Hurricane Irma and Maria's effect on the vegetation of secondary forests dominated by the Indian almond tree (*Terminalia catappa*)

by

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Introduction

Between the 19th century and the early 20th century, most of Puerto Rico's land cover was constantly exposed to intense anthropogenic disturbances, which facilitated the establishment and naturalization of nonnative tree species such as the Indian Almond tree (Grau et al., 2003; Little et al., 1977; Lugo, 2004). The Indian Almond tree is a widely distributed species in Puerto Rico that forms monodominant novel stands in littoral dunes and coastal zones previously used for coconut plantations (Francis and Lowe, 2000b; Little et al., 1977; Weaver and Gould, 2013). Coastal novel forests dominated by *T. catappa* can sustain a variety of ecosystem services such as biodiversity conservation, shoreline protection, nutrient storage and cycling, as well as providing recreational and touristic areas (Hobbs et al., 2014; Martínez et al., 2007). An improvement in knowledge of coastal novel forests dominated by *T. catappa* can be a basis for improved context-specific recommendations and management decisions that account for coastal novel forests (Hobbs et al., 2014). Therefore, if managed well, forests dominated by *T. catappa* may be of great importance to our society as a natural resource.

To improve context-specific recommendations and management decisions, environmental factors that affect the species assemblages in Puerto Rico must be accounted for (Ewel and Whitmore, 1973; Marcano-Vega et al., 2015). The ecosystems of Puerto Rico are subject to the effects of hurricanes every ten years, such as the recent category 4 Hurricane Maria, on September 20, 2017 (Lugo, 2008; Pasch et al., 2018). Months after Hurricane Maria's passing, the vegetation index loss of 31 percent on Puerto Rico was correlated to the hurricane's intensity and distance, even though landscape and forest fragmentation also had an effect (Feng et al., 2018; Van Beusekom et al., 2018). Nevertheless, further remotely sensed data and analysis are needed to provide more precise estimates of the hurricane's effects on the vegetation of specific forests and the possible role of coastal forests as costal protection from hurricanes.

To provide a better understanding of the effect hurricanes on coastal novel forest dominated by *T. catappa* the following study question was established: How was the successional trajectory of the forest dominated by the Indian Almond tree affected after Hurricane Irma and Maria? This question will be answered by evaluation three different vegetation indexes using satellite images of forest before and periodically after Hurricane Irma and Maria. It expect a decrease in the vegetation indexes immediately after Hurricane Irma and Maria, followed by a steady increase in the vegetation indexes after the hurricanes, as well as, differences between the different vegetation indexes through the dates evaluated. Consequently, this study will provide remotely sensed information as a base to which future experiments, regarding hurricane effects on secondary coastal forests, can use as a starting point, as well as, improve and complement the already established knowledge.

Objectives

- Study the dynamics of the vegetation succession on "Survival beach" forest dominated by *T. catappa* after Hurricane Irma and Maria.

Methods

Survival beach, is located in the subtropical moist zone of Puerto Rico, specifically in Aguadilla (Ewel and Whitmore, 1973). The Sentinel-2A satellite images (see Figure 1) of Survival beach were obtained from EarthExplorer the following four dates: (1) September 6, 2017, (2) October 25, 2017, (3) October 30, 2018 and (4) October 25, 2019. The Normalized Difference Vegetation Index (NDVI), Soil Adjusted Vegetation Index (SAVI) and Enhanced Vegetation Index (EVI) of each satellite image was analyzed as provided in Jensen (2014) with ArcGIS software (ESRI, 2011). After analyzing the vegetation indexes (see Figure 1) of the satellite images, the symbology of the images was changed to classify and classified as six groups ranging from -1 to 0, 0 to 0.2, 0.2 to 0.4, 0.4 to 0.6, 0.6 to 0.8 and 0.8 to 1 (Van Beusekom et al., 2018). Then, the program was trained to differ between the different ranges in the images to perform a Maximum Likelihood Classification. All of the supervised classifications were then changed from raster to polygon (see Figure 1) with "Raster to polygon" tool, the area of interest was clipped and dissolved. The information obtained at this point was displayed as layouts with coordinates, north arrow, legends, titles and descriptions.

