ILLICIT CROPS, PLANNING OF SUBSTITUTION WITH SUSTAINABLE CROPS BASED ON REMOTE SENSING. APPLICATION IN THE SIERRA NEVADA OF SANTA MARTA - COLOMBIA

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Abstract

This paper explores the use of remote sensing techniques for the planning of sustainable crops in the Sierra Nevada de Santa Marta (Colombia), in areas affected by deforestation caused by the spread of illicit crops. Remote sensing, digital cartography and satellite images were used to identify the places affected with coca crops; followed by a vegetation quality analysis using the normalized difference vegetation index (NDVI). This observation, combined with the test and modelling of environmental indices such as, hydrometeorological parameters (temperature, precipitation and relative humidity) were used to select sustainable crops to be considered in a simulation model for the study area. The results revealed that the range of NDVI index where coca crops are found is between 0.36 to 0.51; In addition, the results of the mathematical programming model recommend that mechanized rice, plantain and cassava should be cultivated, as substitute alternatives that maximize the profits and availability of farmers, according to the agroclimatic conditions that allow the development of sustainable crops.

The analytic protocol and the results of this work have the potential to better inform illegal crop substitution policy, the strategic planning of economic inclusion for the affected communities, and to inform and optimize the impact of field interventions, both, in the short and long term.

Key Words: Sustainable crops, simulation model, normalized difference vegetation index.

1. Introduction

Remote sensing methods, such as satellite imagery, are commonly used in environmental research due to their low current cost and even their free availability at satisfactory time and space resolutions, in addition to their easy processing with the map algebra tools of the GIS software (do Valle Júnior, y otros, 2019). Crop mapping and updating spatial information allow spatio-temporal monitoring of crops, contributing to planning and managing water resources, predicting yields and adapting agriculture to climate change (FAO: Food and Agriculture Organization, 2003). The identification of crops, their location and their extension are key properties for agricultural planning and best-use proposals.

These remote sensing techniques - and other similar - have been used for the detection and monitoring of illegal crops worldwide, with emphasis on the analysis of time series, GIS and GPS software, and the use of SPOT and Landsat images as documented by Lisita et al.,(2013); Armenteras et al., (2013) and Davalos et-al., (2011).

In the case of Colombia, illicit crops represent a big problem in different areas of the country because they affect the environment where they are found, generating conflicts in the social, economic and environmental fields. Being the Coca cultivation the one generating the most dramatic impact, and which cultiaviton in Colombia since 2013, has increased at an average rate of 45% per year, from 48,000 ha in 2013 to 146,000 ha in 2016 (UNODOC, 2017).

In an historical context, Colombia became a producer and exporter of marijuana in the 60s; cultivated in the Sierra Nevada de Santa Marta and in the Serranía del Perijá (Díaz & Sánchez, 2004). Since then, in the northern area of the Sierra Nevada de Santa Marta still a presence of illicit crops according to the United Nations Office on Drugs and Crime (UNODOC, 2017). The environmental and social problems in this area of the Sierra Nevada de Santa Marta have been generated by decades of deforestation of a large strip of forests for planting ilicit crops, in a practice in which these crops are camouflaged in the middle of the wild/native vegetation, but which can be located through satellite photos (Perez, 2001).

In relation to the management of illicit crops in Colombia, different approaches have been explored, moving from manual eradication and aerial fumigation with glyphosate, to more comprehensive and integral approaches involving policies of social and economic inclusion, development of infrastructure and crop substitution by crops with alternative/substitute local economic value. The manual eradication proved to be effective – but costly and slow - in mountain areas if combined with economic inclusion and effective law enforcement. However, more recent policies are promoting the use of glyphosate despite the controversy around it in terms of efficacy in the long run and health and ecosystemic cost (Solomon, et al., 2007). Regarding the call for a more comprehensive approach, the USAID report 2009 (Felbab-Brown, et al., 2009) advocated for the implementation of integral interventions in the affected territories, giving particular importance to the crop substitution – by crops with similar local economic value - followed by the delivery of infrastructure to facilitate the socio-economic inclusion of the communities involved.

