TOWARDS A MONITORING OF DRYLANDS:

CLOUD GEOPROCESSING FOR ASSESSING SUSTAINABLE DEVELOPMENT GOAL INDICATORS IN COLOMBIA

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PARA OPTAR AL TÍTULO DE **ECÓLOGO**

PROGRAMA

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PREGUNTA DE INVESTIGACIÓN

¿Cuál es el nivel de cumplimiento de los Objetivos de Desarrollo Sostenible respecto la extensión de los ecosistemas secos colombianos durante el periodo 2015-2019?

OBJETIVO GENERAL

Determinar cómo ha variado la extensión de los ecosistemas secos de Colombia durante el periodo 2015 a 2019, para conocer el aporte que se puede estar generando en el complimiento de metas dentro de los Objetivos de Desarrollo Sostenible

Objetivos específicos

- Identificar las áreas potenciales de los ecosistemas secos en Colombia.
- Comparar el cambio en la extensión de los ecosistemas secos en Colombia durante el periodo 2015-2019
- Evaluar el cumplimiento de los Objetivos de Desarrollo Sostenible sobre la extensión de los ecosistemas secos en Colombia durante el periodo 2015-2019

Marco Teórico extendido

Gabriel Alejandro Perilla

Ecosistemas secos en Colombia

En Colombia, a través de la Ley 461 de (1998) se aprobó la UNCCD, a partir del cual se desarrolló el Plan de Acción Nacional (PAN) de Lucha Contra la Desertificación y la Sequía en Colombia (Ministerio de Ambiente y Desarrollo Sostenible 2008). Bajo este marco se definen con un índice de aridez < 0.65 a los ecosistemas secos del país, al tiempo que son declarados como ecosistemas estratégicos. En la normativa estos ecosistemas son llamados zonas secas, de modo que, a partir de estas definiciones y regulaciones, se entienden como términos intercambiables. Sin embargo, es posible que ese término "zona seca", al no ser un tipo de ecosistema como tal, halla dificultado los esfuerzos para estudiarlos y manejarlos.

Además, para Colombia esta definición resulta problemática, pues al solo tomar en cuenta el índice de aridez, cerca al 21% del país es clasificado como zona seca incluyendo algunos páramos, manglares y humedales (MADS 2005). Los cuales, están por debajo del umbral definido, pero que claramente no son identificados como ecosistemas secos pues no tienen una biota especializada a condiciones secas; y además no presentan escases de agua, teniendo fuentes hídricas diferentes a la precipitación como escorrentía, ríos, mar, humedad del ambiente entre otros.

Igualmente, la falta prolongada de lluvia da condiciones especiales en el suelo: salinos, sódicos, ústicos, údicos y arídicos. Típicos de ecosistemas secos, además, por edafogénesis, de las 76 clases de suelo para el Colombia 32 tienen un origen por regímenes de humedad seco (IDEAM; MAVDT; IGAC, 2010).

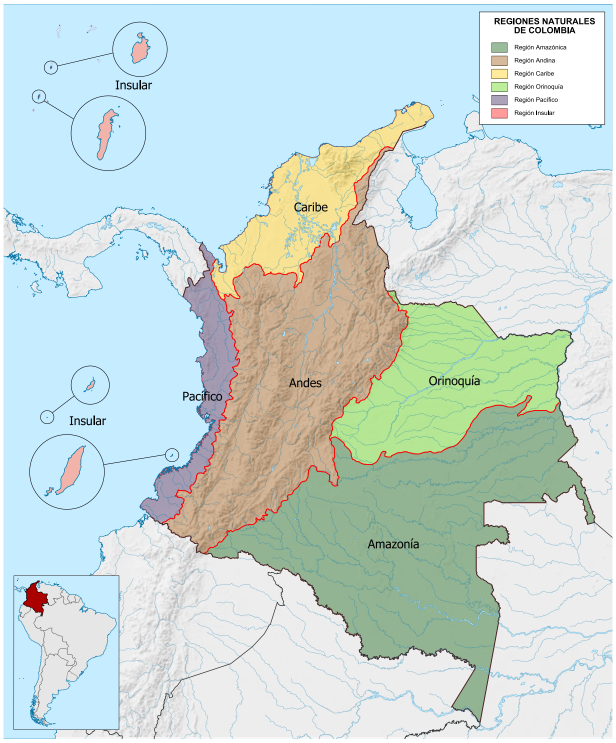

Figura 1. Regiones naturales de Colombia (IGAC, 2012). *Los ecosistemas secos en Colombia solo ocurren en la región caribe, región andina y muy poco en la región Orinoquia.*

Las regiones donde principalmente se encuentran zonas secas, son Caribe, Andina y áreas puntuales en la Orinoquia (figura 1). Las cuales las 2 primeras presentan regímenes bimodales de precipitación (con máximos en mayo y noviembre), mientras que la Orinoquia tiene lluvias monomodales con un máximo entre junio y agosto (MINAMBIENTE; IDEAM, 2015). Para el Caribe los ecosistemas secos representan el 35,53% del total de zonas secas, y principalmente son: desierto en la Guajira (el área más al norte del país), y bosque seco. Para los Andes, estas áreas son el 23,21% del total y son: relictos de bosque seco y enclaves xerofíticos, producto de sombra de lluvia. Mientras que para la Orinoquia se encuentra aparentemente el 35.53% de las zonas secas y son principalmente sabanas (MADS 2005, MADS; IDEAM 2012).

Los ecosistemas secos en Colombia que, si cumplen con un índice de aridez necesario para ser considerados secos, y además poseen una biota especializada a la escasez hídrica según el IDEAM (2017) son:

- Bosque basal seco
- Bosque andino seco
- Bosque subandino seco
- Subxerofitia basal
- Subxerofitia subandina
- Subxerofitia andina
- Xerofitia árida
- Xerofitia desértica
- Desierto

Estos ecosistemas presentan la mayor presión por el agua, donde para 2041 se esperan mayores conflictos por los recursos al pronosticar menores precipitaciones y mayores temperaturas que el promedio de nacional (IDEAM; MAVDT; IGAC, 2010). Además, la degradación de suelos tanto por erosión como por salinización se concentra en las zonas de ocurrencia de estos ecosistemas; valles interandinos y el caribe principalmente (IDEAM, 2015, 2017b) (figura 2), muestra de ello es que siete de estos ecosistemas tienen erosión muy severa o severa (IDEAM, 2017a). Igualmente, de acuerdo a la lista roja de ecosistemas (Etter et al., 2017), 11 de las 20 coberturas de ecosistemas que se encuentran en peligro crítico son secos, lo que significa que "están riesgo de colapso por reducción de su distribución geográfica o de la degradación de sus procesos clave y componentes bióticos".

Finalmente, Colombia es un país megadiverso, y se encuentra dentro de las prioridades de conservación global (McNeely, Miller, Reid, Mittermeier, & Werner, 1990). Además los ecosistemas secos colombianos son especialmente importantes debido a sus recursos genéticos únicos, servicios ecosistémicos, y valor paleontológico arqueológico cultural (Ministerio de Ambiente y Desarrollo Sostenible, 2005).

Adicionalmente los ecosistemas secos son mayormente habitados por población rural campesina o indígena, en condiciones vulnerables y/o empobrecidas, realizando actividades principalmente de auto abastecimiento. Aun así, también puede encontrarse agricultura intensiva con especies semestrales, ganadería (caprina intensiva, ovina, y bovina limitada), extracción de recursos naturales, mineros y petróleo y se espera que estas zonas sean frentes de expansión de desarrollos agropecuarios industriales de exportación (MADS 2005).

Teniendo en cuenta el tipo de población que habita estos ecosistemas, la escasez hídrica actual, los esperados cambios climáticos que agravaran la desertificación y degradación, y los planes de hacer proyectos agropecuarios industriales; las zonas secas colombianas son perfectas para tener múltiples conflictos ambientales (en el presente y futuro) (Pérez-Rincón, 2014).

Monitoreo del cambio en ecosistemas

Según Greenville et al. (2017), la investigación sobre ecosistemas secos ha tenido un crecimiento exponencial desde 1940 a la actualidad. Sin embargo, no fue hasta finales de los años 80 y principios de los años 90, que este tema de investigación tuvo un impulso donde empezaron a realizar y publicar gran cantidad de investigaciones. A partir de ese momento comenzó un fuerte interés global por estudiar los ecosistemas secos, y desde ese momento, la percepción remota ha sido una herramienta muy utilizada y sugerida, a pesar de tener una baja tasa de crecimiento en investigación. Luego de

1994, con la firma del UNCCD, en las 194 naciones firmantes se han promovido la generación y/o adopción de monitoreos y medidas para luchar contra la desertificación y degradación en zonas secas.

En Colombia, a escala nacional, se han hecho diferentes estudios y análisis de variables, que pueden ser homólogos, por ejemplo: el establecimiento de los principios y criterios para la delimitación de páramos (Rivera Ospina and Rodríguez 2011) y humedales (Jaramillo et al. 2015); o también, más enfocado hacia zonas secas, se planteó el protocolo para la identificación y evaluación de los procesos de degradación de suelos y tierras por desertificación (IDEAM; MAVDT; IGAC 2010) –procesos que afectan mayoritariamente a ecosistemas secos- y una propuesta para la gestión integral ambiental del recurso suelo (MADS; IDEAM 2012). Demostrando así, que Colombia si tiene la capacidad de generar este tipo de trabajos, pero aun así ha sido negligente con el monitoreo a ecosistemas secos.

No obstante, estos procesos no se presentan en todas las zonas secas, ni son exclusivos de ellas. Además, estos monitoreos en muchos casos se centran en otros ecosistemas (Naciones Unidas, 1994; Wang, Hua, & Ma, 2016), y en Colombia no se están realizando periódicamente (observación personal). Llevando así a que se siga omitiendo la vigilancia de los ecosistemas secos del país. El único monitoreo de ecosistemas periódico actualmente en vigencia es monitoreo de cobertura de bosque anual (IDEAM, 2014), dejando de lado el resto de ecosistemas no boscosos.

Esta desatención a los ecosistemas secos, a pesar de su enorme valor resulta paradójico, teniendo en cuenta que mundialmente se han utilizado y sugerido formas eficientes para su monitoreo, especialmente a través de percepción remota (Huang et al. 2017, Salih et al. 2017, García et al. 2018, Joseph et al. 2018, Tomasella et al. 2018). Incluso existen nuevas herramientas de geoprocesamiento en la nube (como Google Earth Engine), que facilitan el acceso a información espacial, tienen bajos costos y rápida actualización de los datos, y permiten el rápido análisis de datos masivos (SEEG et al. 2016, Gorelick et al. 2017, Shelestov et al. 2017, Xiong et al. 2017). Permitiendo monitoreos muy completos, casi en tiempo real, es escalas grandes con información relevante para escalas locales como los mapas de deforestación global (Hansen et al., 2013), y los mapas de cuerpos de agua y sus cambios globales (Pekel, Cottam, Gorelick, & Belward, 2016).

Para Colombia el uso de “big-data” para análisis geoespaciales es casi nulo (Kumar & Mutanga, 2018), de modo que, se espera que este trabajo marque un antecedente en el uso de datos masivos en el país, y así facilitar la toma de decisiones al ampliar la gama de posibilidades a la hora de abordar asuntos geoespaciales.

Objetivos y metas globales

Mundialmente en las últimas décadas ha crecido un interés por los ecosistemas secos, por ejemplo creando objetivos globales de conservación y desarrollo, como son los objetivos de desarrollo sostenible y las metas Aichi. Los cuales, han sido adoptados por Colombia.

Sin embargo, al revisar los indicadores nacionales de las estas metas sostenible (tabla 1) (Comision ODS, 2015; United Nations, 2017), se evidencia la desatención nacional respectos estos ecosistemas. Donde un monitoreo de ecosistemas secos podría: llenar la falta de indicadores y, por lo tanto, hacer posible la evaluación de la meta 15.3; complementar el indicador de la meta 15.1 (al aportar información desagregada por ecosistema); y servir de insumo para poder facilitar el cumplimento de la meta 13.2 (pues al ser los ecosistemas mas afectados por cambio climático , un monitoreo de ecosistemas secos podría ser integrado en planes de gobierno subnacionales, como proxy e indicador de estrategias para combatir el cambio climático).

Asimismo podrían considerarse también las metas Aichi, puntualmente las metas 5 "Para 2020, se habrá reducido por lo menos a la mitad y, donde resulte factible, se habrá reducido hasta un valor cercano a cero, el ritmo de pérdida de todos los hábitats naturales, incluidos los bosques, y se habrá reducido de manera significativa la degradación y fragmentación", y 11 "Para 2020, al menos el 17% de las zonas terrestres y de las aguas interiores y el 10% de las zonas marinas y costeras, especialmente las que revisten particular importancia para la diversidad biológica y los servicios de los ecosistemas, se habrán conservado por medio de sistemas de áreas protegidas administrados de manera eficaz" (UICN, 2014), haciendo alusión a objetivos globales de conservación de biodiversidad.

Aun así, debido a que las metas Aichi, culminan en el año 2020, se sugiere que dichas metas sean incluidas y articuladas directa o indirectamente con el cumplimiento de los objetivos de desarrollo sostenible, que estarán vigentes hasta el 2030.

Objetivo	**Meta global**	**Meta nacional**	**Indicador nacional**
13 cambio climático	13.2 Incorporar medidas relativas al cambio climático en las políticas, estrategias y planes nacionales	13.2 Incorporar medidas relativas al cambio climático en las políticas, estrategias y planes subnacionales	13.2.1 Porcentaje de municipios y Departamentos con Planes de Ordenamiento Territorial (POD y POT) que incorporan el componente de cambio climático
15 vida de ecosistemas terrestres	15.3 Para 2030, luchar contra la desertificación, rehabilitar las tierras y los suelos degradados, incluidas las tierras afectadas por la desertificación, la sequía y las inundaciones, y procurar lograr un mundo con una degradación neutra del suelo	15.3 no adoptado, sin evaluar, y sin datos disponibles. se propone: proteger los ecosistemas secos, deteniendo la degradación y la desertificación que los amenaza considerablemente más	sin indicador. se propone: número de hectáreas de ecosistemas secos
	15.1 Para 2020, velar por la conservación, el restablecimiento y el uso sostenible de los ecosistemas terrestres y los ecosistemas interiores de agua dulce y los servicios que proporcionan, en particular los bosques, los humedales, las montañas y las zonas áridas, en consonancia con las obligaciones contraídas en virtud de acuerdos internacionales	15.1 Conservar y Restaurar los Ecosistemas Terrestres y de Agua Dulce	15.1.2 número de hectáreas de áreas protegidas

Tabla 1. Objetivos de desarrollo sostenible, metas e indicadores nacionales que pueden valerse en distintas medidas de un monitoreo de ecosistemas secos.

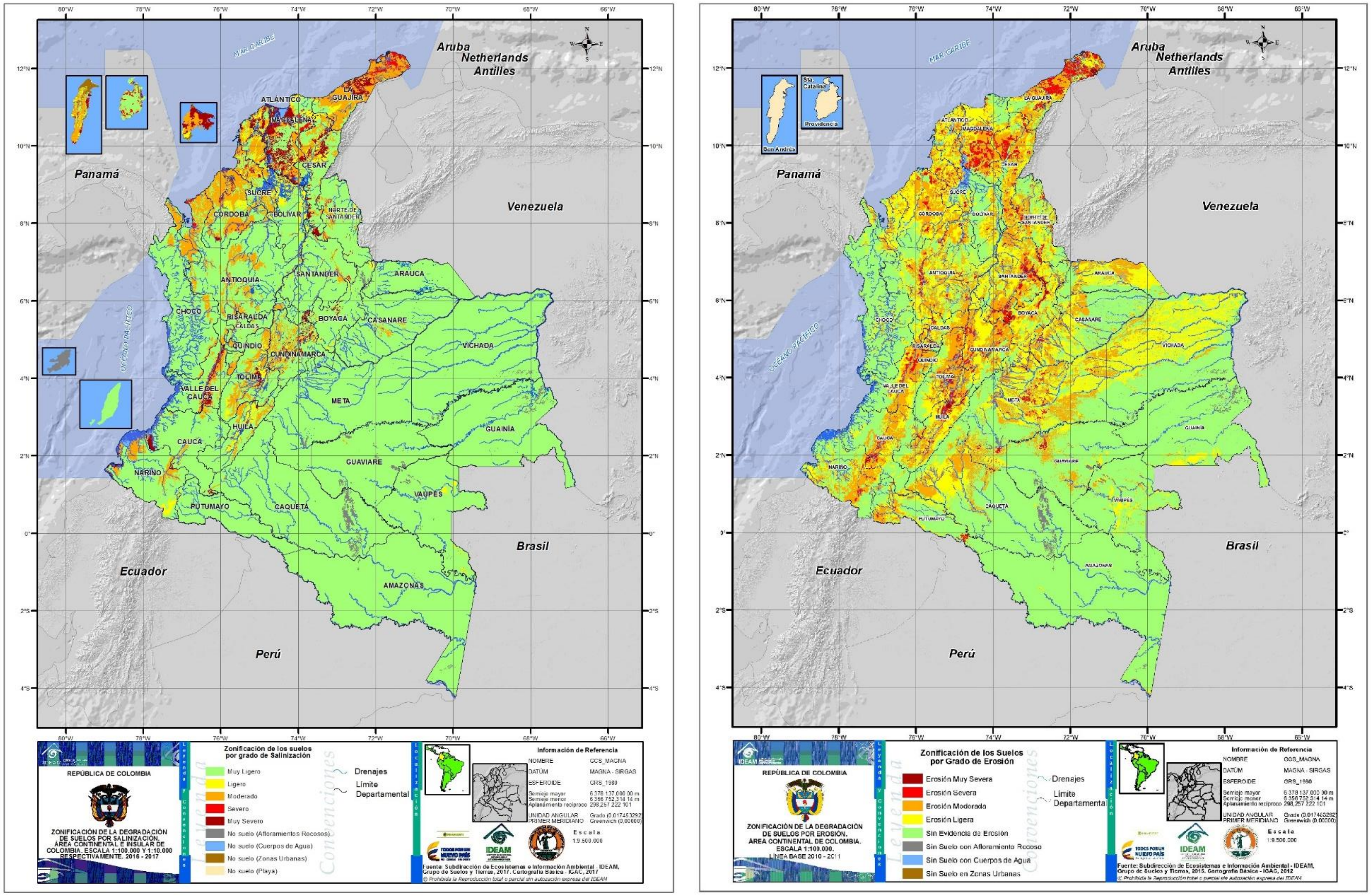

Figura 2. Mapas de degradación de suelos. Izquierda: mapa de degradación por salinización (IDEAM, 2017b). *Derecha: mapa de degradación edáfica por erosión* (IDEAM, 2015). *Nótese la concentración de degradación de suelos, en el caribe (norte del país), y valles interandinos.*

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Metodología extendida

Gabriel Alejandro Perilla

Área de estudio

Colombia es un país tropical, ubicado el norte de Suramérica con una extensión continental de 1’142.000 km^2, de los cuales , el 21.5 % del territorio nacional corresponde a zonas secas (Fig. 1, Plan Acción Nacional: Lucha contra la desertificación y la sequía en Colombia, PAN, 2005). Estas áreas en la práctica están definidas exclusivamente con el índice de aridez Precipitacion/ Evapotranspiración Potencial (Ministerio de Ambiente Vivienda y Desarrollo Territorial -MAVDT-, 2007). Sin embargo, en el PAN se definen además por tener una biota especializada a condiciones de sequía (Ministerio de Ambiente y Desarrollo Sostenible, 2005).