The data information from the previous prosses was exported to an Excel work sheet and, then, statistical analysis was obtained with Infostat. Two analysis of variance (ANOVA) were obtained by (1) classifying the independent variables, indexes and dates, the dependent variable was the area segregated by range, and (2) classifying the independent variables, indexes and range, the dependent variable was area segregated by dates. This information was displayed in two separate box plots with the same specifications as the ANOVA's.

Results and discussion

There are some visible variations between the NDVI of Survival beach before and periodically after Hurricane Irma and Maria (see Image 1), but these variations cannot be quantified from the image alone and it cannot be determined if there are statistical differences between them. By obtaining the area occupied by the range of vegetation index in every image, I was able to quantify and compare the areas between vegetation indexes and ranges in the indexes. As result, it was found that there is a significant difference (See appendix and Image 2) of the sum of the areas of the vegetation index ranges between September 6, 2017 and October 25, 2017. Specifically, the largest difference between the dates previously mentioned was in the ranges 0.2 to 0.4 and 0.4 to 0.6. This decrease in the vegetation indexes concurs with the 31 percent vegetation greenness loss on Puerto Rico after Hurricane Irma and Maria. (Feng et al., 2018; Van Beusekom et al., 2018). Also, the average of the SAVI differed (see Appendix and Image 3) from the average of the other vegetation indexes in the 1 to 0.8 range. The SAVI takes into account the soil's effect on the vegetation index, therefor after Hurricane Irma and Maria the SAVI differed from the other vegetation indexes due to the abundant exposed land cover (Jensen 2014). Consequently, the SAVI might be the most precise vegetation index after the hurricanes, when compared with NDVI and EVI.