To suppor the design of policies and field activities for the managent of illicit crops in Colombia, the monitoring of coca crops has been supported with the interpretation of medium resolution satellite images and the validation of data obtained by aerial reconnaissance (UNODOC, 2017). Similarly, a mapping of the types of crops and identification of the area of greatest cultivation was carried out in Morocco using data provided by the NDVI and LANDSAT 8 index for a highly fragmented and intensive agricultural system. The results of the study demonstrated that LANDSAT 8 satellite images will allow to achieve annual inventories of crops in irrigated, highly fragmented, heterogeneous and intensive agricultural systems (Ouzemou et al., 2018).
Also, from a field spectroradiometer, spectral signatures of coca crops have been captured according to their phenological status: juvenile, vegetative and mature (Angel, 2012). Furthermore, the use of statistical models have allowed estimating the yield of the crops under study from agroclimatic variables of the areas where they are found (Ramírez, y otros, 2019).

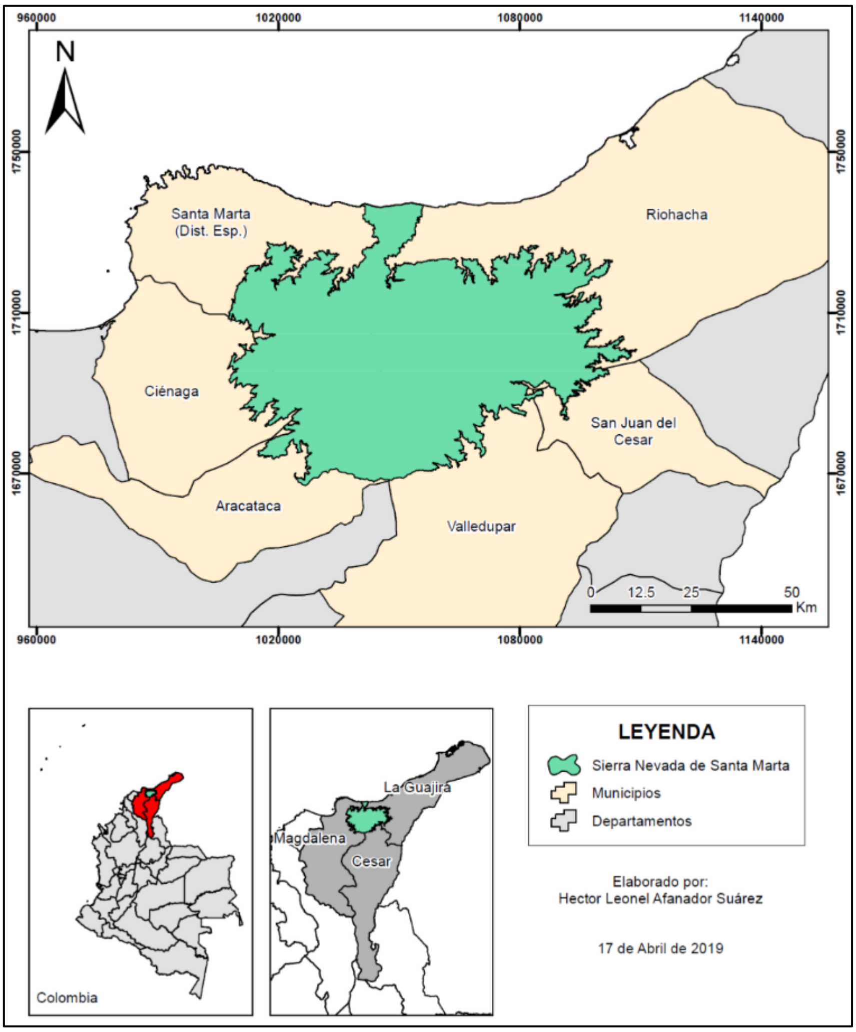
Within this context, this work was carried out with the purpose of searching for different sustainable crop planning alternatives in the Sierra Nevada de Santa Marta areas. where there are crops for illicit use through the analysis of environmental indices (vegetation, humidity, temperature, precipitation, among others) which will allow knowing the quantity and quality of vegetation, bodies of water and other properties necessary for decision-making.

2. Methodology

2.1. Study area

The project is developed in the Sierra Nevada de Santa Marta, specifically in the department of Magdalena and La Guajira, in the jurisdiction of the municipalities of Santa Marta Dist. Esp., Riohacha and Dibulla, and three Regional Autonomous Corporations CORPAMAG, CORPOCESAR, and CORPOGUAJIRA, as can be seen in Figure 1. The northern areas that have been historically afected by – the current expansion - of liicit crops.

Figura I. Study area location.