Los ecosistemas secos son además caracterizados por una lata variabilidad tanto en escala temporales como espaciales, siendo ecosistemas con marcada estacionalidad y cambios repentinos del estado del tiempo (Fensholt et al., 2012; Ohana-Levi et al., 2018; Schwinning et al., 2004).

Adicionalmente, estos ecosistemas son prioritarios para la conservación tanto a nivel nacional, siendo declarados como ecosistemas estratégicos (Ministerio de Ambiente y Desarrollo Sostenible, 2005), como a nivel internacional (United Nations, 2011). En ellos habítan cerca de 2100 millones de personas, la mayoría en países en vía de desarrollo y en pobreza (United Nations Development Programme, 2011). Además, también los medios de vida en estos ecosistemas son altamente dependiente de los recursos naturales (Bohle et al., 1994; Reynolds et al., 2007), de modo que la vulnerabilidad en estos ecosistemas se ve incrementada por efecto del cambio climático, degradación del suelo y variabilidad ambiental (Prăvălie, 2016; Turner II et al., 2003). De modo que sus habitantes, muchas veces, en un intento de mejorar su calidad de vida, recurren a la sobreutilización y manejos no sostenibles de los recursos naturales, promoviendo el deterioro y degradación ambiental, paradójicamente empeorando su situación inicial (Charney, 1975; Lopez Porras et al., 2019; Sachs et al., 2004).

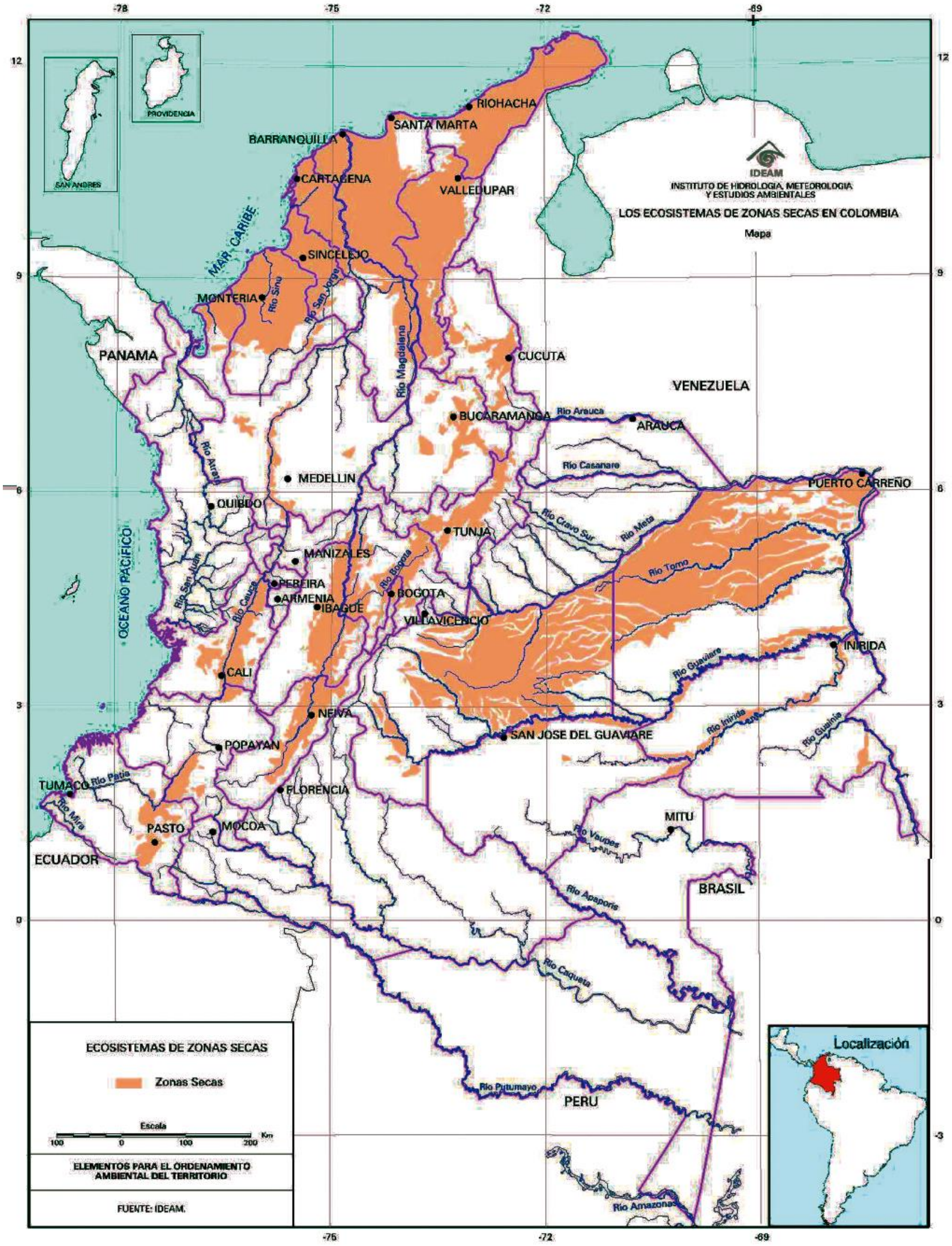

Figura 1. Área de estudio. mapa de zonas secas según el IDEAM.

Resumen metodológico

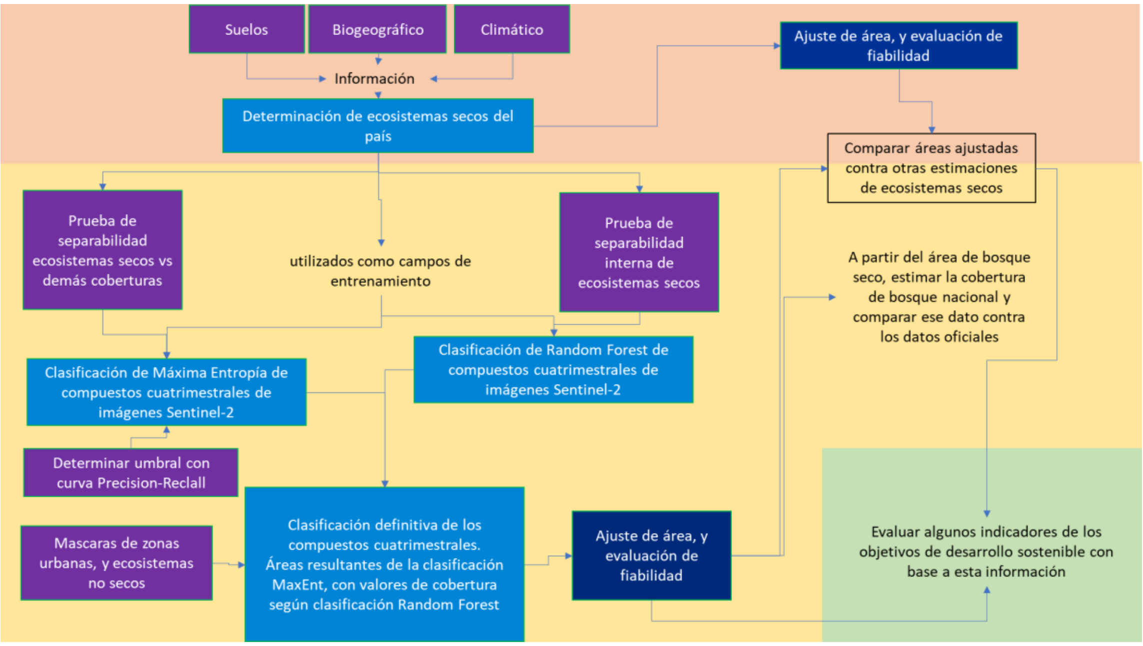

Figura 2. Diagrama metodológico. Cajas azul claro: mapas generados. Cajas moradas: pasos complementarios necesarios. Cajas azul oscuro: estimaciones de área. Fondo rosa: metodología que responde al objetivo 1. Fondo amarillo: metodología que responde al objetivo 2. Fondo verde: metodología que responde al objetivo 3.

Con el fin de evaluar el cambio en la extensión de los ecosistemas secos del país, (Fig. 2), fue necesario redefinir y determinar las áreas potenciales de ocurrencia de estos ecosistemas, ya que las áreas definidas por el IDEAM incluían ecosistemas con condiciones biofísicas diferentes (Etter et al., 2018; Ministerio de Ambiente y Desarrollo Sostenible, 2005), p. ej., humedales, manglares y las sabanas de la Orinoquia. Una vez determinada las áreas potenciales de ocurrencia se llevó a cabo la evaluación de fiabilidad y ajustes de área para comparar y conocer la calidad de esta delimitación.

Posteriormente a partir de esta delimitación de las áreas potenciales se realizaron pruebas de separabilidad para determinar la mejor combinación de bandas que diferencie a los ecosistemas secos. Adicionalmente la delimitación fue utilizada como puntos de entrenamiento que junto con las bandas de separabilidad fueron usados para realizar la(s) clasificación(es) de los compuestos de imágenes satelitales. Dichas clasificaciones fueron enmascaradas para reducir los errores de comisión, y se les realizo la evaluación de fiabilidad y ajustes de área. Una vez ya determinadas las áreas ajustadas, se realizaron comparaciones contra otras fuentes de información para evaluar la calidad de estas estimaciones.

Finalmente, a partir de las estimaciones de área, se evaluó el desempeño de algunos indicadores de los objetivos de desarrollo sostenible respecto ecosistemas secos, para Colombia.

Determinación de las zonas secas del país

Dado que se propone un trabajo con un sistema de clasificación semiautomático, para ecosistemas secos, fue necesario primero determinar preliminarmente donde se encuentran los ecosistemas secos, para usarlos como campos de entrenamiento. El primer paso fue determinar y delimitar los ecosistemas secos del país, para lo que se usaron tres fuentes principales de información (Anexo a): (1) información de suelos, (2) información biogeográfica e (3) información climática.

Con estas tres fuentes de información se procedió a delimitar las áreas de entrenamiento utilizadas en el clasificador (Fig. 3).

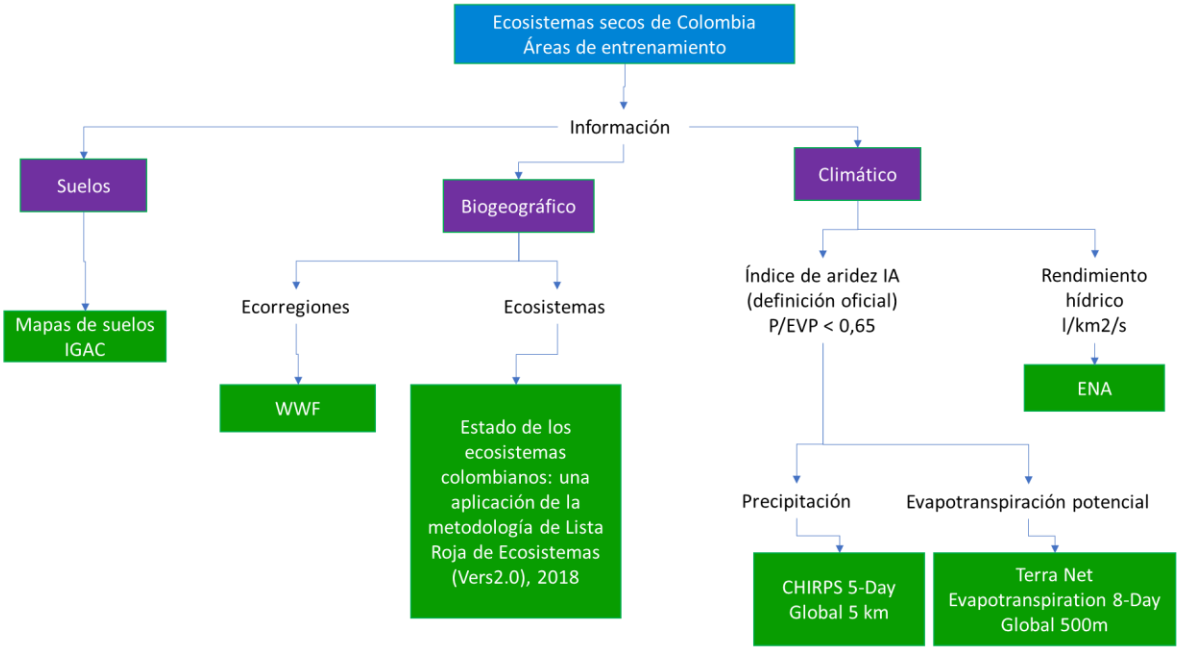

Figura 3 Diagrama de Fuentes de información

Edáfico

Se unificó el sistema de clasificación de taxonomía de suelos del Soil Survey del Departamento de Agricultura de Estados Unidos (Soil Survey, 1999, 1975), puesto que esta clasificación incluye propiedades ecológicas y de pedogénesis, que pueden servir de proxy para determinar la presencia de un ecosistema seco (IDEAM; MAVDT; IGAC, 2010). En total, están reportados 424 diferentes taxones de suelo para Colombia.

Los mapas del IGAC, se dividen en unidades cartográficas de suelos (UCS), cada una con un tipo de clima, y compuesta por distintos taxones de suelo (componentes) en proporciones específicas (porcentajes %) (Tabla 1).

Tabla 1. Ejemplo de los atributos de los mapas de suelos; unidades cartográficas de suelos (UCS), tipo de clima, taxones de suelo (componentes), en proporciones específicas (porcentajes P), valores asignados a cada taxon (V), Ponderación de los valores asignados a cada taxon por su porcentaje correspondiente (∑), suma de las ponderaciones de cada UCS (suma de ∑), valor asignado al clima (C), y promedio de la suma de las ponderaciónes con el valor asignado al clima (Calificación final).

UCS	Clima	Componente1	Componente2	Componente3	P1	P2	P3	V1	V2	V3	∑1	∑2	∑3	Suma de ∑	C	Final
RC	Medio Húmedo	Typic Haplustolls	Typic Ustorthents	Indefinido	45	45	0	0,5	1	0	22,5	45	0	67,5	0	33,8
RWI	Cálido Seco	Typic Haplustepts	Aeric Fluvaquents	Typic Haplustolls	60	20	20	1	0	0,5	60	0	10	70	100	85
AR	Cálido seco a cálido húmedo	Typic Haplustepts	Ustic Endoaquerts	Oxyaquic Haplustepts	40	30	30	1	1	0	40	30	0	70	50	60

Luego, usando criterio experto y según los manuales de suelos con sus descripciones (Soil Survey, 1999, 1975), se asignaron valores (V) de 0 a los suelos que según sus propiedades no corresponden a ecosistemas secos; 0,5 a los suelos que según sus características corresponden a ecosistemas estacionales con al menos un periodo de sequía continua, y 1 a los suelos que por su pedogénesis y propiedades corresponden a ecosistemas secos (Tabla 1). Además, se asignó un valor (C) de 0, 50 o 100 dependiendo si el clima reportado corresponde a un ecosistema seco, a un ecosistema estacionalmente seco o a otro ecosistema no seco.

Siguiendo la ecuación 1, se calculó entonces el valor final del componente suelo (f_x), donde x es la unidad de suelo (UCS), i es el número de componente, V es el calor asignado a los taxones de suelo, P es el porcentaje de cada componente y C es el valor asignado al clima.

Ecuación 1

$$f_x = \left(\frac{\sum_x (V_i * (P_i)) * C_x}{2}\right)$$

Biogeográfico

La información **biogeográfica,** se construyó a partir de la información de Biomas de la capa de Ecorregiones de World Wildlife Fund (WWF) (Dinerstein et al., 2017; Olson et al., 2001), y el mapa de Estado de los Ecosistemas Colombianos (Etter et al., 2018). Para ambos mapas se tomaron los ecosistemas o las ecorregiones (según correspondiera) correspondientes a bosques secos, desiertos o sabanas secas, asignando a cada una un valor de 100. El valor final fue el promedio entre las dos fuentes (tabla 2).

Tabla 2 Ejemplo de los atributos de los mapas de ecorregiones y ecosistemas, y como fueron reclasificados en la información ecosistémica final.