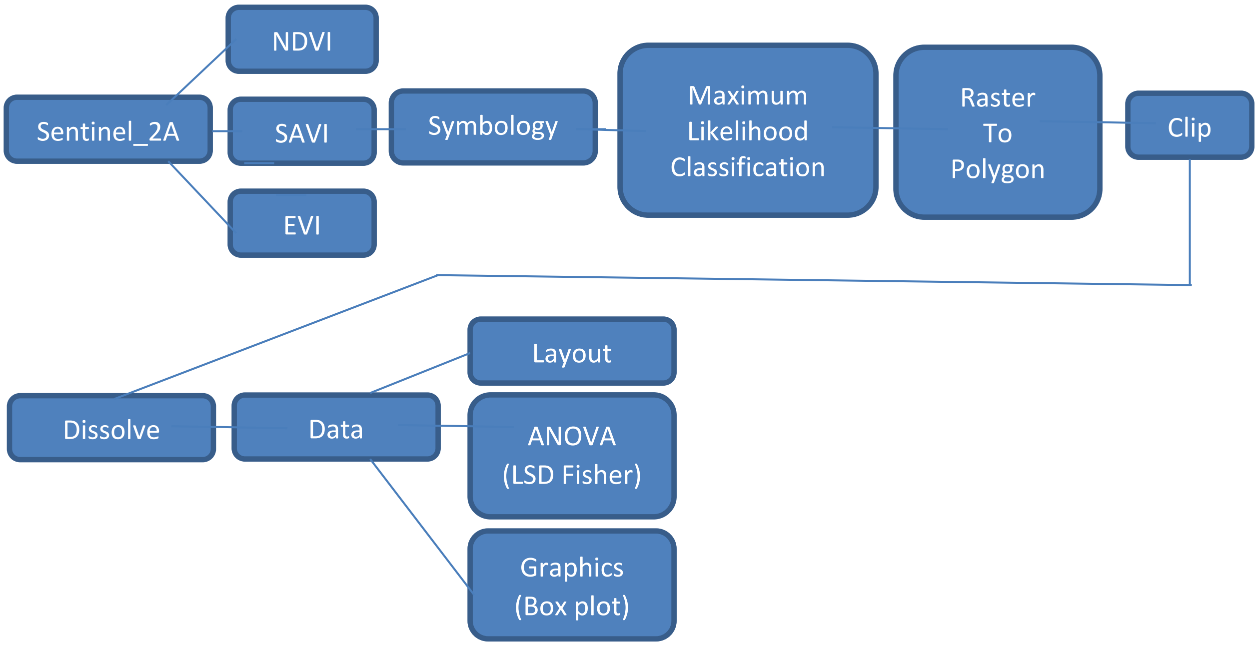

Figure 1. Flow chart of the procedure used in the study to determine the area ocupied by the different ranges of vegetation indexes before and after Hurricane Irma and Maria, statistical analysis and graphics.

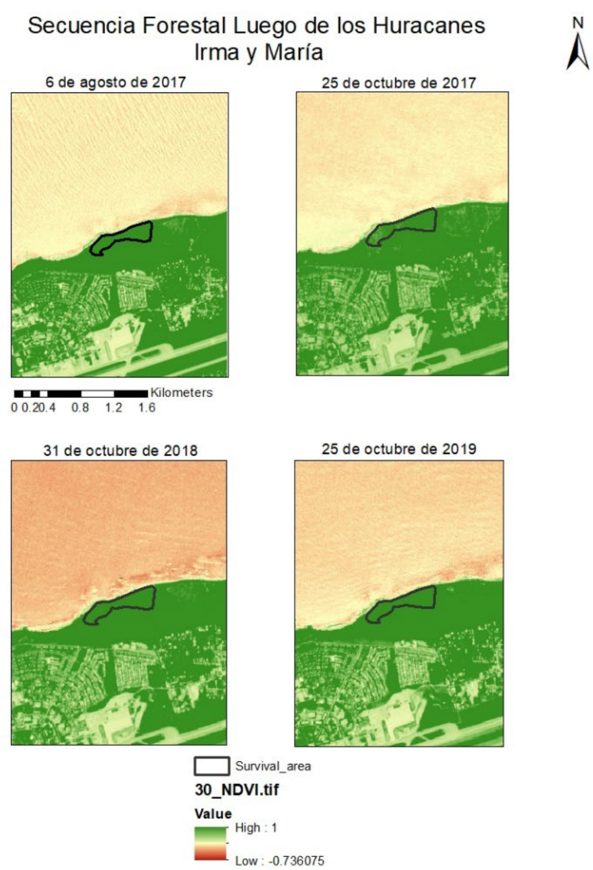

Image 1. A layout of the NDVI of Survival beach before and after Hurricane Irma and Maria.