The Sierra Nevada de Santa Marta is a triangular territory of the Andes mountain range, located in the northeast of Colombia, around the geographical coordinates 10 ° 49'N and 73 ° 39'W. The north flank borders the Caribbean Sea from the flat and arid lands of the south of the La Guajira peninsula to the surroundings of the city of Santa Marta, at the mouth of the Manzanares River (Organizacion Colparques, n.d.). The stuy area is of interest not ust for the historical cultivation of illicit crops, but also for its biodiversity Including some portected areas), challenging topographic conditions, and socio-econimic importnace that involves native aborgin populations, settlers, and a diversity of agro-economic activites ranging from small farms to agroindustrial developmentes.

2.2. Data used and processing

In the present investigation, we used the vegetation index as an analysis tool to identify the vegetation cover (Ouzemou, y otros, 2018). The NDVI processing was developed from geoprocessing satellite images with ArcGIS Pro ver software. 2.4.1; which allows conducting different processes with Landsat satellite images obtained from the USGS (United States Geological Service) Earth Explorer platform (https://earthexplorer.usgs.gov/). Table I shows the periods chosen to carry out the investigation and identification of each of the Landsat images used in this study.

Table I. Landsat images used in the project.

DATE DD/MM/AAAA	LANDSAT IMAGE ID
20/12/1997	LT05_L1TP_008052_19971220_20161228_01_T1_B4
20/12/1997	LT05_L1TP_008052_19971220_20161228_01_T1_B3
20/07/1997	LT05_L1TP_009052_19970720_20161230_01_T1_B4
20/07/1997	LT05_L1TP_009052_19970720_20161230_01_T1_B3
30/06/1998	LT05_L1TP_008052_19980630_20161223_01_T1_B3
30/06/1998	LT05_L1TP_008052_19980630_20161223_01_T1_B4
17/03/1998	LT05_L1TP_009052_19980317_20161226_01_T1_B3
17/03/1998	LT05_L1TP_009052_19980317_20161226_01_T1_B4
26/12/1999	LT05_L1TP_008052_19991226_20161217_01_T1_B3
26/12/1999	LT05_L1TP_008052_19991226_20161217_01_T1_B4
15/01/1999	LT05_L1TP_009052_19990115_20161220_01_T2_B3
15/01/1999	LT05_L1TP_009052_19990115_20161220_01_T2_B4
29/01/2001	LT05_L1TP_008052_20010129_20161212_01_T1_B3
29/01/2001	LT05_L1TP_008052_20010129_20161212_01_T1_B4
05/02/2001	LT05_L1TP_009052_20010205_20161212_01_T1_B3
05/02/2001	LT05_L1TP_009052_20010205_20161212_01_T1_B4
11/09/2007	LT05_L1TP_008052_20070911_20161111_01_T1_B3
11/09/2007	LT05_L1TP_008052_20070911_20161111_01_T1_B4
18/09/2007	LT05_L1TP_009052_20070918_20161112_01_T1_B3
18/09/2007	LT05_L1TP_009052_20070918_20161112_01_T1_B4
04/01/2015	LC08_L1TP_008052_20150104_20170415_01_T1_B4
04/01/2015	LC08_L1TP_008052_20150104_20170415_01_T1_B5
27/11/2015	LC08_L1TP_009052_20151127_20170401_01_T1_B4
27/11/2015	LC08_L1TP_009052_20151127_20170401_01_T1_B5
30/12/2018	LC08_L1TP_008052_20181230_20190130_01_T1_B4
30/12/2018	LC08_L1TP_008052_20181230_20190130_01_T1_B5
05/12/2018	LC08_L1TP_009052_20181205_20181211_01_T1_B4
05/12/2018	LC08_L1TP_009052_20181205_20181211_01_T1_B5

Source: Author, 2019.

The NDVI index was performed through the processing of the bands of the satellite images; for Landsat 5 band 3 (Red) and 4 (Near Infrared), and Landsat 8 band 4 (Red) and 5 (Near Infrared) by of the following equation (Zaitunah, Samsuri, Ahmad, & Safitri, 2018):

$$NDVI = \frac{NIR-}{NIR+}, \qquad (1)$$

Where:

NIR: Near Infrared

RED: Reflectivity of the red band

The formulation of the simulation model of this research takes into account information related to the crops available to plant in the municipality of Santa Marta and Dibulla. The definition of each of the parameters used is described below.