Ecorregiones WWF		Ecosistemas Potenciales		Información final
Bioma	Valor asignado	Cobertura	Valor asignado	Promedio mapas
Desiertos y matorrales xerófilos	100	Arbustal de desierto tropical	100	100
Bosques húmedos tropicales y subtropicales	0	Bosque alto húmedo tropical	0	0
Bosques secos tropicales y subtropicales	100	Bosque ripario húmedo tropical	0	50

Clima

La delimitación **climática** de los ecosistemas secos se realizó, en parte, con base al índice de aridez según el límite definido por las Naciones Unidas: (precipitación/evapotranspiración potencial) <0,65 (Naciones Unidas, 1994). Aun así, se han desarrollado más de 30 diferentes índices de aridez, la mayoría usando variables sencillas de medir en campo como son: precipitación, temperatura, evaporación, # de días de lluvia, humedad, entre otros (Stadler, 1998). Estas variables, el IDEAM las mantiene monitoreadas con estaciones meteorológicas en todo el país; una forma de poder mejorar los datos de insumo consiste en utilizar la información terrestre del IDEAM, en vez de los datos climáticos satelitales.

Los ecosistemas secos son altamente estacionales, tanto intra como interanualmente (Le Houerou et al., 1988), por lo que el índice de aridez se estimó a nivel mensual para incluir esta variabilidad. La información de precipitación se obtuvo a partir de la base de datos global del proyecto CHIRPS (Funk et al., 2015) a resolución temporal de 5 días y espacial de 5km. Se utilizo también el producto de evapotranspiración potencial de MODIS (Moderate-Resolution Imaging Spectroradiometer) de la NASA (Running et al., 2017), a una resolución temporal de 8 días y espacial de 500m. las áreas sin información para las imágenes de evapotranspiración fueron interpoladas con los valores de los pixeles más cercanos (Fig. 4).

Ambas variables fueron totalizadas a nivel mensual usando el promedio mensual multianual desde junio de 2015 hasta junio de 2019 (Fig. 5), ya que estas son las fechas con imágenes Sentinel-2 disponibles (las imágenes usadas para hacer la clasificación, explicadas más adelante). Las dos variables fueron remuesteradas a una resolución espacial de 500 m usando el método del vecino más cercano.

Se debe reconocer que la información satelital, es menos fiable que la información de estaciones meteorológicas (del IDEAM) (Urrea et al., 2016). La información de precipitación satelital (CHIRPS, para este trabajo), si bien representa los comportamientos generales de la lluvia anual y estacionalmente (Urrea et al., 2016), tiene los inconvenientes de no poder representar adecuadamente la lluvia en períodos de tiempo menores (semanas días) , suele sobreestimar los valores, y pierde fiabilidad en terrenos con mucha variabilidad altitudinal (Collarani Anagua and Villazon, 2018; Rivera et al., 2018; Urrea et al., 2016)(caso colombiano con 3 cordilleras). De modo, que es fuertemente recomendado que, en el futuro, se utilice la información climática in situ del IDEAM, en lugar de la información satelital.

Paralelamente, para cada una de las 48 capas generadas en el periodo se definieron las áreas secas acorde al umbral del índice de aridez (<0,65). Todos los valores menores a 0,65 se igualaron a uno y los valores mayores o iguales a 0,65 se igualaron a cero. Después, estos mapas se sumaron, de modo que los valores fueran igual a la cantidad de meses que cada píxel fue clasificado como seco, siendo el valor máximo posible 48 y el mínimo 0. Posteriormente se invirtió la escala, restándole al valor máximo (48) el valor de cada píxel para que los pixeles más secos tuvieran valores menores (Fig. 6). Esto con el fin que ambas capas (número de meses secos y promedio de índice de aridez) tengan el mismo comportamiento (valores más bajos equivalen a (pixeles con condiciones más secas, y valores mayores equivalen a condiciones menos secas).

Figura 4 imágenes de evapotranspiración potencial, en la península de la Guajira. Izquierda, imagen original con áreas faltantes. Derecha, imagen interpolada.

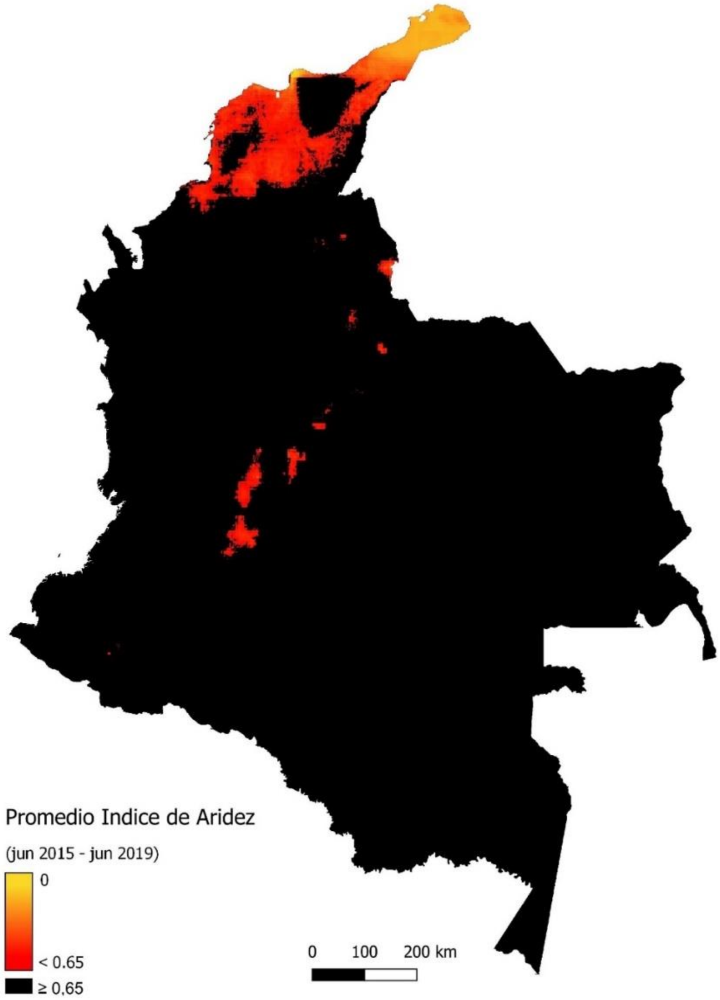

Figura 5 mapa de promedio del índice de aridez desde junio de 2015 hasta junio de 2019, Solo se resaltan los pixeles que tuvieron un valor medio considerado seco.

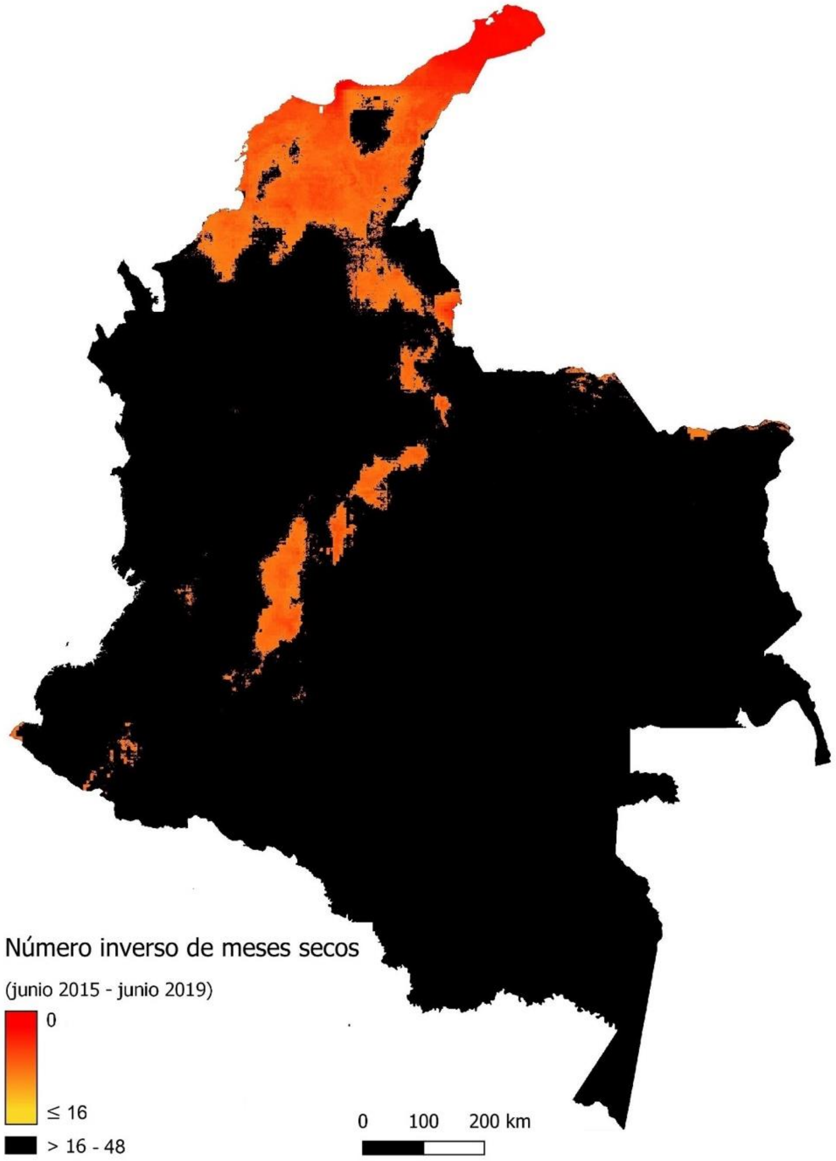

Figura 6 mapa de Número de meses secos desde junio de 2015 a junio de 2019, nótese que la escala esta invertida. Solo se resaltan los pixeles con al menos una estación seca al año (4 meses).

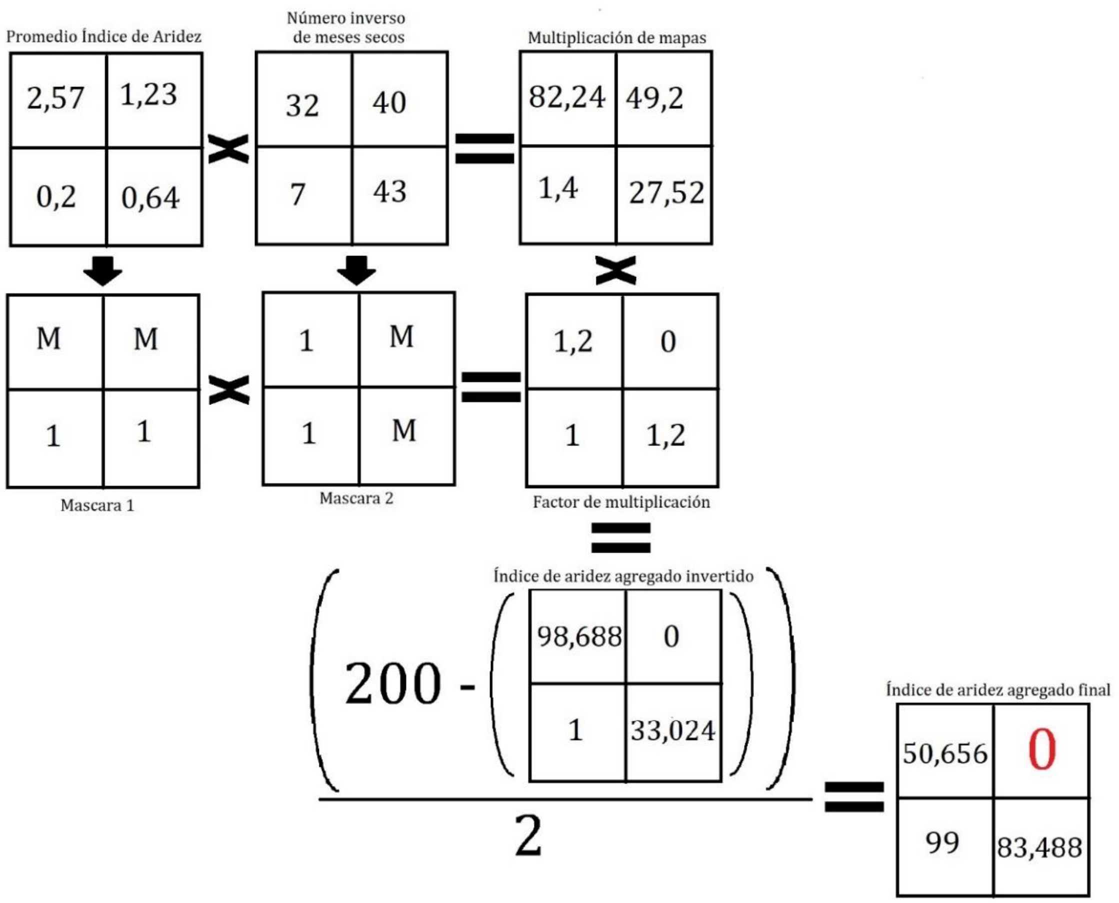

Figura 7 diagrama de proceso para lograr el índice de aridez agregado final.

Luego estas dos capas fueron procesadas de la siguiente manera (Fig. 7):

- Se enmascararon los pixeles cuyo promedio del índice de aridez, fuera superior o igual a 0,65 (en la figura 7: mascara 1).
- Debido a que una estación seca para bosque seco se considera de al menos cuatro meses (Janzen, 1988); este trabajo considera que un ecosistema seco deberían al menos permanecer seco por 4 meses al año. Por lo que se enmascararon todos los pixeles que fueron secos menos de 16 meses secos (en la figura 7: mascara 2, nótese que la capa tiene la escala invertida).
- Ambas mascaras fueron fusionadas, de modo que, si un píxel estaba enmascarado en ambas capas, tomaría un valor 0; si un píxel tenía valores en ambas capas, tomaría un valor 1; mientras que, si estaba enmascarado solamente en una capa, tomaría un valor de 1,2. (en la figura 7: factor de multiplicación).
- Luego se multiplicaron los mapas de promedio de índice de aridez y de numero inverso de meses secos (en la figura 7: multiplicación de capas).
- Posteriormente la capa “multiplicación de capas” fue multiplicada por la capa “factor de multiplicación” (en la figura 7: índice agregado invertido).
- Para estandarizar la escala y las unidades de la capa “índice agregado invertido”, se le aplico la ecuación 2, la cual se diseñó de tal manera que el valor final mínimo para

ser considerado ecosistema seco fuera 50, que significaría 50 % de probabilidad de ser un ecosistema seco, (en la figura 7: índice de aridez agregado final).

Ecuación 2.

$$f(x) = \begin{cases} cuando\ \text{"indice agregado invertido"} = 0, & x = 0 \\ cuando\ \text{"indice agregado invertido"} > 0, & x = \dfrac{200 - "indice\ agregado\ invertido"}{2} \end{cases}$$

Es importante aclarar que el índice de aridez utilizado está planteado con valores anuales. Mientras que este trabajo hizo los cálculos de dicho índice de forma mensual. Esto responde al hecho que los ecosistemas secos del mundo tienen estacionalidad fuerte intra-anual (Fensholt et al., 2012; Ohana-Levi et al., 2018; Schwinning et al., 2004). Sin embargo, este cambio añade error en el modelo al ser una medida no diseñada para datos mensuales. Aun así, Araghi et al., 2018 proponen que es importante revisar los índices de aridez mensual y anualmente, especialmente en tierras áridas, pues de no hacerlo se desconocerían procesos estacionales intrínsecos a estos territorios. Para hacer frente a este problema, varios autores proponen realizar una corrección de errores temporales “temporal bias correction” (Aryal and Zhu, 2016; Cao et al., 2019; Li et al., 2010), y así reducir el error de las escalas temporales. A pesar de ello, Aryal and Zhu, 2016 concluyen que mientras el modelo no pretenda ser predictivo en escenarios futuros, los errores dados por escalas temporales pueden no afectar el resultado de modo que es válido no hacer dicha corrección en casos como aplica en este trabajo.

Por otro lado, se tomó el mapa de rendimiento hídrico a partir del Estudio Nacional del Agua 2014 (ENA), definido como la cantidad de agua superficial por unidad de área en un tiempo determinado (MINAMBIENTE; IDEAM, 2015). Esto permite tener en cuenta algunos ecosistemas con poca precipitación local, pero con fuentes de agua superficiales, generalmente ríos, que generaría condiciones que no necesariamente conducirían a clasificarlos como secos.

Para ello, se reclasificó, tomando el valor mínimo y máximo reportado (0 y 200 litros/km2/s respectivamente), y considerando que un ecosistema con 0 l/km2/s de rendimiento hídrico sería un ecosistema totalmente seco se asignó a este valor la probabilidad máxima (100). A su vez, un ecosistema con un rendimiento hídrico de 200 l/km2/s constituiría un ecosistema con probabilidad 0 de ser considerado seco. Subsecuentemente se clasificaron las categorías intermedias de forma correspondiente (Tabla 3).

Tabla 3. Reclasificación de los datos de rendimiento hídrico, resaltando los valores mínimo, máximo y medio.

Rendimiento hídrico l/km2/s	Probabilidad de ecosistema seco
0	100
3	97
6	95
10	92,5
15	90

20	85
40	80
50	75
70	65
100	50
150	25
200	0

La información climática es el promedió del mapa del índice de aridez agregado final, con el de rendimiento hídrico reclasificado, para dar un valor definitivo al componente climático.

Definición de la distribución potencial de los ecosistemas secos en Colombia

Hay consideraciones respecto a las escalas. Puede resultar problemático tomar variables climáticas, ecológicas, y geológicas, y promediarlas todas juntas, debido a que cada una de ellas ocurre en escalas de tiempo diferentes. Sin embargo, teniendo en cuenta la escala geológica es tan lenta, para efectos prácticos, acá se asume como si fuera constante e invariable; por otro lado, para las variables climáticas, definitivamente si se puede mejorar al tomar periodos de tiempo de al menos 30 años para su evaluación, y finalmente para variables ecológicas este trabajo depende de insumos creados por terceros, cuya actualización es demorada de modo que para efectos prácticos, se debe asumir como variable constante, al menos hasta que se publique nueva información ecológica mejor y más actual.