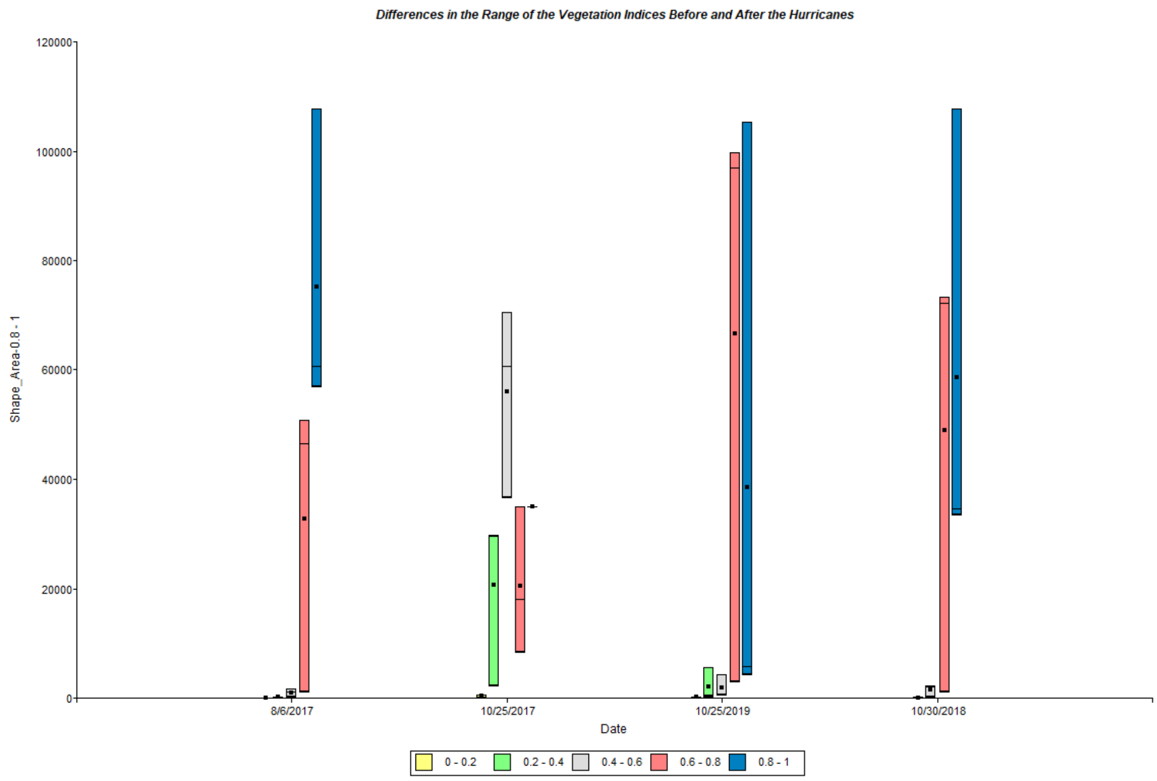

Image 2. Box plot of the area occupied the different vegetation index ranges before and after Hurricane Irma and Maria.