Set:

$i \in I: Cropsreadyforseeding$Decision variable:

$$A_i: Amountofareasowforthecropi[ha]$$

Parameters:

$$Rend_i: Cropperformancei[ton/ha]$$

$$Precio_i: Cropvaluei[\$/ton]$$

$$Costos_i: Cropcosti[\$/ha]$$

$$A_{disp}: Areaavailableforthecrop[ha]$$

$$v_{disp}: Availableinvestment[\$]$$

$$E_i: \text{Estimated proportion for cultivation} i$$

The mathematical programming model has the following structure:

Objective function:

$$MaxZ_{utilidad}: [\sum_{i:1}^{n}(Rend_i * Precio_i * A_i) - (Costos_i * A_i)], \quad (1)$$

Restrictions:

$$\sum_{i:1}^{n}(Costos_i * A_i) \leq Inv_{disp}, \quad (2)$$

$$\frac{A_i}{A_{disp}} \geq E_i \forall i \in I, \quad (3)$$

$$\sum_{i:1}^{n} \frac{A_i}{A_{disp}} = 1, \quad (4)$$

$$\sum_{i:1}^{n} A_i \leq A_{disp}, \quad (5)$$

$$A_i \geq 0, \quad (6)$$

Equation (2) refers to the calculation related to the maximum utility that can be achieved by each of the selected crops, which meet the agroclimatic characteristics of the area, equation (3) limits the investment capacity of the takers of decision, equation (4), allows to establish proportionality conditions for different crops in the same available area, restrictions (5) and (6), allow the full use of the available area and limits its use according to its availability.

3. Results and Analysis

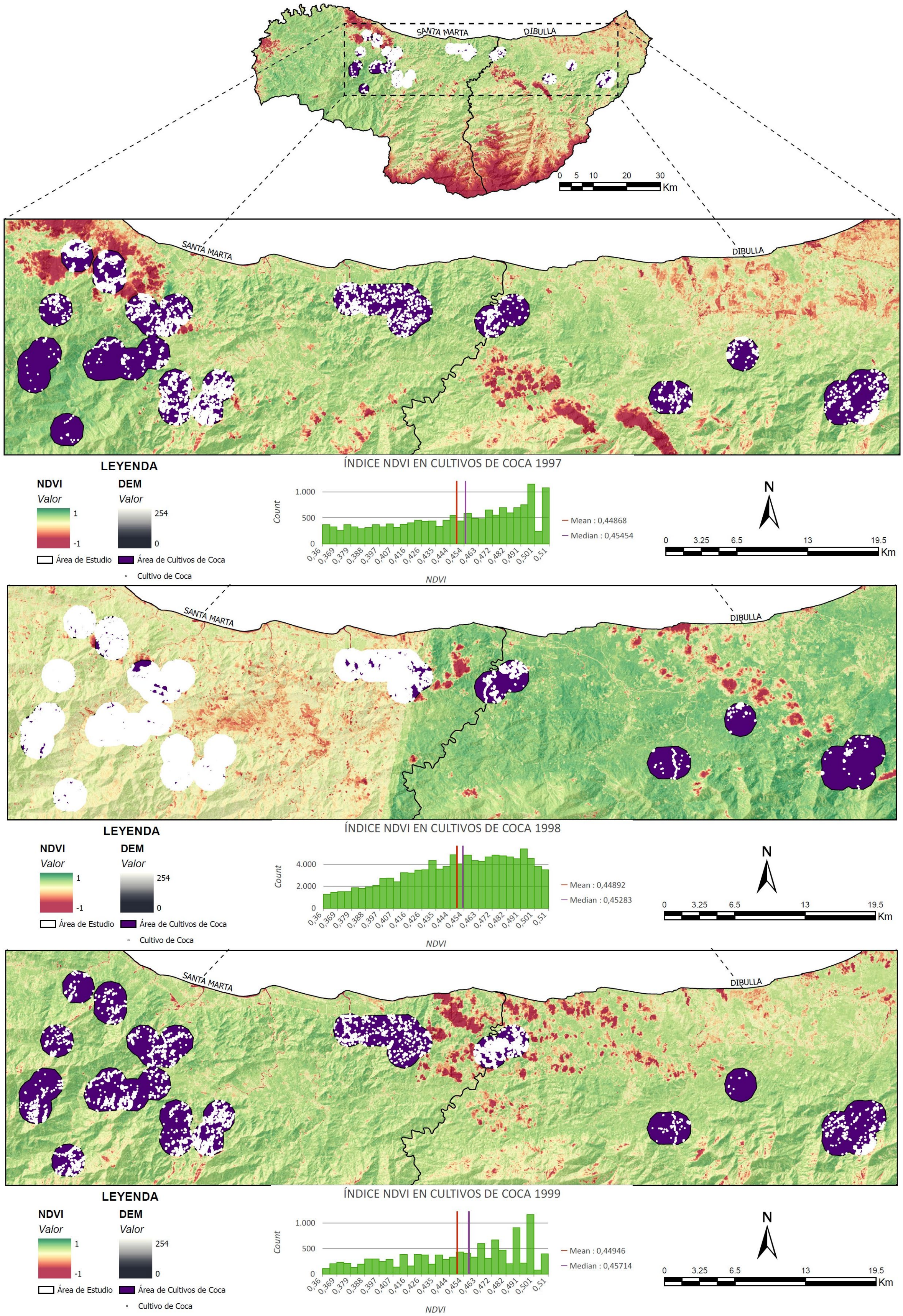
The NDVI index has been implemented over different periods in order to identify changes in the vegetation cover of the study area. The result of this indicator varies from -1 to 1, where the minimum value reflects bare soil, arid terrain, urban areas and/or rock on maps up to values close to 0 and values greater than 0 show soils with healthy and vigorous vegetation (Islam et al., 2016).