Adicionalmente las escalas espaciales también tienen otro inconveniente pues los mapas de insumo vienen en resoluciones espaciales diferentes, por lo que los resultados deben ser evaluados a la luz del ruido que estos errores producen.

Una vez se tuvieron las tres fuentes de información completas (edáfica, biogeográfica & climática), estas fueron promediadas, dando como resultado un mapa de probabilidades de ecosistemas secos. Se determino, mediante prueba y error, un valor umbral de 50 como definición de los ecosistemas secos, tomando como marco de referencia la detección espacial del área seca del Cañón de Chicamocha en Santander. Así, todas las áreas con un valor mayor o igual a 50 serían considerados ecosistemas secos potenciales de Colombia.

A estos ecosistemas secos potenciales (Fig 8), se les asignó el atributo de cobertura según el Mapa de Estado de los Ecosistemas Colombianos (Etter et al., 2018). Dichas coberturas se agruparon en tres ecosistemas secos: **desierto tropical**, **bosque seco tropical**, y **sabanas secas,** las cuales incluyen arbustales secos y enclaves xerofíticos. Adicionalmente, se descartaron todas las áreas que, por sus coberturas, no representan ecosistemas secos, donde también fueron descartadas las áreas transformadas del país, de modo que solo nos enfocamos en los ecosistemas secos remanentes de Colombia. Finalmente, a este mapa se le realizó la evaluación de fiabilidad y ajustes de área (revisar subtitulo Evaluación de fiabilidad y Ajustes de Área, en el siguiente título).

Figura 8 Ecosistemas secos remanentes.

Cambio en la extensión de los ecosistemas secos en Colombia durante el periodo 2015-2019

Preprocesamiento de las imágenes satelitales

Se utilizaron imágenes de la misión Sentinel-2 del programa Copernicus, puesto que son imágenes multiespectrales libres de muy alta resolución espacial (10 m bandas de luz visible) y temporal (5 días de intervalo de revisita)(European Space Agency, 2015), las cuales son idóneas para evaluar y monitorear cambios de cobertura (Mas et al., 2016). La misión Sentinel-2, empezó a tomar imágenes a partir de junio de 2015 hasta la actualidad (European Space Agency, 2015), por lo que la temporalidad de este trabajo se limita a dichas fechas.

Sin embargo, para Colombia las primeras imágenes validas datan de septiembre de 2015 (obs. pers.).

Las imágenes fueron obtenidas a través de la plataforma de Google Earth Engine (https://developers.google.com/earth-engine/datasets/catalog/sentinel-2), solamente utilizando aquellas con un porcentaje de nubes menor a 40%. No obstante, las imágenes hasta noviembre de 2018 son nivel 1-c es decir imágenes que carecen de corrección atmosférica, mientras que las imágenes a partir de diciembre de 2018 hasta la actualidad son de nivel 2-a, es ya vienen corregidas atmosféricamente (Gorelick et al., 2017, obs. pers.). Para realizar la corrección atmosférica de las imágenes en nivel 1-c se utilizó el método "Sensor Invariant Atmospheic Corecction (SIAC)" (Yin et al., 2019), el cual, adicionalmente crea una máscara de nubes y se encuentra implementado en GEE (Yin, 2019).

A partir de la información en las bandas de nubes de cada imagen se creó una máscara adicional de nubes. Además, usando la banda B8A (infrarrojo cercano, Red Edge 4), se enmascararon las sombras (Zhu et al., 2015), dejando así imágenes limpias y corregidas. Luego se calculó y se añadió el índice de vegetación normalizado (Rouse et al., 1973), por su amplio uso para identificar cambios estacionales y fenológicos en ecosistemas secos (Fensholt et al., 2012; Joseph et al., 2018; Pastick et al., 2018).

Finalmente, estas imágenes (solo Colombia) sin nubes, sin sombras y corregidas atmosféricamente, fueron agrupadas en periodos de cuatro meses (por la forma de entender estaciones en este trabajo), para crear compuestos cuatrimestrales, usando la mediana de cada banda para cada píxel. Es importante reconocer que la forma en la que se decidió agrupar los meses fue arbitraria según un criterio calendario, sin embargo, se puede tomar en cuenta un criterio climático, y hacer las agrupaciones correspondiendo a los periodos de lluvias y secas. Esto seguramente idealmente mejoraría los resultados, en futuros estudios.

Separabilidad

Para que la clasificación sea mejor, y solo tome la información espectral que permite diferenciar mejor las clases de interés (ecosistemas secos, en este caso), sin incluir información redundante y evitar errores de colinealidad, se sugiere realizar una prueba de separabilidad (Jiménez & Mas *in press*).

Para determinar la combinación optima de bandas que efectivamente detecta los ecosistemas secos se empleó el índice de medida de la divergencia entre poblaciones multinomiales definido por Bhattacharyya (1946). Este es un índice de separabilidad, el cual asume la normalidad de los datos, y utiliza el promedio y las matrices de varianza-covarianza de cada 2 clases para poder determinar la separabilidad, es decir, las bandas que mejor separan la clase de interés frente a las demás.

Para que la separabilidad sea exitosa debe tener suficiente información representativa de la variabilidad espectral de cada clase ingresada. Para ello se ingresa una capa vectorial con clases sobre una capa con información espectral, y el proceso extrae todos los valores espectrales (valor de cada banda) disponibles para cada clase (todos los pixeles dentro de cada clase), y a partir de ellos crear las matrices necesarias.

Sin embargo, el cálculo de separabilidad es muy demandante computacionalmente, para ejecutarlo con una capa vectorial que abarque todo el país. Por lo que se realizaron buffers de 2 km de radio en 10000 puntos aleatorios, repartidos proporcionalmente según su area, entre todas las coberturas del Mapa de Estado de los Ecosistemas Colombianos (Etter et al., 2018), salvo ecosistemas secos (pues se utilizaron las áreas intactas determinadas como potenciales ecosistemas secos remanentes) y otras categorías que por su pequeña área no alcanzaron a tener ni un punto dentro de ellas; las cuales igualmente se mantuvieron intactas. De este modo se redujo el tamaño de la capa vectorial, reduciendo a su vez los valores para crear las matrices, pero manteniendo aun así una representatividad espectral.

La capa con información espectral utilizada fue el primer compuesto cuatrimestral creado (septiembre 2015-diciembre 2015), el cual, utilizado, junto con la capa vectorial recién creada permitieron realizar dos pruebas de separabilidad: la primera para encontrar la combinación de bandas que mejor separa los ecosistemas secos de las demás coberturas, y la segunda para encontrar la combinación que mejor separa los ecosistemas secos entre ellos mismos.

La primera separabilidad dio una combinación de 6 bandas: 3 de luz visible; **Roja**, **Verde**, **Azul** y 3 de luz infrarroja; **Red Edge 1**, **Red Edge 2**, **Red Edge**. Mientras que la segunda separabilidad dio una combinación de 5 bandas: 2 de luz visible; **Roja** y **Azul** y 3 de luz infrarroja; **Red Edge 1**, **Red Edge 2**, **Red Edge 3.**

Clasificación Máxima Entropía (MaxEnt)

Se decidió hacer una clasificación en dos pasos, para reducir al máximo la confusión espectral. Una primera clasificación, determinaría las áreas de lo ecosistemas secos para cada compuesto, y una segunda clasificación determinaría el tipo de ecosistema seco dentro las áreas determinadas por el primer clasificador.

Para la primera clasificación, se escogió un clasificador de máxima entropía (Mann et al., 2009) dado que permite realizar una clasificación de dos categorías (en este caso ecosistema seco o no), y resulta en un mapa de probabilidad. Este tipo de clasificador, es ampliamente usado para modelar distribución de especies con localidades georreferenciadas, para presencia y pseudo ausencia de la especie objetivo (Phillips et al., 2006). La elección del umbral permite, para el usuario, tener un control del “trade-off” entre errores de omisión y comisión.

Tomando en cuenta la combinación de bandas de la **separabilidad 1**, se llevó a cabo una clasificación binaria (ecosistema seco / demás clases), para cada compuesto cuatrimestral, usando como datos de entrenamiento 1000 puntos aleatorios, en ecosistemas secos (según la determinación de ecosistemas secos potenciales) y 5000 puntos aleatorios fuera de los ecosistemas secos, para el resto del país. Dando como resultado mapas de probabilidades.

A estos mapas se les calculó la curva Precision-Recall, la cual es una medida similar a la curva ROC, pero que en vez de usar especificidad utiliza precisión. Esta curva se ajusta mejor, a casos donde las poblaciones están numéricamente desbalanceadas (Saito and Rehmsmeier, 2015), como en este caso. A partir de este cálculo se determinaron los mejores umbrales que mejor balancean el error de omisión y comisión para cada cuatrimestre, y también, el ajuste del modelo (área bajo la curva) (Anexo b).

Finalmente, con los respectivos umbrales, se crearon los mapas binarios (ecosistemas secos o no), los cuales fueron editados para eliminar y minimizar el error de comisión. Para ello, se eliminaron, áreas urbanas (IGAC, 2018), y solo se tomaron en cuenta las áreas clasificadas como ecosistema seco que coincidieran con las coberturas de ecosistemas secos de la ESA (European Space Agency and Land Cover CCI partnership, 2017).

Clasificación Random Forest

Los mapas resultantes de la clasificación anterior, fueron reclasificados internamente con un clasificador de Random forest (Breiman, 2001), con la combinación de bandas de la **separabilidad 2**, y 1000 nuevos puntos de entrenamiento para cada ecosistema seco (desierto tropical, bosque seco tropical, sabanas secas). Dando así finalmente los mapas de ecosistemas secos cuatrimestrales (Anexo c).

Este trabajo fue posible gracias a la capacidad de GEE para hacer geoprocesamiento en la nube, y poner a la disposición repositorios de imágenes satelitales. Se logró hacer la corrección atmosférica de 8189 imágenes (cerca de 5 terabytes) demorando 5,7 minutos en promedio por imagen. Asimismo, hizo posible construir todas las seis imágenes compuestas, de alrededor de 150 gigabytes, en cerca de 1 hora cada una. Del mismo modo, GEE permitió hacer todas las clasificaciones correspondientes (MaxEnt y Random Forest) demorando una hora por clasificación.

Evaluación de fiabilidad y Ajustes de Área

Posteriormente se evaluó la fiabilidad, siguiendo la metodología propuesta por Olofsson et al. (2014; 2013). A partir de la cual, se determinó un número de puntos de evaluación siguiendo la ecuación 3. Donde N es el número de puntos, S(Ô) es error estándar de la fiabilidad total que se desea alcanzar, Wi es el área proporcional de todo el mapa de la clase i, y Ui es la fiabilidad esperada por el usuario para la clase mapeada como i.

Ecuación 3.

$$N = \left(\frac{\sum Wi * Ui}{S(\hat{O})}\right)^2$$

Los puntos de evaluación fueron comprados contra distintos mapas de referencia, según correspondiera (tabla 4), creando así las diferentes matrices de confusión (Anexo d). Para evitar usar las áreas calculadas directamente de los mapas, las cuales intrínsecamente contienen errores de omisión y comisión, se usó un código en R desarrollado por Mas et al. (2014), con la cual se realizaron correcciones de área propuestos por Card (1982). A partir del cual se determinaron las áreas ajustadas, y sus respectivos intervalos de confianza (Anexo e).

Adicionalmente, a modo de aproximación para determinar si este trabajo fue capaz de detectar correctamente cambios en los ecosistemas, se hizo una prueba realizando unas evaluaciones de fiabilidad adicionales, evaluando solamente los bosques secos tropicales clasificados en los mapas de (Sep. – Dic. 2015), la suma de los bosques secos de (Ene. – Abr. 2016) y (May.- Ago. 2016) lo cuales fueron analizados como uno solo, y los bosques secos de (Sep. – Dic. 2018). Sus mapas de referencia fueron respectivamente los mapas nacionales de superficie cubierta por bosque natural del 2015, 2016 y 2018 (IDEAM, 2019, 2018, 2016). De modo que al final resultaron 3 datos de área boscosa corregida (independiente si es seca o no) de 2015, 2016 y 2018 con sus respectivos intervalos de confianza, los cuales se compararon con los datos oficiales de extensión boscosa.

Tabla 4. Mapas evaluados para fiabilidad, y sus mapas de referencia. Los últimos 2 mapas de áreas protegidas son explicados en el siguiente titulo

Mapa evaluado	Mapa de referencia
Ecosistemas secos potenciales	Imágenes de Google Earth
Clasificación (Sep. – Dic. 2015)	Mapa de Estado de los Ecosistemas Colombianos
Clasificación (May – Ago. 2019)	Imágenes de Google Earth
Cobertura de bosque seco (Sep. – Dic. 2015)	Superficie nacional cubierta por bosque natural de 2015
Adición de ambas Cobertura de bosque seco (Jan. – Apr. 2016) y (May – Aug. 2016)	Superficie nacional cubierta por bosque natural de 2016
Cobertura de bosque seco (Sep. – Dec. 2018)	Superficie nacional cubierta por bosque natural de 2018
Clasificación (May – Ago. 2019) áreas protegidas	Imágenes de Google Earth
Ecosistemas secos potenciales en áreas protegidas	Imágenes de Google Earth

Vale aclarar que la fiabilidad y ajustes de área para las clasificaciones solo fueron realizados para los periodos (Sep. – Dic. 2015) y (May. – Ago. 2019) debido a que para los demás periodos no existen fuentes de información con las cuales contrastar los mapas. A partir de estos mapas, se calcularon las áreas respectivas y se graficó el cambio de los ecosistemas secos para los últimos 4 años (2015-2019).

Evaluación de desempeño de los Objetivos de Desarrollo Sostenible (ODS)

Se evaluaron todas las metas relacionadas con la extensión y el cambio de extensión de ecosistemas propuestas en los objetivos de desarrollo sostenible y las metas Aichi (Tabla 5).

Para esta evaluación se calcularon las áreas de cada cuatrimestre (para el primer y último cuatrimestre se realizó además el ajuste de área), y se graficó el cambio ecosistemas secos para los últimos 4 años

Adicionalmente el mapa de ecosistemas secos potenciales, y la última clasificación (May. – Ago. 2019) fueron recortadas con el mapa de áreas naturales protegidas (Parques Nacionales Naturales de Colombia, 2018). Y se les realizo la evaluación de fiabilidad y ajustes de área, a partir de los cuales se evaluó el porcentaje de ecosistemas secos protegidos.

Tabla 5. Resumen de cumplimiento de los objetivos de desarrollo sostenible.

Marco	Meta	Descripción	Estado actual 2019	Cumplimiento
ODS 13 Meta 13.2	Para 2030 que el 100% de los municipios y Departamentos con Planes de Ordenamiento Territorial, que incorporan el componente de cambio climático	Para este objetivo, se sugiere que la metodología de clasificaciones cuatrimestrales puede ser un insumo, incluido en los planes de ordenamiento territorial, ayudando asi a incorporar el componente de cambio climático, ya que los ecosistemas secos son los más vulnerables al cambio climático	0,1%	Al 2019 debería ser alrededor de 14%, **no se cumple**
ODS 15 Meta 15.1 Aichi 11	Asegurar la conservación, restauración y manejo sostenible de los ecosistemas terrestres… y sus servicios ecosistémicos, especialmente ecosistemas secos (zonas secas) …	Para este objetivo ya existe el indicador de número de hectáreas de áreas protegidas y su meta es para el 2030 tener 30000 hectáreas protegidas. Sin embargo, se sugiere, desagregar este indicador según el tipo de ecosistema, para saber si se están protegiendo los ecosistemas vulnerables. Para ello tómanos la meta Aichi 11, proteger el 17% de los ecosistemas terrestres.	• 30300 ha • 2,4% ecosistemas secos • 2,7% desiertos • 4,8% bosque seco tropical • 0,1% sabanas secas	Al 2019 **se cumple** la meta de las 30000 ha protegidas, sin embargo, es una falla grave no tener en cuenta cuales ecosistemas se están protegiendo. Los ecosistemas secos siguen muy poco representados y **no cumplen** la meta Aichi 11
ODS 15 Meta 15.3 Aichi 5	Para 2030, luchar contra la desertificación, rehabilitar las tierras y los suelos degradados, incluidas las tierras afectadas por la desertificación, la sequía y las inundaciones, y procurar lograr un mundo con una degradación neutra del suelo	Este objetivo no ha sido adoptado por Colombia, y por lo tanto no tiene indicador. Se sugiere: “proteger y no reducir el área de los ecosistemas secos, deteniendo la degradación y la desertificación que los amenaza considerablemente más” Y usar como indicador el número de hectáreas de ecosistemas secos. Aspirando a vincularlo con la meta Aichi 5, reducir al menos a la mitad la tasa de perdida y degradación de los ecosistemas, y de ser posible reducirla hasta 0	Cambio de km^2 • Ecosistemas secos: +4271 • Desiertos: -1607 • Bosques secos: -399 • Sabanas secas: +3902 Tasa de cambio promedio de: • Ecosistemas secos: 1% • Desierto: -6% • Bosque seco tropical: -4% • Sabana seca: 19%	Los ecosistemas secos como una sola categoría y las sabanas han aumentado su área, (lo más seguro por degradación o error y no por restauración) **no se cumple** Los desiertos y bosques redujeron su área **no se cumple** Las tasas de cambio no llegan a 0 **no se cumple**