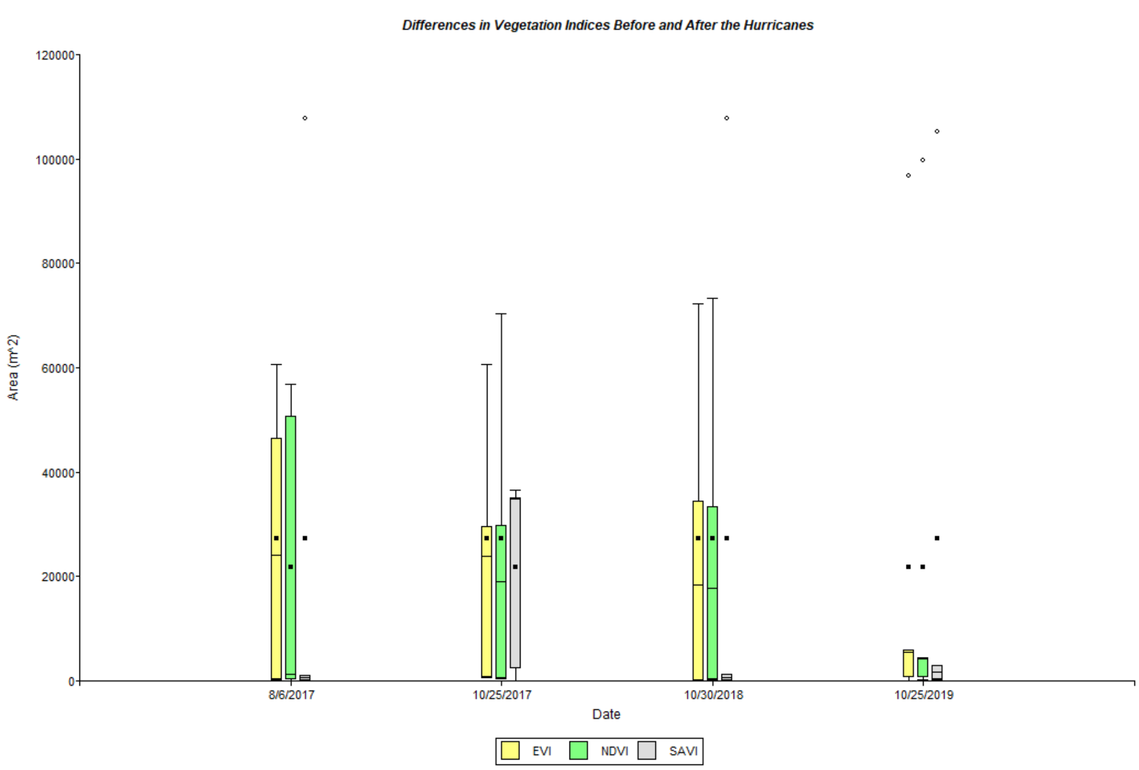

Image 3. Box plot of the area occupied the different vegetation indexes before and after Hurricane Irma and Maria.

Conclusion

In general, the vegetation indexes in Survival beach decreased after Hurricane Irma and Maria, but steadily increased each year. As expected, there are differences between the Survival beach vegetation indexes before and after the hurricanes. This difference is mainly seen in the immediate decrease of vegetation greenness after the hurricanes physical forces affected the forest vegetation. Additionally, there were differences between SAVI and the other vegetation indexes in the same dates. Consequently, the SAVI is the most precise vegetation index, in this instance, due to it taking into account the soils effect on the index while most of the land cover was exposed after the hurricanes. Also, there were differences between the sum of the area of some vegetation index ranges, whereas others, in the same date, remained unchanged.

Unfortunately, one of my two fellow students could not provide results, but the other, Natasha M. Torres Rios, did provide results that complement my findings. In them, Natasha explains that even though she could not compare the tree density from 2016 with the tree density of 2018, she did find a decrease in the tree height from the year 2016 to the year 2018. Like the vegetation index, tree height is a measure of structure, therefor they are related. Due to the dates of the decrease in tree height, it could be concluded that the physical effects of Hurricane Irma and Maria are responsible for this change, similar to how they affected the vegetation indexes in my study.

Recommendations

For future studies, the sample size must be larger in order to minimize the standard error in the statistical analysis, therefor, provide more precise conclusions. Also, the statistical analysis could be done in ArcGIS instead of Infostat. The quality of certain statistical analysis in ArcGIS could provide better results and publishing opportunities. Also, I would like to recommend more teamwork while doing this type of studies, because some of my coworker's findings reaffirmed my findings. Therefor, providing more weight to my conclusions.

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Appendix

Análisis de la varianza

Date	Variable	N	R^2	R^2 Aj	CV
8/6/2017	Shape Area	13	0.79	0.58	90.69

Datos desbalanceados en celdas.
Para otra descomposición de la SC
especifique los contrastes apropiados.. !!

Cuadro de Análisis de la Varianza (SC tipo I)

F.V.	SC	gl	CM	F	p-valor
Modelo	11912227415.62	6	1985371235.94	3.82	0.0640
Index	91375328.68	2	45687664.34	0.09	0.9171
range	11820852086.93	4	2955213021.73	5.68	0.0308
Error	3121533295.80	6	520255549.30		
Total	15033760711.41	12			

Test:LSD Fisher Alfa=0.05 DMS=38126.76731

Error: 520255549.2994 gl: 6

Index	Medias	n	E.E.	
NDVI	21798.00	5	10200.54	A
SAVI	27247.49	4	11404.56	A
EVI	27247.49	4	11404.56	A

Medias con una letra común no son significativamente diferentes (p > 0.05)