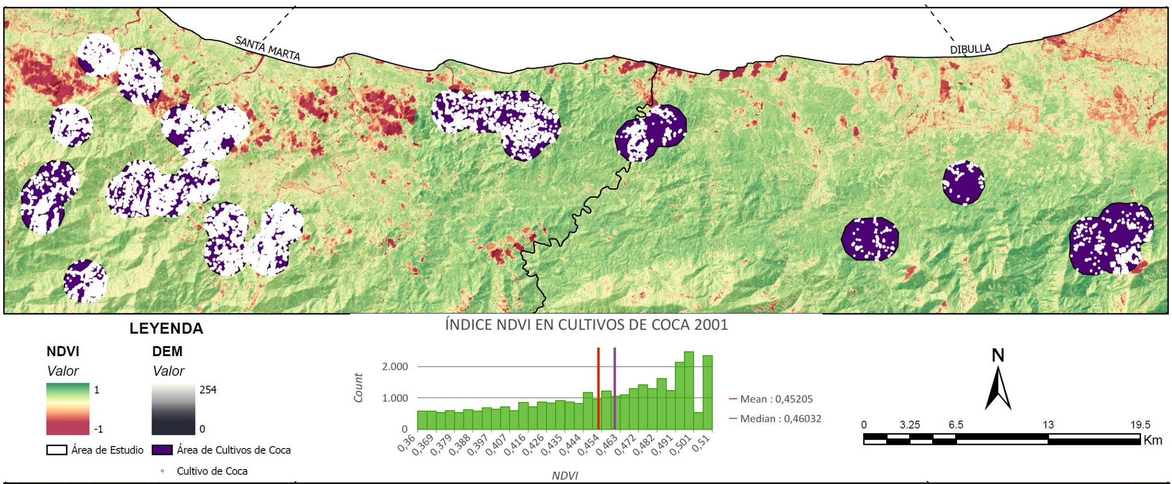
From the index range of 0.36 to 0.51, a selection was made by attributes to know the places in the different years of study where these values were present, as can be seen in Figure 2.