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ANEXOS

Anexo a. fuentes de información

Insumo	Fuente de obtención	Referencia
mapas de suelos por departamento	https://geoportal.igac.gov.co/contenido/datos-abiertos-agrologia	(IGAC, 1988, 1994, 2009, 2013, 2014, 1997, 1998, 2000, 2001, 2002, 2004, 2006, 2007)
Mapa de ecorregiones globales	https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world	(Olson et al., 2001)
Mapa de Ecosistemas	Personal	(Etter et al., 2018)

potenciales de Colombia y		
Mapa de rendimiento hídrico	http://www.siac.gov.co/catalogo-de-mapas	(MINAMBIENTE; IDEAM, 2015)
Mapas de precipitación cada 5 días	https://developers.google.com/earth-engine/datasets/catalog/UCSB-CHG_CHIRPS_PENTAD	(Funk et al., 2015)
Mapas de evapotranspiración potencial cada 8 días	https://developers.google.com/earth-engine/datasets/catalog/MODIS_006_MOD16A2	(Running et al., 2017)
Coberturas terrestres	https://www.esa-landcover-cci.org/	(European Space Agency and Land Cover CCI partnership, 2017)
Imágenes Sentinel-2 nivel 1c	https://developers.google.com/earth-engine/datasets/catalog/COPERNICUS_S2	(European Space Agency, 2015)
Imágenes Sentinel-2 nivel 2a	https://developers.google.com/earth-engine/datasets/catalog/COPERNICUS_S2_SR	(European Space Agency, 2015)
Perímetro urbano	https://geoportal.igac.gov.co/contenido/datos-abiertos-igac	(IGAC, 2018)
Áreas protegidas	http://www.siac.gov.co	(Parques Nacionales Naturales de Colombia, 2018)
Áreas de bosque nacional	http://smbyc.ideam.gov.co/MonitoreoBC-WEB/reg/indexLogOn.jsp	(IDEAM, 2019, 2018, 2016)

Anexo b curvas Precision-Recall

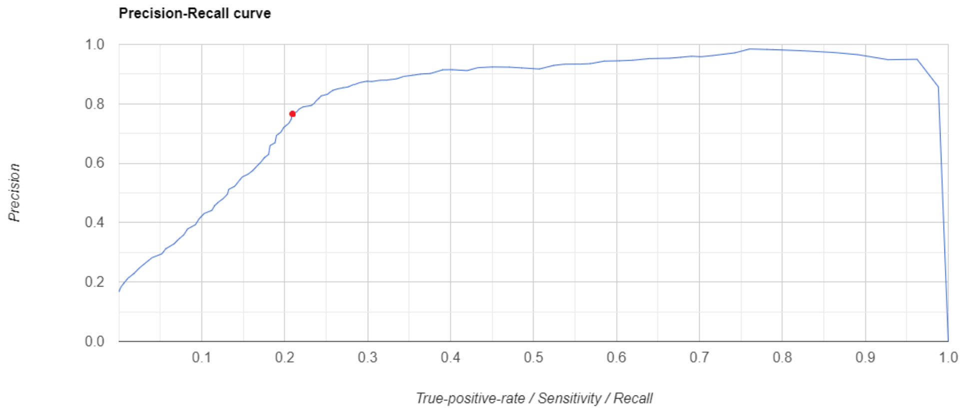


Figura 1. Curva Precision-Recall (Recall modificado como (sensistividad-1) ^2) Sep. – Dic. 2015. Área bajo la curva: 0,8199. Mejor umbral (punto rojo): 0,41. Precisión del mejor umbral: 0,756. Recall del mejor umbral: 0,543.

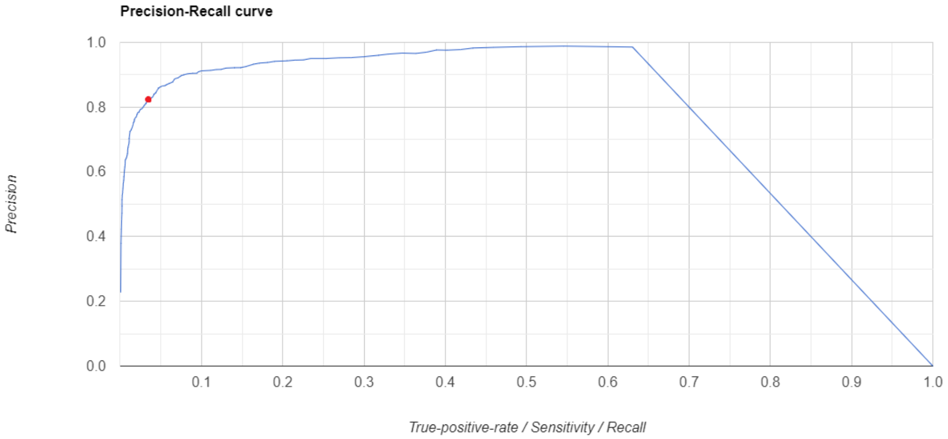


Figura 2. Curva Precision-Recall (Recall modificado como (sensistividad-1) ^2) ene-abr 2016. Área bajo la curva: 0,780171145. Mejor umbral (punto rojo): 0,454545455. Precisión del mejor umbral: 0,821572581. Recall del mejor umbral: 0,815.

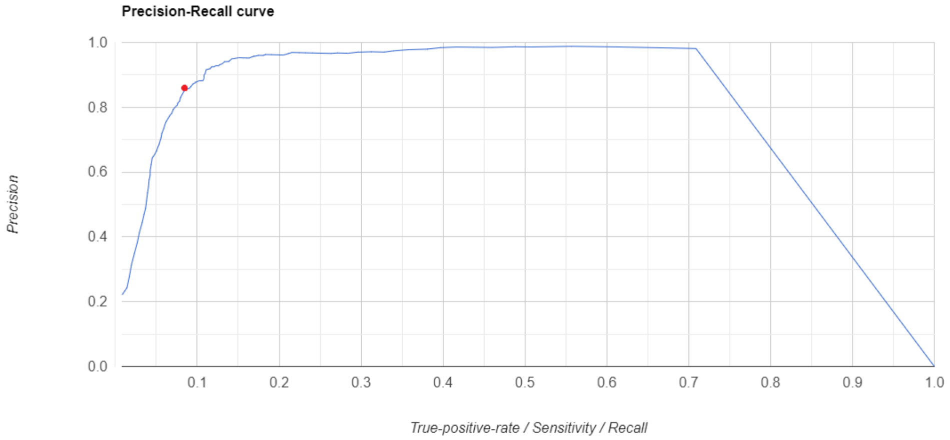


Figura 3. Curva Precision-Recall (Recall modificado como (sensistividad-1) ^2). May. - Ago. 2016. Área bajo la curva: 0,793480474. Mejor umbral (punto rojo): 0,383838384. Precisión del mejor umbral: 0,845422117. Recall del mejor umbral: 0,711.

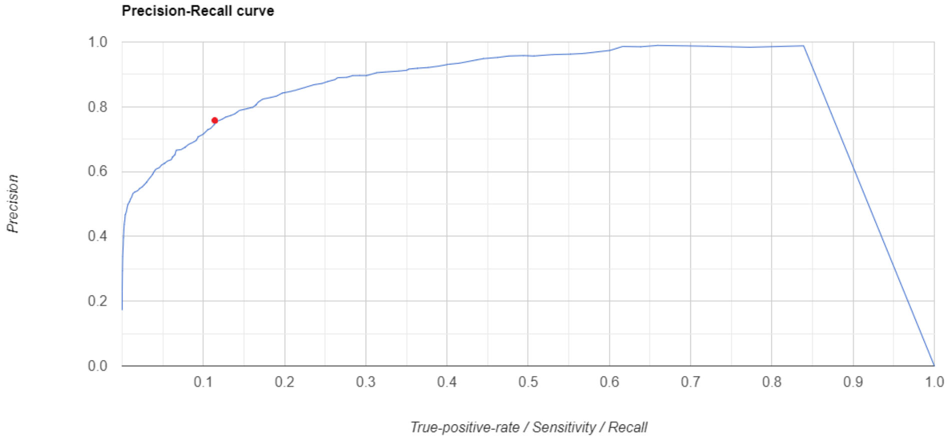


Figura 4. Curva Precision-Recall (Recall modificado como (sensistividad-1) ^2). Sep. – Dic. 2018. Área bajo la curva: 0,825131588. Mejor umbral (punto rojo): 0,464646465. Precisión del mejor umbral: 0,750283768. Recall del mejor umbral: 0,661.

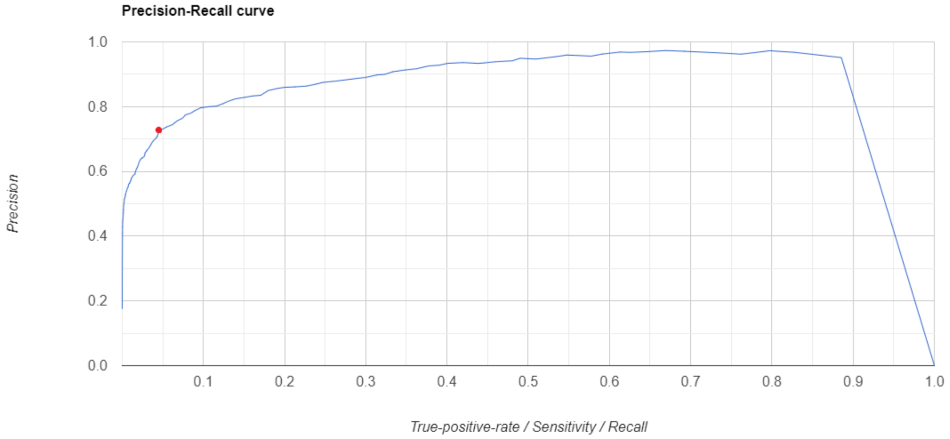


Figura 5. Curva Precision-Recall (Recall modificado como (sensistividad-1) ^2). Ene. – Abr. 2019. Área bajo la curva: 0,851168514. Mejor umbral (punto rojo): 0,414141414. Precisión del mejor umbral: 0,725254394. Recall del mejor umbral: 0,784.

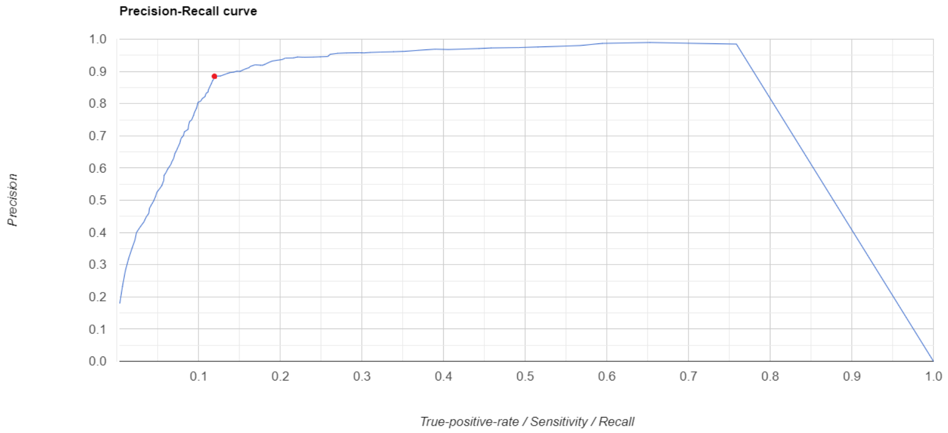


Figura 6. Curva Precision-Recall (Recall modificado como (sensistividad-1) ^2). May – Ago. 2019. Área bajo la curva: 0,802843359. Mejor umbral (punto rojo): 0,505050505. Precisión del mejor umbral: 0,871523179. Recall del mejor umbral: 0,658.

Anexo c. mapas cuatrimestrales clasificados.