Test:LSD Fisher Alfa=0.05 DMS=53919.39142

Error: 520255549.2994 gl: 6

range	Medias	n	E.E.		
0 - 0.2	9.29	1	22809.11	A	
0.2 - 0.4	132.81	3	13168.85	A	
0.4 - 0.6	1014.83	3	13168.85	A	
0.6 - 0.8	32749.95	3	13168.85	A	B
0.8 - 1	75089.29	3	13168.85		B

Medias con una letra común no son significativamente diferentes (p > 0.05)

Date	Variable	N	R^2	R^2 Aj	CV
10/25/2017	Shape Area	13	0.80	0.60	57.73

Datos desbalanceados en celdas.
Para otra descomposición de la SC
especifique los contrastes apropiados.. !!

Cuadro de Análisis de la Varianza (SC tipo I)

F.V.	SC	gl	CM	F	p-valor
Modelo	5115681443.95	6	852613573.99	4.04	0.0566
Index	91375496.67	2	45687748.34	0.22	0.8112
range	5024305947.28	4	1256076486.82	5.96	0.0276
Error	1264876394.70	6	210812732.45		
Total	6380557838.66	12			

Test:LSD Fisher Alfa=0.05 DMS=24270.01484

Error: 210812732.4506 gl: 6

Index	Medias	n	E.E.	
SAVI	21797.99	5	6493.27	A
NDVI	27247.49	4	7259.70	A
EVI	27247.49	4	7259.70	A

Medias con una letra común no son significativamente diferentes (p > 0.05)

Test:LSD Fisher Alfa=0.05 DMS=34322.98415

Error: 210812732.4506 gl: 6

range	Medias	n	E.E.		
0 - 0.2	388.72	3	8382.77	A	
0.6 - 0.8	20417.38	3	8382.77	A	
0.2 - 0.4	20562.23	3	8382.77	A	
0.8 - 1	35067.88	1	14519.39	A	B
0.4 - 0.6	55932.35	3	8382.77		B

Medias con una letra común no son significativamente diferentes (p > 0.05)

Date	Variable	N	R^2	R^2 Aj	CV
10/30/2018	Shape Area	12	0.55	0.17	125.66

Cuadro de Análisis de la Varianza (SC tipo III)

F.V.	SC	gl	CM	F	p-valor
Modelo	8552341728.45	5	1710468345.69	1.46	0.3266
Index	0.00	2	0.00	0.00	>0.9999
range	8552341728.45	3	2850780576.15	2.43	0.1632
Error	7033852033.85	6	1172308672.31		
Total	15586193762.30	11			

Test:LSD Fisher Alfa=0.05 DMS=59241.25139

Error: 1172308672.3087 gl: 6

Index	Medias	n	E.E.	
SAVI	27247.49	4	17119.50	A
NDVI	27247.49	4	17119.50	A
EVI	27247.49	4	17119.50	A

Medias con una letra común no son significativamente diferentes (p > 0.05)

Test:LSD Fisher Alfa=0.05 DMS=68405.90487

Error: 1172308672.3087 gl: 6

range	Medias	n	E.E.	
0.2 - 0.4	74.40	3	19767.89	A
0.4 - 0.6	1475.68	3	19767.89	A
0.6 - 0.8	48891.13	3	19767.89	A
0.8 - 1	58548.77	3	19767.89	A

Medias con una letra común no son significativamente diferentes (p > 0.05)

Date	Variable	N	R²	R² Aj	CV
10/25/2019	Shape Area	14	0.44	0.00	182.96

Datos desbalanceados en celdas.
Para otra descomposición de la SC
especifique los contrastes apropiados.. !!