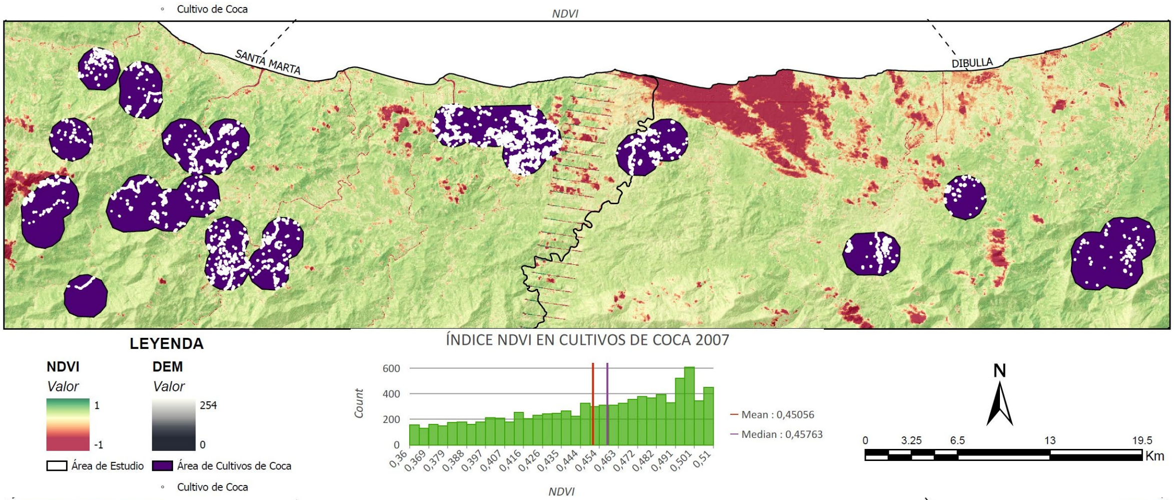
In 1998 it can be seen (Figure 2) a marked change in color of the NDVI index (red to green) and coca crops (purple- area of coca crops in 2017 according to Ministry of Justice; white- coca crops of the study year) between the municipality of Santa Marta and Dibulla. This is because of the selection of a satellite image from another month concerning the municipality of Dibulla.

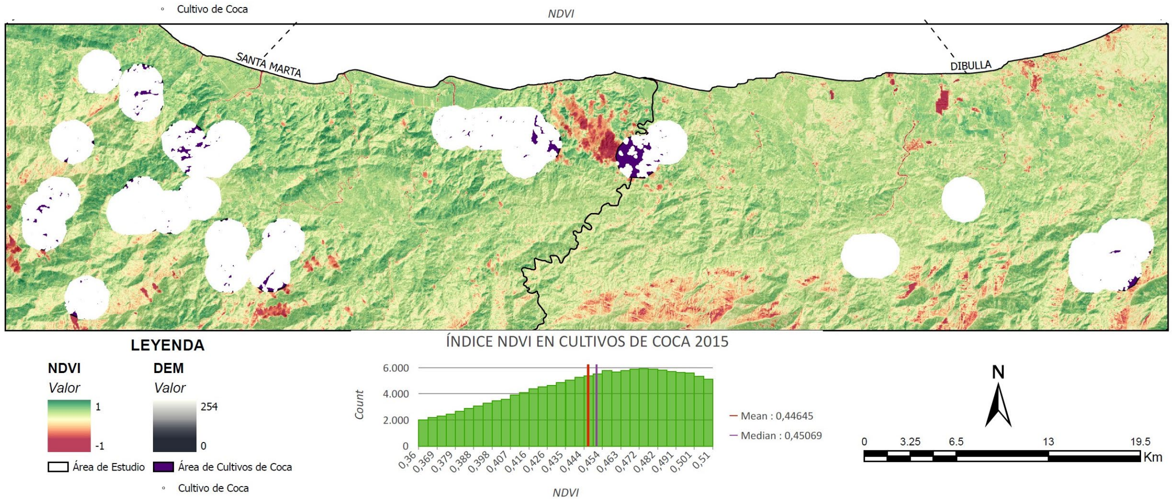
Coca cultivation from 2001 to 2007 decreased significantly in the Santa Marta area and a little in the municipality of Dibulla. However, coca crops increased for 2015 and 2018 compared to 2007. For 2018 it is evident that the area of coca crops is not completely white, which represents a decrease in these crops.

In addition to the colors, it is also possible to analyze the histograms found on the maps. From 1997 to 2007, an uneven amount of the NDVI index values is observed, compared to the years 2018 and 2015, where the values of the graphs tend to be constant.