Figura 1. Mapa de ecosistemas secos Sep. – Dic. 2015

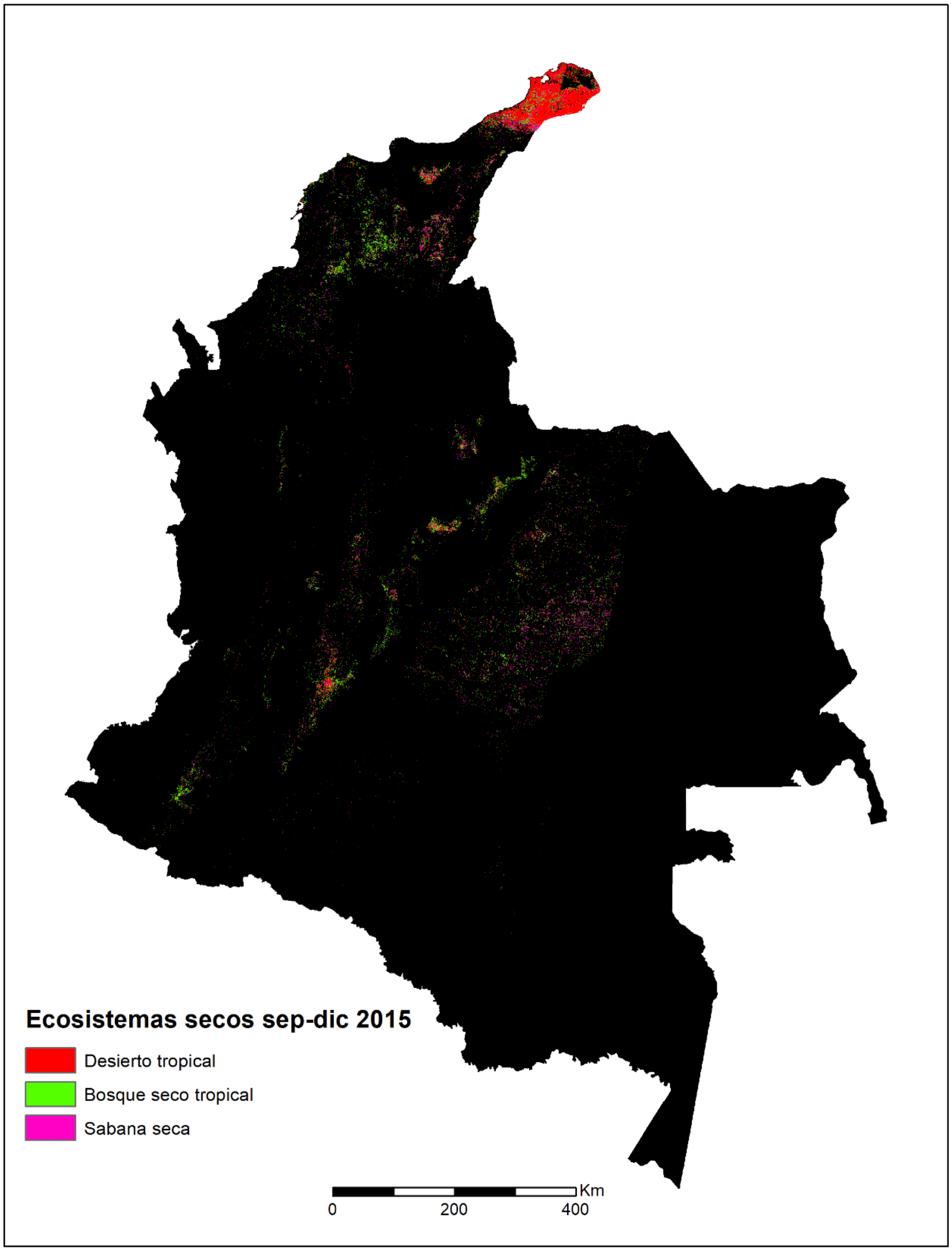


Figura 2. Mapa de ecosistemas secos Ene. – Abr. 2016

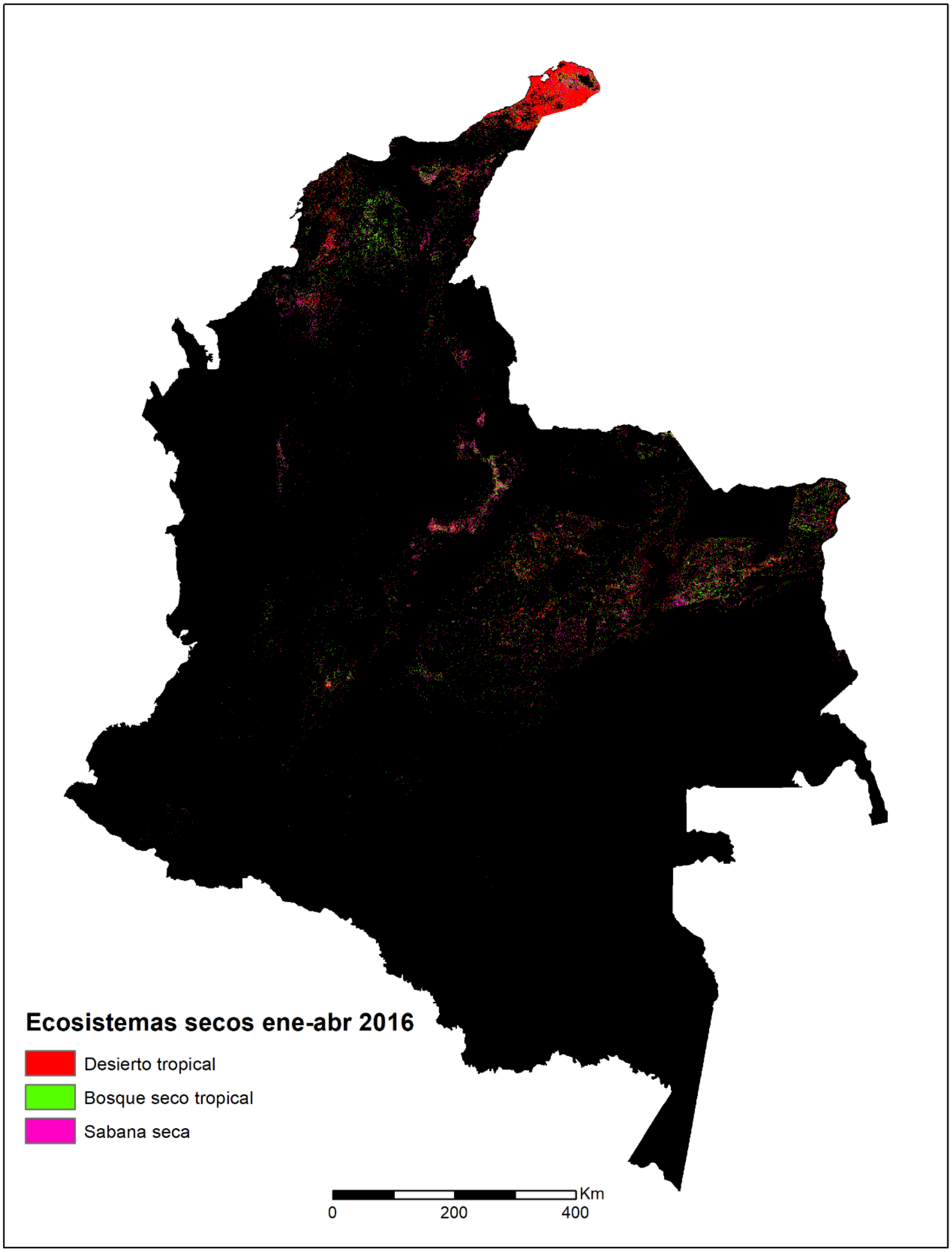


Figura 3. Mapa de ecosistemas secos May. – Ago. 2016

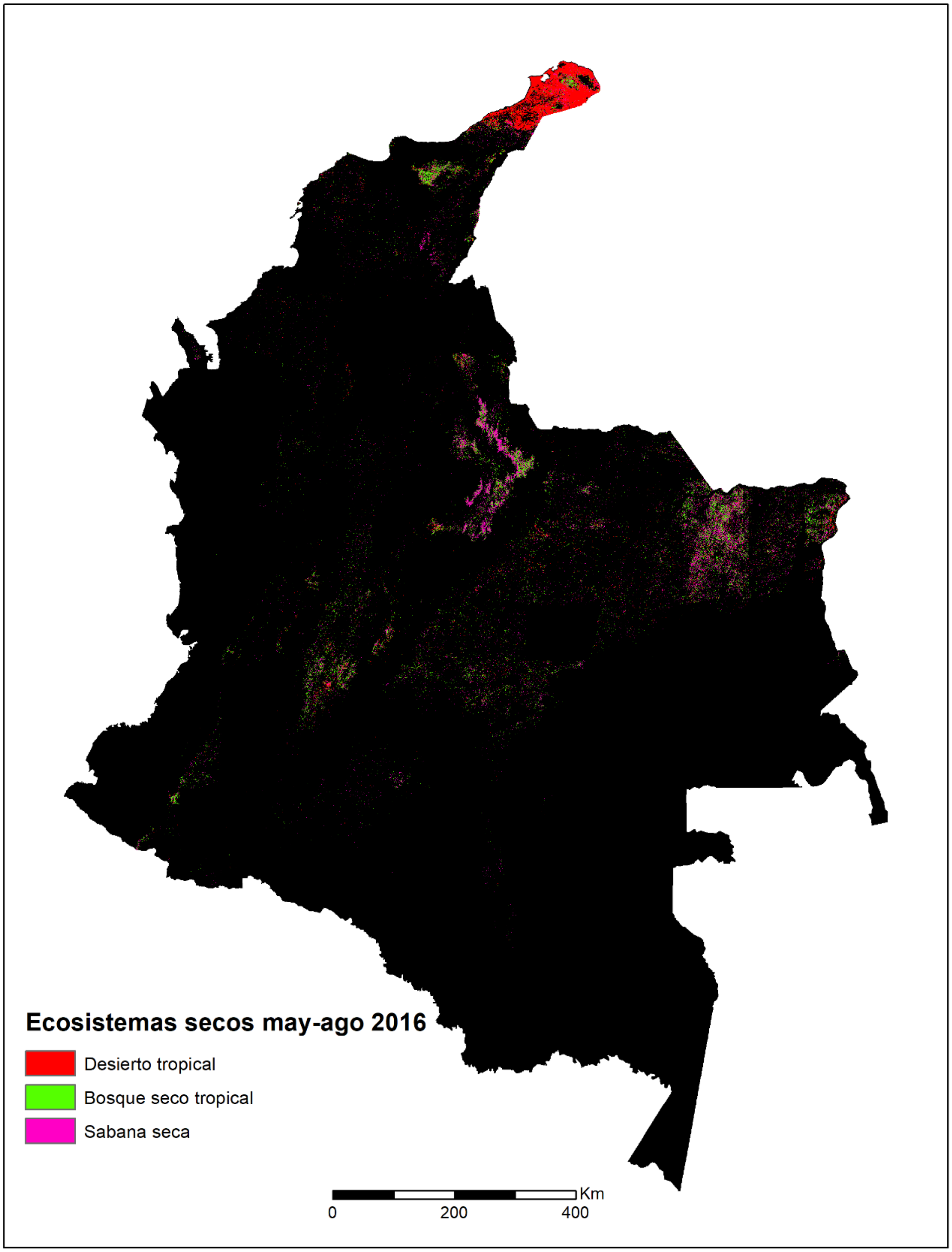


Figura 4. Mapa de ecosistemas secos Sep. – Dic. 2018

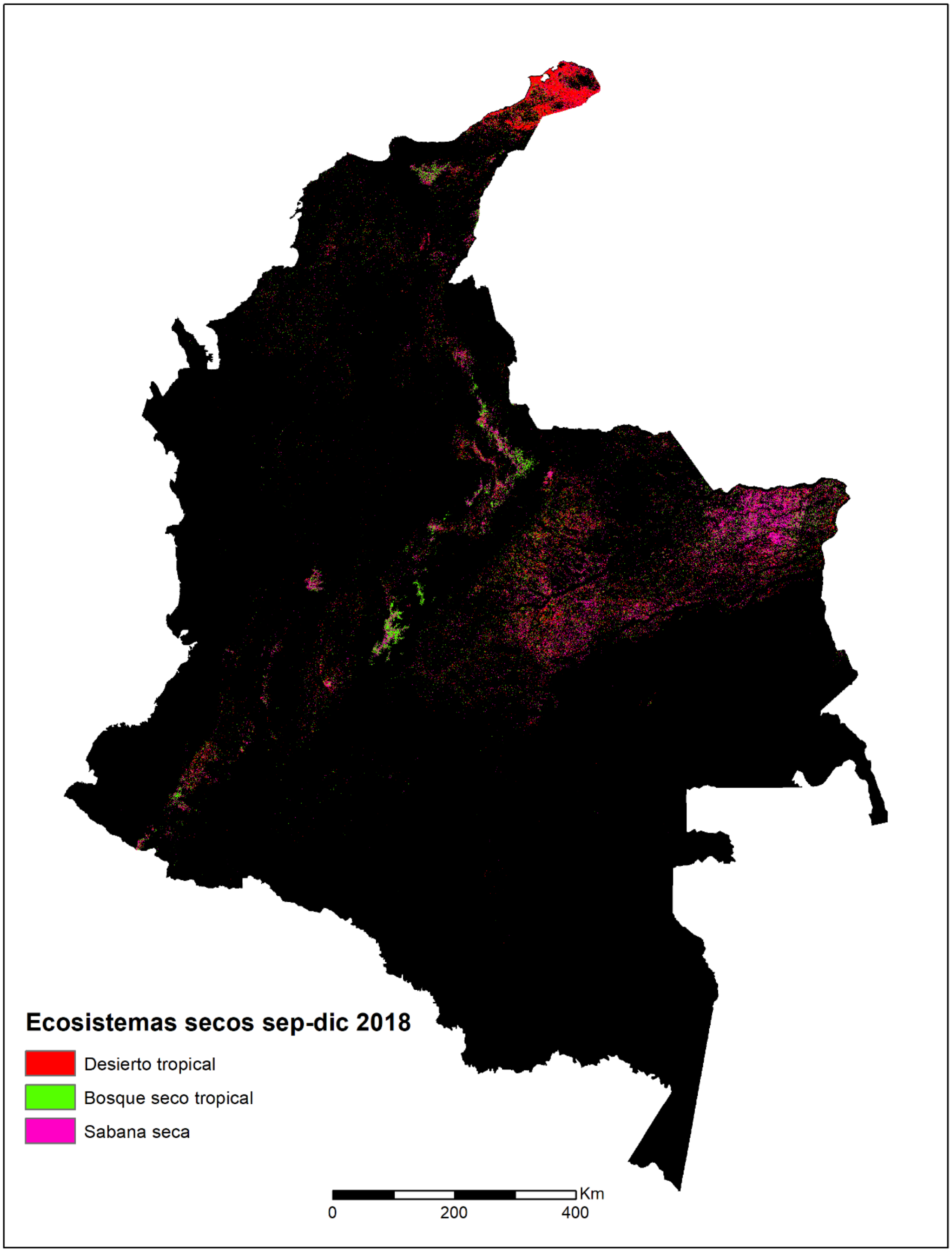


Figura 5. Mapa de ecosistemas secos Ene. – Abr. 2019

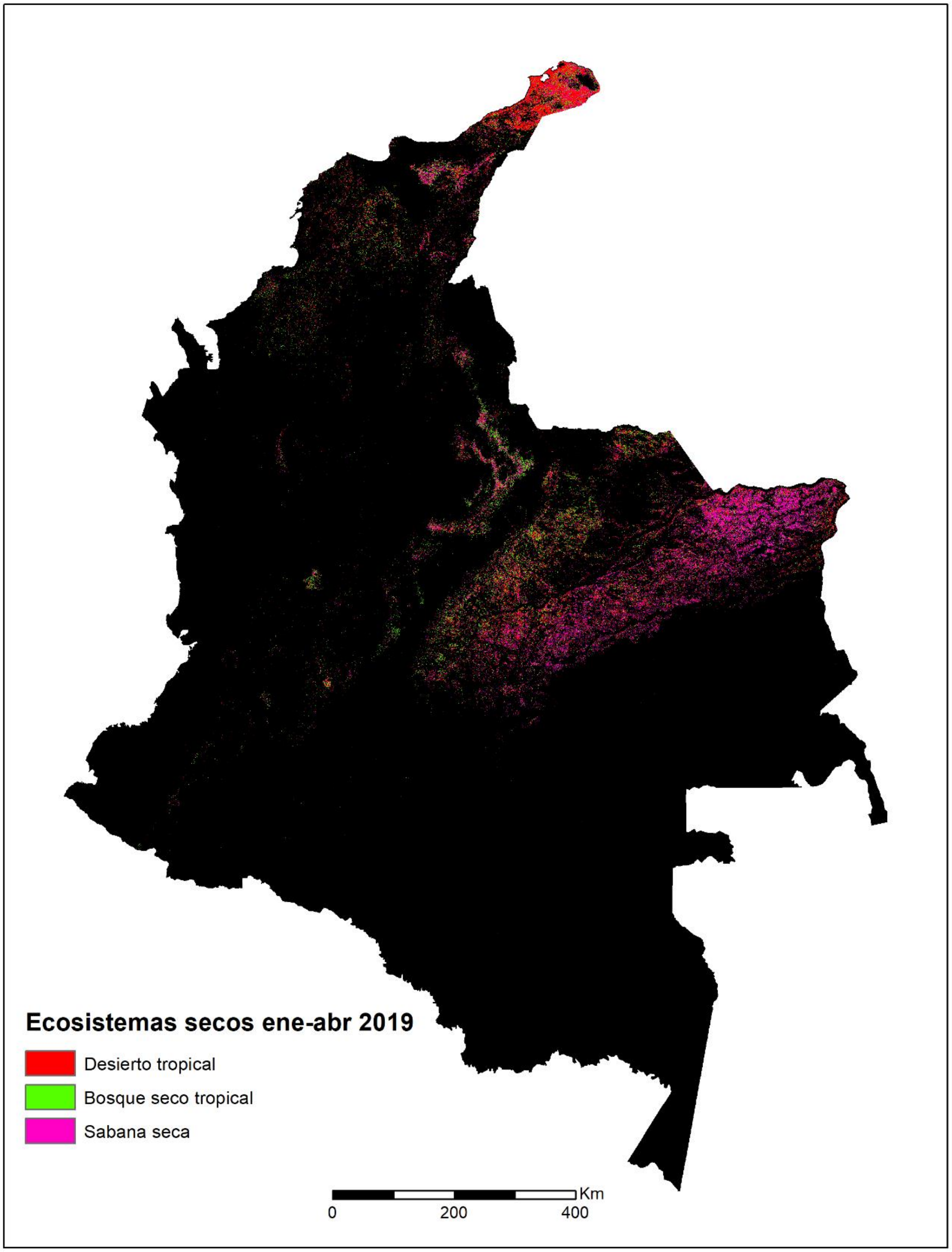
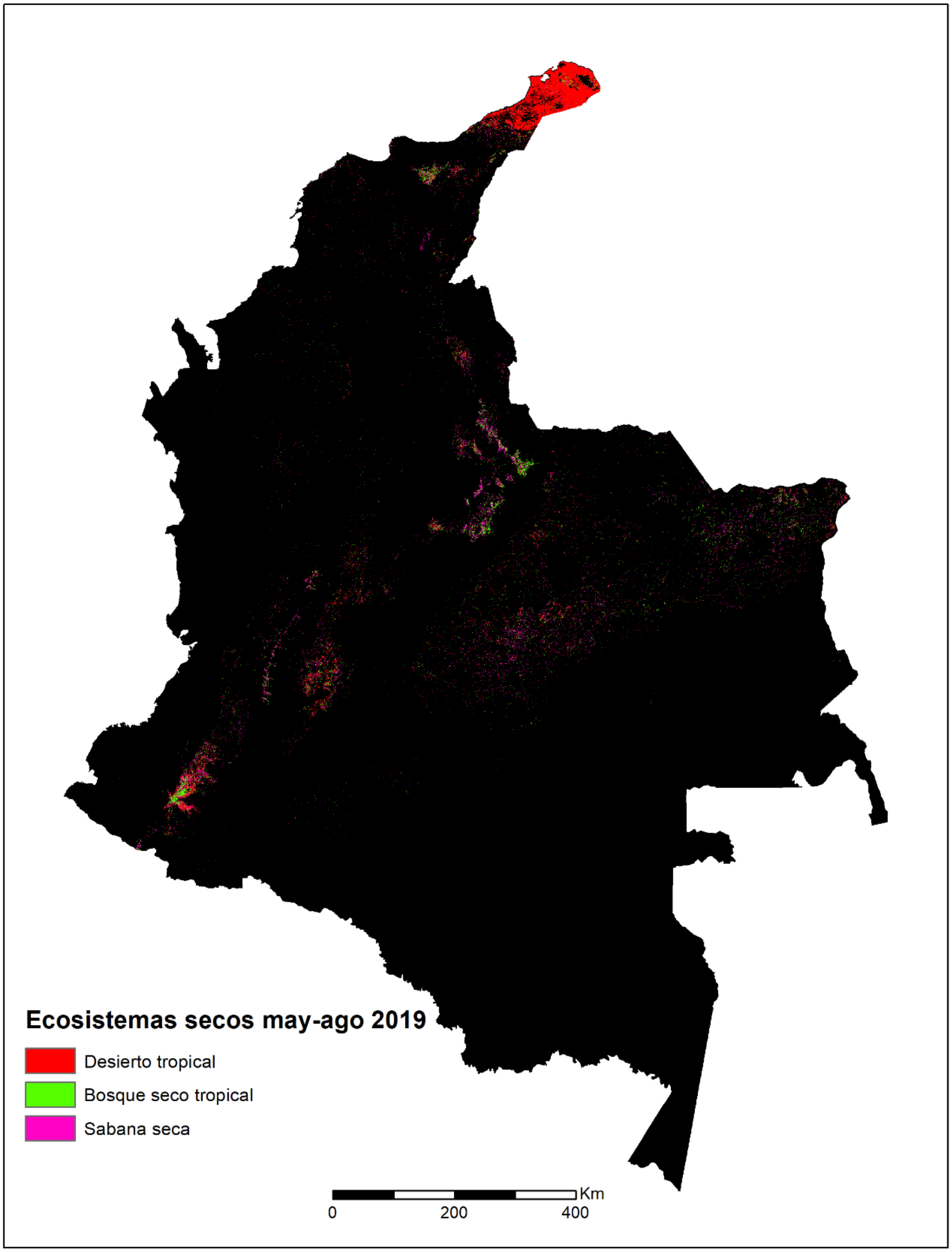


Figura 6. Mapa de ecosistemas secos May. – Ago. 2019.



Anexo d. Matrices de confusión de los mapas con evaluación de fiabilidad.

Tabla 1. Matrices de confusión del mapa de ecosistemas secos potenciales. Tabla superior ecosistemas secos desagregados. Tabla inferior ecosistemas secos como una sola categoría.

	Desierto Tropical	**Bosque Seco Tropical**	**Sabanas Secas**	Otros ecosistemas	**Puntos Totales**	**Error de Comisión**	**Fiabilidad del Usuario**
Área Total (km^2)	7283,5	3215,0	2482,6	1133549,4			
Desierto Tropical	48	1	0	1	50	4 %	0,96 ± 0,05
Bosque Seco Tropical	2	36	3	9	50	28 %	0,72 ± 0,12
Sabanas Secas	0	7	33	10	50	34 %	0,66 ± 0,13
Otros ecosistemas	0	3	6	473	482	1,87 %	
Puntos Totales	50	47	42	493	632		
Error de Omisión	4 %	23,4 %	21,43 %	4,06 %			
Fiabilidad del Productor	0,98 ± 0,0004	0,23 ± 0,007	0,1 ± 0,01				General: 0,98 ± 0,01

	Ecosistemas secos	Otros ecosistemas	**Puntos Totales**	**Error de Comisión**	**Fiabilidad del Usuario**
Área Total (km^2)	12981,1	1133549,4			
Ecosistemas secos	130	20	150	13,33 %	0,87 ± 0,05
Otros ecosistemas	9	473	482	1,87 %	
Puntos Totales	139	493	632		
Error de Omisión	6,47 %	4,06 %			
Fiabilidad del Productor	0,35 ± 0,15				General: 0,98 ± 0,01

Tabla 2. Matrices de confusión del mapa clasificado de ecosistemas secos del primer cuatrimestre Sep. – Dic. 2015. Tabla superior ecosistemas secos desagregados. Tabla inferior ecosistemas secos como una sola categoría.

