to perform crops surveys (Gómez-Candón et al., 2014). However, the use of high resolution images demands high processing capacity and expensive software. An issue that remains to be answered is what spatial resolution to characterize the N status in maize and prescribe N variable rate is required.

These results belong to an ongoing study that includes observations at different levels, from AOI within plots up to on farm N rate strips in maize. Preliminarily, we could detect changes in biomass and LAI with very high precision using VI calculated from an uncorrected aerial photograph obtained with a modified RGB camera at V10 growth stage. Images with pixel size of 5 cm outperformed images with 12.6 cm pixel size when the study was carried out at plots level.

REFERENCES

Batchelor, W.D.; Basso, B. and J.O. Paz. 2002. Examples of strategies to analyze spatial and temporal yield variability using crop models. European Journal of Agronomy. 18:141-158.

Fiez, T.E.; Miller, B.C. and W.L. Pan. 1994. Winter wheat yield and grain protein across varied landscape positions. Agronomy Journal. 86:1026-1032.

Flowers, M.; Weisz, R.; Heiniger, R.; Tarleton, B. and A. Meijer. 2003. Field Validation of a Remote Sensing Technique for Early Nitrogen Application Decisions in Wheat. 95 (1): 167-176.

Gilabert, M.A.; Gandía, S.; and J. Meliá. 1996. Analysis of spectral-biophysical relationships for a corn canopy. Remote Sensing of Environment. 55:11-20.

Gitelson, A.A. 2004. Wide dynamic range vegetation index for remote quantification of biophysical characteristics of vegetation. Journal of Plant Physiology. 161:165-173.

Gómez-Candón, D.; De Castro, A. I. and F. López-Granados. 2014. Assessing the accuracy of mosaics from unmanned aerial vehicle (UAV) imagery for precision agriculture purposes in wheat. Precision Agriculture. 15:44–56.

Lamb, D. W., Trotter, M. G., & Schneider, D. A. 2009. Ultra low-level airborne (ULLA) sensing of crop canopy reflectance: A case study using a Crop CircleTM sensor. Computers and Electronics in Agriculture. 69: 86–91.

Lebourgeois V., Bégué, A. Labbé, S.; Mallavan, B.; Prévot, L. and B. Roux. 2008. Can commercial digital cameras be used as multispectral sensors? A crop monitoring test. Sensors. 8: 7300-7322.

Mamo, M.; Malzer, G.L.; Mulla, D.J.; Huggins, D.R. and J. Strock. 2003. Spatial and temporal variation in economically optimum nitrogen rate for corn. Agronomy Journal. 95: 958–964.

Melkonian, J. van Es, H. M. and L. Joseph. 2005. Precision nitrogen management model: simulation of nitrogen and water fluxes in the soil-crop-atmosphere continuum in maize (Zea mays L.) production systems. Version 1.0. Dept. of Crop and Soil Science, Research Series Nº R 05-2. Cornell University, Ithaca, NY, USA.

Montgomery, E. G. 1911. Correlation studies of corn. Nebraska, Agr. Esp. Sta. 24th Ann. Rpt.

Mulla, D.J. and J.S. Schepers. 1997. Key processes and properties for site-specific soil and crop management. In: The State of Site Specific Management for Agriculture. Ed: F.J. Pierce and E.J. Sadler. ASA-CSSA-SSSA. Madison, WI.

Raun, W. R.; Solie, J. B.; Stone, M. L.; Martin, K. L.; Freeman, K. W.; Mullen, R. W.; Zhang, H.; Schepers, J. S. and G. V. Johnson. 2005. Optical Sensor-Based Algorithm for Crop Nitrogen Fertilization. Communications in Soil Science and Plant Analysis. 36: 2759–2781.

Raun W.R. and J.S. Schepers. 2008. Nitrogen management for improved use efficiency. In: Nitrogen in Agricultural Systems. Ed: Schepers J.S and W. Raun ASA-CSSA-SSSA. Madison, WI.

Scharf, P.C.; Shannon, D.K.; Palm, H.L.; Sudduth, K.A.; Drummond, S.T.; Kitchen, N.R.; Mueller, L.J.; Hubbard, V.C. and L.F. Oliveira. 2011. Sensor-based nitrogen applications out-performed producer-chosen rates for corn in on-farm demonstrations. Agronomy Journal. 103(6):1683-1691

Scharf, P.C. and J.A. Lory. 2002. Calibrating corn color from aerial photographs to predict sidedress nitrogen need. Agronomy Journal. 94(3):397–404.

Solari, F., Shanahan, J., Ferguson, R., Schepers, J., Gitelson, 2008. Active sensor reflectance measurements of corn nitrogen status and yield potential. Agronomy Journal. 100 (3): 571-579.

Sripada, R.P.; Heiniger, R.W.; White, J.G and R. Weisz. 2005. Aerial Color Infrared Photography for Determining Late-Season Nitrogen Requirements in Corn. Agronomy Journal. 97: 1443-1451.

Vega, C. R.C. and V. O. Sadras. 2003. Size-dependent growth and the development of inequality in maize, sunflower and soybean. Annals of Botany. 91: 795-805.

Vélez, J. P. 1; Melchiori, R.J.M. 2, Méndez, A. 1; Villaroel, D. 1, Scaramuzza, F. 2012. Fotografía aérea multiespectral para el diagnóstico de fertilización nitrogenada por sitio especifico en maíz. In: 10mo Curso Internacional de Agricultura de Precisión y 5ta Expo de Máquinas Precisas, Córdoba-Argentina.

Viña, A.; Gilteson, A.A.; Rundquist, D.C.; Keydan, G.; Leavittand, B and J. Schepers. 2004. Monitoring maize (Zea mays L.) phenology with remote sensing. Agronomy Journal. 96:1139-1147.

Viña A. and A.A. Gitelson. 2005. New developments in the remote estimation of the fraction of absorbed photosynthetically active radiation in crops. Geophysical Research Letters. 32:L17403.

Zhang, C. and J. M. Kovacs. 2012. The application of small unmanned aerial systems for precision agriculture: a review. Precision Agriculture. 13: 693-712.