SANTA MARTA
DIBULLA
0 5 10 20 30 Km
LEYENDA
NDVI
Valor
1
-1
DEM
Valor
254
0
Área de Estudio
Área de Cultivos de Coca
Cultivo de Coca
ÍNDICE NDVI EN CULTIVOS DE COCA 1997
Count
1.000
500
0
0,36 0,369 0,379 0,388 0,397 0,407 0,416 0,426 0,435 0,444 0,454 0,463 0,472 0,482 0,491 0,501 0,51
NDVI
Mean : 0,44868
Median : 0,45454
N
0 3.25 6.5 13 19.5 Km
SANTA MARTA
DIBULLA
LEYENDA
NDVI
Valor
1
-1
DEM
Valor
254
0
Área de Estudio
Área de Cultivos de Coca
Cultivo de Coca
ÍNDICE NDVI EN CULTIVOS DE COCA 1998
Count
4.000
2.000
0
0,36 0,369 0,379 0,388 0,397 0,407 0,416 0,426 0,435 0,444 0,454 0,463 0,472 0,482 0,491 0,501 0,51
NDVI
Mean : 0,44892
Median : 0,45283
N
0 3.25 6.5 13 19.5 Km
SANTA MARTA
DIBULLA
LEYENDA
NDVI
Valor
1
-1
DEM
Valor
254
0
Área de Estudio
Área de Cultivos de Coca
Cultivo de Coca
ÍNDICE NDVI EN CULTIVOS DE COCA 1999
Count
1.000
500
0
0,36 0,369 0,379 0,388 0,397 0,407 0,416 0,426 0,435 0,444 0,454 0,463 0,472 0,482 0,491 0,501 0,51
NDVI
Mean : 0,44946
Median : 0,45714
N
0 3.25 6.5 13 19.5 Km


SANTA MARTA
DIBULLA
LEYENDA
NDVI
Valor
1
-1
DEM
Valor
254
0
Área de Estudio
Área de Cultivos de Coca
Cultivo de Coca
ÍNDICE NDVI EN CULTIVOS DE COCA 2001
Count
2.000
1.000
0
0,36 0,369 0,379 0,388 0,397 0,407 0,416 0,426 0,435 0,444 0,454 0,463 0,472 0,482 0,491 0,501 0,51
NDVI
Mean : 0,45205
Median : 0,46032
N
0 3.25 6.5 13 19.5
Km


SANTA MARTA
DIBULLA
LEYENDA
NDVI
Valor
1
-1
DEM
Valor
254
0
Área de Estudio
Área de Cultivos de Coca
Cultivo de Coca
ÍNDICE NDVI EN CULTIVOS DE COCA 2007
Count
600
400
200
0
0,36 0,369 0,379 0,388 0,397 0,407 0,416 0,426 0,435 0,444 0,454 0,463 0,472 0,482 0,491 0,501 0,51
NDVI
Mean : 0,45056
Median : 0,45763
N
0 3.25 6.5 13 19.5
Km


SANTA MARTA
DIBULLA
LEYENDA
NDVI
Valor
1
-1
DEM
Valor
254
0
Área de Estudio
Área de Cultivos de Coca
Cultivo de Coca
ÍNDICE NDVI EN CULTIVOS DE COCA 2015
Count
6.000
4.000
2.000
0
0,36 0,369 0,379 0,388 0,398 0,407 0,416 0,426 0,435 0,444 0,454 0,463 0,472 0,482 0,491 0,501 0,51
NDVI
Mean : 0,44645
Median : 0,45069
N
0 3.25 6.5 13 19.5
Km