	Desierto Tropical	**Bosque Seco Tropical**	**Sabanas Secas**	Otros ecosistemas	**Puntos Totales**	**Error de Comisión**	**Fiabilidad del Usuario**
Área Total (km^2)	8121,6396	8833,087	6434,2977	1123141,478			
Desierto Tropical	37	5	3	5	50	26 %	0,74 ± 0,12
Bosque Seco Tropical	8	10	10	22	50	80 %	0,20 ± 0,11
Sabanas Secas	8	6	17	19	50	66 %	0,34 ± 0,13
Otros ecosistemas	7	3	3	475	488	2,66 %	
Puntos Totales	60	24	33	521	638		
Error de Omisión	38,33 %	58,33 %	48,48 %	8,83 %			
Fiabilidad del Productor	0,24 ± 0,12	0,17 ± 0,15	0,19 ± 0,15				General: 0,96 ± 0,014

	Ecosistemas secos	Otros ecosistemas	**Puntos Totales**	**Error de Comisión**	**Fiabilidad del Usuario**
Área Total (km^2)	23389,0243	1123141,478			
Ecosistemas secos	104	46	150	30,67 %	0,69 ± 0,07
Otros ecosistemas	13	475	488	2,66 %	
Puntos Totales	117	521	638		
Error de Omisión	11,11 %	8,83 %		638	
Fiabilidad del Productor	0,35 ± 0,12				General: 0,97 ± 0,014

Tabla 3. Matrices de confusión del mapa clasificado de ecosistemas secos del último cuatrimestre May. – Ago. 2019. Tabla superior ecosistemas secos desagregados. Tabla inferior ecosistemas secos como una sola categoría.

	Desierto Tropical	**Bosque Seco Tropical**	**Sabanas Secas**	Otros ecosistemas	**Puntos Totales**	**Error de Comisión**	**Fiabilidad del Usuario**
Área Total (km^2)	10990,378	5162,4721	7067,0167	1123310,636			
Desierto Tropical	32	1	8	9	50	36 %	0,63 ± 0,13
Bosque Seco Tropical	1	16	1	32	50	68 %	0,32 ± 0,13
Sabanas Secas	2	2	18	28	50	64 %	0,36 ± 0,13
Otros ecosistemas	2	2	7	476	487	2,26 %	
Puntos Totales	37	21	34	545	637		
Error de Omisión	13,51 %	23,81 %	47,06 %	12,66 %			
Fiabilidad del Productor	0,58 ± 0,32	0,24 ± 0,24	0,12 ± 0,08				General: 0,97 ± 0,01

	Ecosistemas secos	Otros ecosistemas	**Puntos Totales**	**Error de Comisión**	**Fiabilidad del Usuario**
Área Total (km^2)	23219,8668	1123310,636			
Ecosistemas secos	81	69	150	46 %	0,54 ± 0,08
Otros ecosistemas	11	476	487	2,26 %	
Puntos Totales	92	545	637		
Error de Omisión	11,96 %	12,66 %			
Fiabilidad del Productor	0,33 ± 0,13				General: 0,97 ± 0,02

Tabla 4. Matriz de confusión del mapa de bosque a partir del bosque seco clasificado en el 2015 (Sep. - Dic. 2015).

	Bosque	No Bosque			
Área Total (km^2)	8833,087	1137697,415	**Puntos Totales**	**Error de Comisión**	**Fiabilidad del Usuario**
Bosque	0	50	50	100 %	0,0 ± 0,0
No Bosque	153	142	295	51,86 %	
Puntos Totales	153	192	345		
Error de Omisión	100 %	26,04 %		638	
Fiabilidad del Productor	0,0 ± 0,0				General: 0,48 ± 0,06

Tabla 5. Matriz de confusión del mapa de bosque a partir del bosque seco clasificado en el 2016 (suma de los bosques secos clasificados en Ene. – Abr. 2016 y May. – Ago. 2016).

	Bosque	No Bosque			
Área Total (km^2)	7088,957	1139441,545	**Puntos Totales**	**Error de Comisión**	**Fiabilidad del Usuario**
Bosque	0	50	50	100 %	0,0 ± 0,0
No Bosque	162	129	291	55,67 %	
Puntos Totales	162	179	341		
Error de Omisión	100 %	27,93 %		638	
Fiabilidad del Productor	0,0 ± 0,0				General: 0,44 ± 0,06

Tabla 6. Matriz de confusión del mapa de bosque a partir del bosque seco clasificado en el 2018 (Sep. – Dic. 2018).

	Bosque	No Bosque			
Área Total (km^2)	11177,5346	1135352,968	**Puntos Totales**	**Error de Comisión**	**Fiabilidad del Usuario**
Bosque	1	49	50	98 %	0,02 ± 0,04
No Bosque	165	131	296	55,74 %	
Puntos Totales	166	180	346		
Error de Omisión	99,4 %	27,22 %		638	
Fiabilidad del Productor	0,0003 ± 0,0007				General: 0,44 ± 0,06

Tabla 7. Matrices de confusión del mapa de ecosistemas secos potenciales en áreas protegidas. Tabla superior ecosistemas secos desagregados. Tabla inferior ecosistemas secos como una sola categoría.

	Desierto Tropical	**Bosque Seco Tropical**	**Sabanas Secas**	Otros ecosistemas	**Puntos Totales**	**Error de Comisión**	**Fiabilidad del Usuario**
Área Total (km^2)	259,1	684,1	13	302229,8			
Desierto Tropical	35	13	2	0	50	30 %	0,7 ± 0,13
Bosque Seco Tropical	1	30	0	19	50	40 %	0,6 ± 0,14
Sabanas Secas	0	7	36	7	50	28 %	0,72 ± 0,12
Otros ecosistemas	0	0	0	467	467	0 %	
Puntos Totales	36	50	38	493	617		
Error de Omisión	2,78 %	40 %	5,26 %	5,27 %			
Fiabilidad del Productor	0,92 ± 0,13	0,86 ± 0,06	0,47 ± 0,34				General: 0,99 ± 0,0003

	Ecosistemas secos	Otros ecosistemas	**Puntos Totales**	**Error de Comisión**	**Fiabilidad del Usuario**
Área Total (km^2)	956,2	302229,8			
Ecosistemas secos	124	26	150	17,33 %	0,82 ± 0,06
Otros ecosistemas	0	467	467	0 %	
Puntos Totales	124	493	617		
Error de Omisión	0 %	5,27 %			
Fiabilidad del Productor	1 ± 0				General: 0,99 ± 0,0002

Tabla 8. Matrices de confusión del mapa clasificado de ecosistemas secos del ultimo cuatrimestre (May. – Ago. 2019) en áreas protegidas. Tabla superior ecosistemas secos desagregados. Tabla inferior ecosistemas secos como una sola categoría.

	Desierto Tropical	**Bosque Seco Tropical**	**Sabanas Secas**	Otros ecosistemas	**Puntos Totales**	**Error de Comisión**	**Fiabilidad del Usuario**
Área Total (km^2)	366,6175	988,6467	932,9964	300897,7269			
Desierto Tropical	8	1	11	29	49	83,67 %	0,16 ± 0,10
Bosque Seco Tropical	0	0	1	48	49	100 %	0 ± 0
Sabanas Secas	0	1	6	44	51	88,24 %	0,12 ± 0,08
Otros ecosistemas	1	2	2	466	471	1,06 %	
Puntos Totales	9	4	20	587	620		
Error de Omisión	11,11 %	100 %	70 %	20,61 %			
Fiabilidad del Productor	0,09 ± 0,16	0 ± 0	0,07 ± 0,1				General: 0,98 ± 0,008

	Ecosistemas secos	Otros ecosistemas	**Puntos Totales**	**Error de Comisión**	**Fiabilidad del Usuario**
Área Total (km^2)	2288,2606	300897,7269			
Ecosistemas secos	28	121	149	81,21 %	0,19 ± 0,06
Otros ecosistemas	5	466	471	1,06 %	
Puntos Totales	33	587	620		
Error de Omisión	15,15 %	20,61 %			
Fiabilidad del Productor	0,14 ± 0,13				General: 0,98 ± 0,008

Anexo e. tabla de áreas ajustadas

Mapa	Clase	Área Original	Área ajustada	Área Mínima	Área Máxima
Mapa de ecosistemas secos potenciales	Ecosistemas secos	12981	32416	18685	46147
	Desierto Tropical	7284	7121	6684	7558
	Bosque Seco Tropical	3215	9863	1877	17850
	Sabanas Secas	2483	15942	4703	27181
Mapa clasificado de ecosistemas secos del del primer cuatrimestre Sep. – Dic. 2015	Ecosistemas secos	23389	46136	29980	62292
	Desierto Tropical	8122	24563	12608	36519
	Bosque Seco Tropical	8833	10255	2345	18166
	Sabanas Secas	6434	11346	3422	19270
Mapa clasificado de ecosistemas secos del último cuatrimestre May. – Ago. 2015	Ecosistemas secos	23220	37911	22956	52866
	Desierto Tropical	10990	11952	5377	18527
	Bosque Seco Tropical	5162	6772	323	13221
	Sabanas Secas	7067	20588	8606	32570
Bosque a partir bosque seco clasificado en el 2015 (Sep. - Dic. 2015).	Bosque	8833	590060	525080	655040
Bosque a partir bosque seco clasificado en el 2016 (suma de los bosques secos clasificados en Ene. – Abr. 2016 y May. – Ago. 2016).	Bosque	7089	634328	569179	699477
Bosque a partir bosque seco clasificado en el 2018 (Sep. – Dic. 2018).	Bosque	11178	634798	570576	699020
Ecosistemas secos potenciales en áreas protegidas	Ecosistemas secos	956	790	732	849
	Desierto Tropical	259	195	152	238
	Bosque Seco Tropical	684	480	381	579
	Sabanas Secas	13	20	5	34
Ecosistemas secos del último cuatrimestre (May. – Ago. 2019) en áreas protegidas	Ecosistemas secos	2288	2985	485	5486
	Desierto Tropical	367	699	0	1951
	Bosque Seco Tropical	989	1303	0	3073
	Sabanas Secas	933	1490	0	3262

Towards a Monitoring of Drylands: Cloud Geoprocessing for Assessing Sustainable Development Goal Indicators in Colombia

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Abstract

Drylands in Colombia have been neglected and understudied, even when they had been declared strategic ecosystems for the nation, acknowledging its ecological, cultural, biological and societal value. Additionally, worldwide, they have been recognized as well, as ecosystems of high interest, as shown in some Sustainable Development Goals and Aichi targets. Unfortunately, conservation targets regarding drylands had not been yet evaluated, thus we tried to set and initial assessment of those targets, by doing a drylands delimitation, and (taking advantage of Google Earth Engine cloud geoprocessing capacities) measure their area changes since 2015, concluding that those targets are not been met in Colombia. Furthermore, this work also aims to be a preliminary work towards development of a cheap, fast, and reliable dryland monitoring system, that can periodically be employed as indicators of some Sustainable Development Goals Targets.

Keywords: Dry, Ecosystems, SDG, Aichi, Targets, Sentinel, Google Earth Engine, Colombia

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1. Introduction

Around 40% of the world's land surface is considered drylands according to the United Nations Convention to Combat Desertification (CCD) (White and Nackoney, 2003). Areas with a relationship between annual precipitation (P) and potential evapotranspiration (EVP) lower than 0,65 are considered drylands (excluding polar and subpolar regions). Drylands are characterized by limited water sources, high evaporation, as well as temporal and spatial variability in precipitation, resulting in ecosystems with marked seasonality patterns which impose critical challenges to their delimitation (Fensholt et al., 2012; Ohana-Levi et al., 2018; Schwinning et al., 2004).

Drylands are critical biodiversity hotspots; they are habitat of numerous endemic and specialized species (White and Nackoney, 2003), which conform complex trophic webs and ecological structures (Ayal et al., 2005). Unfortunately, there are not enough conservation and/or research efforts towards dry ecosystems (Bonkoungou, 2001; Prăvălie, 2016; Reynolds et al., 2004). Therefore, drylands have become a conservation priority due to their vulnerability and threat level worldwide (United Nations, 2011). They host about 2100 million people, 90% of them live in developing countries, and approximately half of them in poverty conditions (United Nations Development Programme, 2011).

Unfortunately, drylands are prone to conflict, authoritarian regimes, state corruption, lack of financing and governance challenges (Gnacadja, 2010; Lopez Porras et al., 2019; Sachs et al., 2004); thus showing an extremely vulnerable population, most of which rely on natural resources for their livelihood (Bohle et al., 1994; Reynolds et al., 2007). Drylands vulnerability is further increased due to their response to climate change, land degradation, and environmental variability (Prăvălie, 2016; Turner II et al., 2003). Therefore, drylands constitute complex socio-ecological systems accounting trade-offs -generally a downward spiral- between social and biophysical components (Folke, 2016), that should be understood and carefully managed.

For example in drylands land degradation and desertification, bioclimatic drivers (like climate change) worsen human well-being, and then anthropogenic drivers (mainly overgrazing and expansion of cropped areas) intending to, ironically, improve human well-being end up promoting land degradation that is aggravated by bioclimatic drivers (Safriel and Adeel, 2005). Ergo, in order to maintain the production, or to improve the social condition in drylands, inhabitants tend to overuse and mismanage the resources (Charney, 1975; Lopez Porras et al., 2019; Sachs et al., 2004).

These conditions have raised a concern about drylands everywhere; evidence of this is the fact that 194 nations signed the CCD (Naciones Unidas, 1994), or that 2006 was designated as the international year of the desert and desertification (United Nations, 2003), and in 2002 was created the Drylands Development Centre, which later changed to Integrated Drylands Development Programme (IDDP) (United Nations Development Programme, 2017).

These efforts have been encompassed by the Sustainable Development Goals (SDG), which aim to "promote prosperity while protecting the environment" (United Nations, 2015), specifically, goals 13 "climate change" and 15 "life on land" have targets concerning drylands (Table 1). Similarly, Aichi biodiversity targets 5 & 11 are related to dryland conservation and should be met by 2020 (Convention on Biological Diversity, 2010). Regardless of reaching the Aichi deadline, its targets should be articulated to the SDGs (UICN, 2014); countries such as Colombia, which agreed to both Aichi targets and SDGs, should reinforce the commitments on biodiversity and ecosystem services.

In Colombia drylands were declared strategic ecosystems in the National Action Plan to fight against desertification and drought (Ministerio de Ambiente y Desarrollo Sostenible, 2005) as a result of having agreed to and signed the CCD (Congreso de Colombia, 1998). However, Colombia is not currently measuring indicators specifically for drylands, failing to comply its signed international agreements, either due to lack or low quality of data, or difficulty disaggregating and comparing indicators through scales (national, regional, municipal), and associated costs regarding tools for measurement and monitoring (Congreso de Colombia, 2019). Consequently, management and protection measures are poorly or not implemented, as evidenced by the lack of an active monitoring protocol for these ecosystems. Monitoring efforts have been focused solely on land degradation (MADS; IDEAM, 2012), and desertification (IDEAM; MAVDT; IGAC, 2010), which are insufficient for understanding dryland dynamics.

Taking this into account, the main purpose of this study is to determine how the extension of Colombia's drylands has changed during the period 2015 to 2019, in order to know the contribution regarding the fulfillment of goals within the Sustainable Development Objectives. For that, the potential areas of dry ecosystems in Colombia were identified, then using remote sensing data and cloud geoprocessing, drylands were classified for ~2015 and ~2019, in order to compare its area changes. Finally, assess the relationship between those changes and the adherence to the goals of the Sustainable Development Objectives for dry ecosystems in the nation.

***Table 1** Goals, targets and indicators both at international and national (Colombia) level concerning drylands. Aichi targets are highlighted under the SDG target they should be articulated* (Comisión Económica para América Latina y el Caribe, 2019; Secretaría Del Convenio Sobre La Diversidad Biológica (SCDB), 2010; United Nations, 2017).

Goal	Global Target	Global Indicator	National (Colombia) Target	National (Colombia) Indicator
13 Take urgent action to combat climate change and its impacts	**13.2** Integrate climate change measures into national policies, strategies, and planning	**13.2.1** Number of countries that have communicated the establishment or operationalization of an integrated policy/strategy/plan which increases their ability to adapt to the adverse impacts of climate change, and foster climate resilience and low greenhouse gas emissions development in a manner that does not threaten food production (including a national adaptation plan, nationally determined contribution, national communication, biennial update report or other)	**13.2** to incorporate measures regarding climate change in national policies/strategies/plans	**13.2.2** percentage of municipalities and departments with territorial arrangement plans that incorporates the climate change component
15 Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	**15.1** By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains, and drylands, in line with obligations under international agreements	**15.1.2** Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type	**15.1** ensure to conserve, restore and use sustainably, the terrestrial ecosystems and inland freshwater and their services, especially forest, wetlands, mountains, and drylands, in consonance to the signed international agreements	**15.1.2** number of hectares of protected areas
	Aichi Target 11: By 2020, at least 17 per cent of terrestrial and inland water, and 10 per cent of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscape and seascapes.			
	15.3 By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought, and floods, and strive to achieve a land degradation neutral world	**15.3.1** Proportion of land that is degraded over total land area	**15.3** this target has not been evaluated, nor has available data yet for Colombia	no indicator
	Aichi target 5: By 2020, the rate of loss of all-natural habitats, including forests, is at least halved and where feasible brought close to zero, and degradation and fragmentation is significantly reduced.			