Cuadro de Análisis de la Varianza (SC tipo I)

F.V.	SC	gl	CM	F	p-valor
Modelo	10107842181.45	6	1684640363.57	0.92	0.5310
Index	84848675.79	2	42424337.90	0.02	0.9771
range	10022993505.66	4	2505748376.41	1.37	0.3346
Error	12781843367.59	7	1825977623.94		
Total	22889685549.04	13			

Test:LSD Fisher Alfa=0.05 DMS=66515.19886
Error: 1825977623.9416 gl: 7

Index	Medias	n	E.E.	
EVI	21797.99	5	19110.09	A
NDVI	21797.99	5	19110.09	A
SAVI	27247.49	4	21365.73	A

Medias con una letra común no son significativamente diferentes (p > 0.05)

Test:LSD Fisher Alfa=0.05 DMS=86528.77553
Error: 1825977623.9416 gl: 7

range	Medias	n	E.E.	
0 - 0.2	109.07	2	30215.70	A
0.4 - 0.6	1802.03	3	24671.02	A
0.2 - 0.4	2123.97	3	24671.02	A
0.8 - 1	38435.20	3	24671.02	A
0.6 - 0.8	66556.06	3	24671.02	A

Medias con una letra común no son significativamente diferentes (p > 0.05)

i. ANOVA with the independent variables, indexes and dates, the dependent variable was the area segregated by range.

Análisis de la varianza

range	Variable	N	R²	R² Aj	CV
0 - 0.2	Shape Area	6	0.98	0.88	37.84

Datos desbalanceados en celdas.
Para otra descomposición de la SC
especifique los contrastes apropiados.. !!

Cuadro de Análisis de la Varianza (SC tipo I)

F.V.	SC	gl	CM	F	p-valor
Modelo	325988.41	4	81497.10	10.55	0.2264
Index	71155.15	2	35577.57	4.61	0.3129
Date	254833.26	2	127416.63	16.50	0.1715
Error	7723.76	1	7723.76		
Total	333712.17	5			

Test:LSD Fisher Alfa=0.05 DMS=1234.54042
Error: 7723.7605 gl: 1

Index	Medias	n	E.E.	
SAVI	54.55	1	87.88	A
NDVI	201.22	3	50.74	A
EVI	367.69	2	62.14	A

Medias con una letra común no son significativamente diferentes (p > 0.05)

Test:LSD Fisher Alfa=0.05 DMS=1234.54042
Error: 7723.7605 gl: 1

Date	Medias	n	E.E.	
8/6/2017	9.29	1	87.88	A
10/25/2019	109.07	2	62.14	A
10/25/2017	388.72	3	50.74	A

Medias con una letra común no son significativamente diferentes (p > 0.05)

range	Variable	N	R^2	R^2 Aj	CV
0.2 - 0.4	Shape Area	12	0.74	0.53	135.43

Cuadro de Análisis de la Varianza (SC tipo III)

F.V.	SC	gl	CM	F	p-valor
Modelo	1047501199.39	5	209500239.88	3.49	0.0801
Index	158563604.83	2	79281802.42	1.32	0.3350
Date	888937594.56	3	296312531.52	4.93	0.0465
Error	360493914.07	6	60082319.01		
Total	1407995113.46	11			

Test:LSD Fisher Alfa=0.05 DMS=13411.47605

Error: 60082319.0113 gl: 6

Index	Medias	n	E.E.	
SAVI	631.27	4	3875.64	A
NDVI	7658.24	4	3875.64	A
EVI	8880.54	4	3875.64	A

Medias con una letra común no son significativamente diferentes (p > 0.05)

Test:LSD Fisher Alfa=0.05 DMS=15486.23862

Error: 60082319.0113 gl: 6

Date	Medias	n	E.E.		
10/30/2018	74.40	3	4475.20	A	
8/6/2017	132.81	3	4475.20	A	
10/25/2019	2123.97	3	4475.20	A	
10/25/2017	20562.23	3	4475.20		B

Medias con una letra común no son significativamente diferentes (p > 0.05)

range	Variable	N	R^2	R^2 Aj	CV
0.4 - 0.6	Shape Area	12	0.94	0.90	54.37

Cuadro de Análisis de la Varianza (SC tipo III)