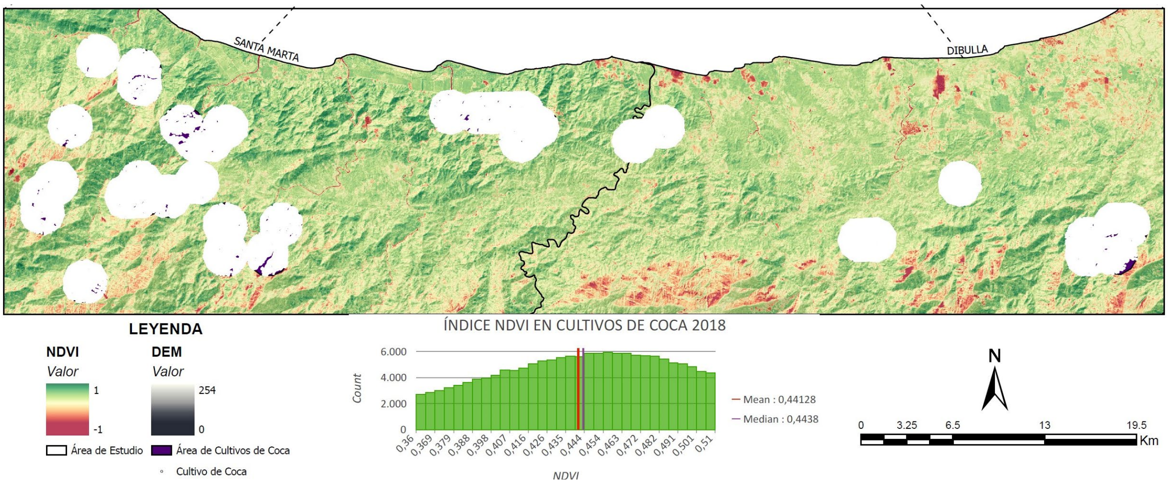


Figure 2. NDVI index in coca crops in the years 1997, 1998, 1999, 2001, 2007, 2015 and 2018. Note in purple the coca crops as reported by the Ministery of Justice, and the more recent coca corps fron images of this study in white.

Since there is still a presence of coca crops in the study area, the viability of alternative crops to replace them is studied. According to (Agronet, 2019), 10 sustainable crop alternatives are selected for the area. Table 2 shows that only four of the ten crops chosen, meet the conditions of relative humidity, precipitation and temperature that occur in the area.

Table 2. Ideal crops for the study area.

No.	Crops	Variable of Decision HR	Variable of Decision PP	Variable of Decision T	Satisfy
1	Mechanized rice	1	1	1	SI
2	Banana	1	1	0	NO
3	Coffee	0	1	0	NO
4	Citrus fruit	1	0	1	NO
5	Beans	1	1	1	SI
6	Traditional corn	1	0	0	NO
7	Mango	1	0	0	NO
8	Palm oil	0	0	1	NO
9	Plantain	1	1	1	SI
10	Cassava	1	1	1	SI

Source: Author, 2019.

The crops that meet the above conditions are: mechanized rice (1), beans (5), plantain (9) and cassava (10). These crops are entered into the crop selection model as shown in the following table.

Table 3. Model crop selection result.

No	Crops	Income ($)	Total Cost ($)	Planting Area (ha)	Utility

1	Mechanized rice	$ 1,392,876,574	$ 922,957,350	150	$ 469,919,224
2	Beans	$ -	$ -	0	-
3	Plantain	$ 661,952,824	$ 403,628,950	50	$ 258,323,874
4	Cassava	$ 4,798,800,000	$ 2,616,060,000	300	$ 2,182,740,000

Source: Author, 2019.

The most useful crop is cassava, with an area of 300 ha, followed by mechanized rice and plantain (150 ha and 50 ha, respectively). This significant difference in utility occurs due to the difference in the yields of each crop. The yield of cassava cultivation is 12 ton/ha, compared to 4 ton/ha of mechanized rice and 5.39 ton/ha of plantain (Agronet, 2019). In this analysis are no results for the cultivation of beans because its utility is negative and does not comply with the restrictions of the crop selection model. The utility of the bean crop is very low in the study area compared to the other crops, being 0.87 ton/ha (Agronet, 2019).

Furthermore, a determining variable in the model is the amount of investment available. According to the data in the table above, an investment of COP 3,942,646,300 (sum of total costs) must be made in order to plant these crops in the area proposed by the simulation model. Not having the investment amount for planting the crops, the data in the model variable can be changed; however, the available area could not be planted in its entirety.

4. Conclusions

Satellite images are a good tool to visualize a multi-temporal change in coca cultivation and extract information on the vegetation cover of the area to be analyzed. Furthermore, the geospatial data offered by the United States Geological Survey is easily accessible. Through the use of ArcGIS Pro software allows the geoprocessing of these images to be able to carry out an analysis and assertive interpretation of the problems present in the area to be studied.

The NDVI index allows us to know not only the state of the vegetation cover but also the location of the coca crops, knowing their rank in this index. According to the study carried out, the range is between 0.36 to 0.51, where the most affected areas are north of the Sierra Nevada de Santa Marta between the municipalities of Santa Marta and Dibulla. Therefore, this document provides a critical cartographic base of plant cover, location, and variation of coca crops in the study area during different years.

This research, together with the generation of new knowledge in the management of the vegetation cover, can provide guidelines in the formulation of land use policies at a regional, national and international scale. Through the implementation of these policies, sustainable crops are proposed as a solution to this problem. According to the parameters of relative humidity, precipitation, temperature, and utility; rice, plantain, and cassava should be sown. Cassava being the crop that generates the highest utility to the population.

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