F.V.	SC	gl	CM	F	p-valor
Modelo	6901459329.04	5	1380291865.81	20.60	0.0010
Index	217089896.92	2	108544948.46	1.62	0.2738
Date	6684369432.12	3	2228123144.04	33.25	0.0004
Error	402075535.66	6	67012589.28		
Total	7303534864.70	11			

Test:LSD Fisher Alfa=0.05 DMS=14163.85377

Error: 67012589.2763 gl: 6

Index	Medias	n	E.E.	
SAVI	9337.52	4	4093.06	A
EVI	16300.46	4	4093.06	A
NDVI	19530.69	4	4093.06	A

Medias con una letra común no son significativamente diferentes (p > 0.05)

Test:LSD Fisher Alfa=0.05 DMS=16355.00957

Error: 67012589.2763 gl: 6

Date	Medias	n	E.E.		
8/6/2017	1014.83	3	4726.26	A	
10/30/2018	1475.68	3	4726.26	A	
10/25/2019	1802.03	3	4726.26	A	
10/25/2017	55932.35	3	4726.26		B

Medias con una letra común no son significativamente diferentes (p > 0.05)

range	Variable	N	R²	R² Aj	CV
0.6 – 0.8	Shape Area	12	0.65	0.37	69.60

Cuadro de Análisis de la Varianza (SC tipo III)

F.V.	SC	gl	CM	F	p-valor
Modelo	9782161540.11	5	1956432308.02	2.27	0.1732
Index	6176862932.78	2	3088431466.39	3.59	0.0944
Date	3605298607.33	3	1201766202.44	1.40	0.3322
Error	5165123478.12	6	860853913.02		
Total	14947285018.23	11			

Test:LSD Fisher Alfa=0.05 DMS=50765.41769

Error: 860853913.0203 gl: 6

Index	Medias	n	E.E.	
SAVI	10068.89	4	14670.16	A
NDVI	58008.53	4	14670.16	A
EVI	58383.46	4	14670.16	A

Medias con una letra común no son significativamente diferentes (p > 0.05)

Test:LSD Fisher Alfa=0.05 DMS=58618.85514

Error: 860853913.0203 gl: 6

Date	Medias	n	E.E.	
10/25/2017	20417.38	3	16939.64	A
8/6/2017	32749.95	3	16939.64	A
10/30/2018	48891.13	3	16939.64	A
10/25/2019	66556.06	3	16939.64	A

Medias con una letra común no son significativamente diferentes (p > 0.05)

range	Variable	N	R²	R² Aj	CV
0.8 – 1	Shape Area	10	0.94	0.86	26.86

Datos desbalanceados en celdas.
Para otra descomposición de la SC
especifique los contrastes apropiados.. !!

Cuadro de Análisis de la Varianza (SC tipo I)

F.V.	SC	gl	CM	F	p-valor
Modelo	13518623810.57	5	2703724762.11	12.33	0.0153
Index	7627545782.39	2	3813772891.20	17.40	0.0106
Date	5891078028.18	3	1963692676.06	8.96	0.0301
Error	876873916.73	4	219218479.18		
Total	14395497727.30	9			

Test:LSD Fisher Alfa=0.05 DMS=32135.69341

Error: 219218479.1824 gl: 4

Index	Medias	n	E.E.		
NDVI	31522.14	3	8548.26	A	
EVI	33655.56	3	8548.26	A	
SAVI	88938.64	4	7403.01		B

Medias con una letra común no son significativamente diferentes (p > 0.05)

Test:LSD Fisher Alfa=0.05 DMS=41108.11713

Error: 219218479.1824 gl: 4

Date	Medias	n	E.E.	
10/25/2017	35067.88	1	14806.03	A
10/25/2019	38435.20	3	8548.26	A
10/30/2018	58548.77	3	8548.26	A
8/6/2017	75089.29	3	8548.26	A

Medias con una letra común no son significativamente diferentes (p > 0.05)

ii. ANOVA with the independent variables, indexes and range, the dependent variable was area segregated by dates.