2. Material and Methods

2.1 Study area

Colombia is a tropical country, in the northernmost part of South-America, with a continental extension of 1’142.000 km^2, from which supposedly 21% are drylands (Ministerio de Ambiente y Desarrollo Sostenible, 2005). Drylands in Colombia are: Tropical Dry Forest, Tropical Desert, Dry savannas, shrublands, and open lands with xerophilic vegetation (IDEAM et al., 2017). In this work dry savannas shrublands and open lands with xerophilic vegetation are going to be grouped as one ecosystem named Dry savannas, as an intermediate ecosystem between desert and forest (more vegetation than a desert, but with less trees and a smaller canopy than a forest).

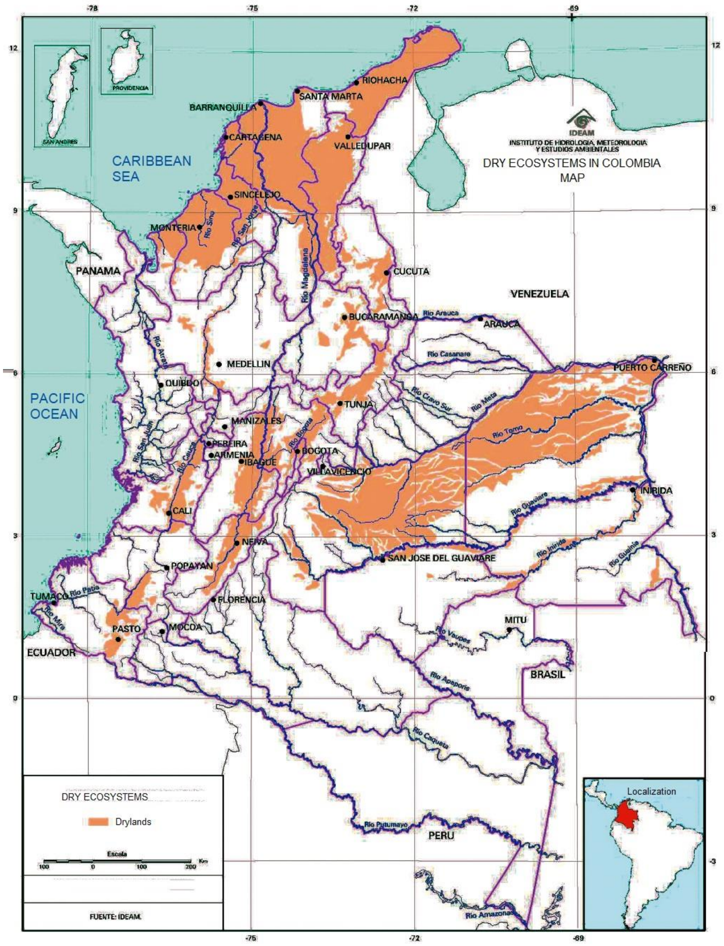


Figure 1. Drylands current official delimitation

Colombian drylands are located in the Caribbean region (northernmost part of the country) Andean region (in the Andes), and Orinoquia region (east of the Andes) (Ministerio del Medio Ambiente y Desarrollo Sostenible, 2017) (Figure 1). They are highly valuable, for example tropical dry forest (the better studied dry ecosystem in Colombia) still preserves two main floristic groups of the dry forest biome, and one of those is endemic to inter Andean valleys in Colombia (Banda et al., 2016), despite being extremely endangered.

For example Colombian tropical dry forests had 8 million hectares original coverage (Pizano and García, 2014), but now 92% of the original cover is lost (Aldana-Domínguez et al., 2017), and only 5% of its current area in Colombia are within protected areas (Pizano and García, 2014). Additionally, resource depletion, weak institutions, wrong technology, and exploitative economic systems promote desertification and land degradation (Reynolds et al., 2007, 2005). These conditions could be exacerbated by landscape transformation (Huang et al., 2016), and climate change (Huang et al., 2017), which is expected to be worse in drylands, than in any other ecosystems (IDEAM; MAVDT; IGAC, 2010).

2.2 Software

Even though paid software ArcMap 10.7 (ESRI, 2019) was used, this work tried to employ mainly free tools like: R 3.5.3 (http://www.r-project.org/) (The R Foundation, 2019), Qgis desktop 3.4.4 (QGIS Development Team, 2018) (http://www.qgis.org/), and Google Earth Engine (GEE) to access, visualize, and process the satellite imagery (https://earthengine.google.com/). GEE is a tool that integrates cloud geoprocessing, massive computational capabilities and a variety of satellite repositories, in order to allow easy and fast large-scale analysis (Gorelick et al., 2017).

2.3 Potential Areas of Drylands Delimitation

In order to begin, it was constructed a drylands delimitation based on three components: soil, climate, and biotic.

The soil component was defined based on a categorization of ecological and pedogenesis characteristics typical for drylands soils applying the United States Department of Agriculture (USDA) soil taxonomy (Soil Survey, 1999, 1975). We used departmental soil maps (Instituto Geográfico Agustín Codazzi IGAC, 2014, 2009, 2007, 2006, 2004, 1998, 1997) ranging values between 0 and 100 representing characteristics that belong (high values) or not (low values) to drylands.

The biotic component account to delimit biogeographic limits of drylands in Colombia. It was created using the WWF ecoregions (Dinerstein et al., 2017; Olson et al., 2001) and the ecosystems delimitation from the Red List of Colombian Ecosystems (Etter et al., 2018). For each ecoregion or ecosystem (as accordingly), it was assigned a value of 100 for drylands, and 0 for other ecosystems. After that, it was calculated the average value between both maps.

For the climate component, we calculated the aridity index according to the CCD. We applied the P/EVP relationship, this index is designed for annual values. Even so, we applied it at monthly level, because is shown that drylands annual index values could omit seasonality, and if the purpose of the study do not include predictions on simulated scenarios, temporal bias due to different temporal scales do not disturb greatly the results (Aryal and Zhu, 2016; Cao et al., 2019; Li et al., 2010).

We used remote sensing data, instead of *in situ* climatic data form the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM). Taking into account its trade-off: overestimations, lowering accuracy on short time periods, and reduced accuracy in terrains with high altitudinal variability (Collarani Anagua and Villazon, 2018; Rivera et al., 2018; Urrea et al., 2016) in exchange for: faster and more intuitive processing.

Precipitation was from the CHIRPS project (Funk et al., 2015), and potential evapotranspiration from the terra MODIS collection (Running et al., 2017)-. We produced two maps: one with the aridity index value, and a binary map of the areas that satisfy the CCD threshold (0.65) (1 = drylands, 0 = anything else).

The 48 aridity index maps (12 months for each years in the period 2015-2019) were averaged to consider areas with an average aridity index < 0,65. The 48 threshold binary maps were summed, and in order to have the same logic with the averaged index (lower values = drier areas), they were inverted as well, so lower values mean more likely to be dryland. At least one-third of the 48 months must have been thresholded as dry in order to consider the pixel as a dryland.

Then, both maps (average aridity index and sum of thresholds), were multiplied. To keep the same relation (drier pixels = lower values), if a pixel were considered not drylands in both maps, it would have a value of 0; if it were considered drylands by just one of the maps, it would be multiplied additionally by 1,2; and if it were considered dryland by both maps it would be multiplied by 1. Hence, low-value pixels (excluding 0) would mean more likely to be dryland, and higher values and 0 would be pixels less likely to be drylands.

Afterward, equation 1 was employed to the multiplication map to invert its scale and to set a minimum value at 0 and a maximum at 100. Being f(x) the final complemented aridity index.

Equation1.

$$f(x) = \begin{cases} when\ "multiplication\ map" = 0, & x = 0 \\ when\ \text{"multiplication map"} > 0, & x = \dfrac{200 - \text{"multiplication map"}}{2} \end{cases}$$

Additionally, the specific discharge map (MINAMBIENTE; IDEAM, 2015) was rescaled and reclassify, so, the areas with high specific discharge would have lower positive values (with a minimum at 0), and areas with low specific discharge would have higher (with a maximum at 100) likelihood of being drylands.

Then the final complemented aridity index and the reclassified discharge maps were averaged, resulting in the final climate component map.

Finally, the three component maps were averaged. We chose a value of 50 to delimit drylands usaing a try-erro process. We found that at this value it was possible to effectively differentiate drylands form other land covers, taking as reference the dry canyon of Chicamocha (a well-known arid area in Colombia). The resulting map was then complemented with landcover attribute at 2014 from the Red List of Colombian Ecosystems (Etter et al., 2018), excluding non-natural drylands (e.g. transformed areas, water bodies, urban areas, agriculture, etc.). This final layer was employed as the remnant drylands in Colombia and as the training polygons for the subsequent classifications. Through this document this map would be referred as the dryland's delimitation.

2.4 Image preprocessing

This study works as a preliminary effort towards future monitoring systems, therefore, it only evaluates the first and last year available, to assess its performance before evaluating (in the future) all available years.

Not all sentinel-2 images were BOA images, so first of all, it was necessary to do the atmospheric correction of every TOA image, so when classifying, the data would represent the surface reflectance, therefore, reducing the classification error (Main-knorn et al., 2017).

Hence, for all TOA images, a Sensor Invariant Atmospheric Correction (SIAC) (Yin et al., 2019), was applied directly in GEE. SIAC method provides not only an atmospheric corrected image but cloud information as well, from which a cloud mask was built, and complemented with another cloud mask from the cloud information in each Sentinel-2 image. Additionally, a shadow mask based on the Red-Edge 4 band (Zhu et al., 2015), was applied in order to have clean images. In addition, the Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1973) was calculated and added to each image as a new band. The cloud and shadow masks, and the NDVI addition were applied to all images, not only to the TOA ones.

After that, images were grouped in 4-months periods, because that is the minimum extent of a dry rain-free season required to determine a dry forest (Janzen, 1988). In order to create triannual composite images measuring the median value of each band for each pixel. In the end, having six composites images (Sep. - Dec. 2015, Jan. - Apr. 2016, May - Aug. 2016, Sep. - Dec. 2018, Jan. - Apr. 2019 and May - Aug. 2019).

2.5 Separability

The first composite image (Sep. - Dec. 2015) was downloaded from GEE, in order to perform a separability test, proposed by Bhattacharyya (1946). This separability index shows the best combination of bands that effectively separates the evaluated groups (in this case, drylands from the rest of land covers). Thus, we randomly sample 10000 points distributed in all the non-drylands areas of the country, and then, applied a 2 km buffer for each point. Those buffers later were merge with the dryland delimitation polygons, therefore having sufficient information that adequately represents the spectral variability of every landcover (dryland and non-dryland). It indicated that the best bands combination were (six bands): [1] visible red light, [2] visible green light, [3] visible blue light, and infrared light; [4] Red Edge 1, [5] Red Edge 2, [6] Red Edge 3.

Moreover, a second separability test was performed to find the best combination of bands that effectively separates the dry land covers within each other — showing that the best bands combination were (five bands): [1] visible red light, [2] visible blue light, and infrared light; [3] Red Edge 1, [4] Red Edge 2, [5] Red Edge 3.

2.6 Classification

We performed the classification process in two steps to better differentiate the spectral variability of Colombian dry ecosystems. First a maximum entropy (Maxent) classifier (Mann et al., 2009) to classify drylands from the composite image, and secondly a Random Forest classifier (Breiman, 2001) to define the dry ecosystems within the previously classified drylands.

The Maxent classifier was employed with 1000 and 5000 sample points for drylands and non-drylands categories, respectively (sampled from the dryland's delimitation), using the combination of bands obtained from the first separability index. It was chosen because it allows performing a dual classification (drylands or not), giving a probability ranging map, that should be thresholded to obtain a final binary map. In order to find the best threshold that balances the omission and commission errors, a Precision-Recall curve was computed (with the same amount, but different, plots from the training ones) because it works better than the typical Receiver Operating Characteristic (ROC) curve when the samples are unbalanced (Saito and Rehmsmeier, 2015), therefore choosing the threshold closest to a perfect classification.

After applying the threshold value found we excluded (to minimize the commission error) urban areas using the urban perimeter map (IGAC, 2018), and the areas outside drylands landcover, according to the ESA landcover map (European Space Agency and Land Cover CCI partnership, 2017).

Afterward, the edited binary map was -again- classified, using a Random Forest classifier with 1000 sample points for each Colombian dry ecosystem (tropical dry forest, tropical desert, and dry savannas), employing, exclusively, the second bands' combinations from the separability index. Finally, resulting in the dry ecosystems (drylands) triannual maps.

2.7 Accuracy assessment and Area adjustment

Accuracy assessment was carried out according to the methodology proposed by Olofsson et al. (2014, 2013). From which the sample size of verification points was determined following equation 2. Where N is the sample size, S(Ô) the standard error of the estimated overall accuracy that is expected to be achieved, W_i the mapped proportion of the area of the category i, and U_i the expected user accuracy of class i (proportion of the area mapped as category i, which is truly i).

Equation 2. $$N = \left(\frac{\sum W_i * U_i}{S(\hat{O})}\right)^2$$

Fifty validation samples are recommended to be assigned as a minimum for every class (Olofsson et al., 2014), letting the remaining samples to be proportionally assigned among the other classes. However, due to drylands only representing around 3,5% of the national territory (check results section), drylands always had been assigned with 150 samples (50 for each dry ecosystem).

From those samples, confusion matrixes were made, and subsequently, from each matrix, taking into account the respective commission and omission errors areas were corrected, following the area adjustment method proposed by Card (1982), however, it is worth noticing that in maps with rare small classes immerse in one very large class, unfortunately it is common to have big confidence intervals(Perilla and Mas, 2019), as in this studied happened with every evaluated map (Table 2).

As a complementary accuracy approach, and in order to evaluate that the area estimates from the proposed dryland monitoring are reliable, total forest national area (dry or not), was estimated based on just the tropical dry forest classification and its commission and omission error (from specifically only-forest additional accuracy assessments). Forest accuracy assessments were made for forest classification against the official in contrast to national forest.

Table 2 *maps where accuracy assessment and area adjustment were performed, and the reference map of which each map was compared.*

Evaluated map	Reference map
Drylands delimitation	Google Earth imagery
Classification (Sep. – Dec. 2015)	Ecosystems from the Red List of Colombian Ecosystems
Classification (May – Aug. 2019)	Google Earth imagery
Forest coverage of (Sep. – Dec. 2015)	National forest coverage of 2015
Addition of both forest coverages (Jan. – Apr. 2016) and (May – Aug. 2016)	National forest coverage of 2016
Forest coverage of (Sep. – Dec. 2018)	National forest coverage of 2018
Classification (May – Aug. 2019) clipped with protected areas	Google Earth imagery
Drylands in protected areas delimitation	Google Earth imagery

2.8 Assessing of SDG indicators

Having all six area estimations we measured the average transformation rate (for each dry ecosystem and drylands as a whole), to compare it with the SDG and Aichi goals. Additionally, comparing them with other estimations of Colombian drylands area, we identified some clustered estimations, therefore, our estimations that fall within those clusters, were regard as more accurate, because they had more redundancy. Then, with those values, we addressed the area changes since 2015, and subsequently the respective SDG indicator.

The last classification (May – Aug. 2019), was clipped with the protected national areas map, along with drylands delimitation, to establish the first value of monitoring of protected drylands area, and to know the delimitation of the protected drylands respectively. Both maps had the accuracy evaluation performed, and the respective adjustment area. With those areas, the indicator regarding protected areas was evaluated.

3. Results

3.1 Drylands Delimitation

This drylands delimitation for Colombia showed a 2,8% of the national territory, and according to its accuracy assessment (Table 3) it was estimated an area of 32416 ± 13731 km^2; specifically, 7121 ± 437 km^2 for tropical desserts, 9863 ± 7986 km^2 for tropical dry forest, and 15942 ± 11239 km^2 for dry savannas. Dry ecosystems were mostly located on isolated regions in the inter Andean valleys and the Caribbean region, and none in the Orinoquia region as initially thought (figure 1). Tropical desserts are mainly in the northmost part of the country (Guajira desert) and a smaller area in the oriental Andes (Tatacoa dessert), but missing desertic areas like the Sabrinsky desert near Bogota, and the Candelaria dessert near Villa de Leyva in Boyaca Department. Tropical dry forest is primarily located in the Caribbean region, followed by the Magdalena River valley and the Cauca River valley, with minor remnants in the Patia river valley, and around Cucuta city. Dry savannas are present in the area between Caribbean and Andean regions, with an additional area in the Chicamocha Canyon in Santander Department.

Additionally, this delimitation area estimate and confidence interval is encompassed by the variability of different measurements of Colombian drylands total area based on 4 climate index (Mendez Neira, 2006).

Table 3 *Confusion matrixes and accuracy for drylands delimitation map. First table: drylands as a whole. Second table: drylands separated by dry ecosystems.*

First	**Drylands**	Non-drylands			
Total Area (km^2)	12981,1	1133549,4	**Total Plots**	**Commission Error**	**Users Accuracy**
Tropical Desert	130	20	150	13,33 %	0,87 ± 0,05
Non-Drylands	9	473	482	1,87 %	
Total Plots	139	493	632		
Omission Error	6,47 %	4,06 %			
Producers Accuracy	0,35 ± 0,15				Overall: 0,98 ± 0,01

Second	**Tropical Desert**	**Tropical Dry Forest**	**Dry Savanna**	Non-drylands	**Total Plots**	**Commission Error**	**Users Accuracy**
Total Area (km^2)	7283,5	3215,0	2482,6	1133549,4			
Tropical Desert	48	1	0	1	50	4 %	0,96 ± 0,05
Tropical Dry Forest	2	36	3	9	50	28 %	0,72 ± 0,12
Dry Savanna	0	7	33	10	50	34 %	0,66 ± 0,13
Non-Drylands	0	3	6	473	482	1,87 %	
Total Plots	50	47	42	493	632		
Omission Error	4 %	23,4 %	21,43 %	4,06 %			
Producers Accuracy	0,98 ± 0,0004	0,23 ± 0,007	0,1 ± 0,01				Overall: 0,98 ± 0,01

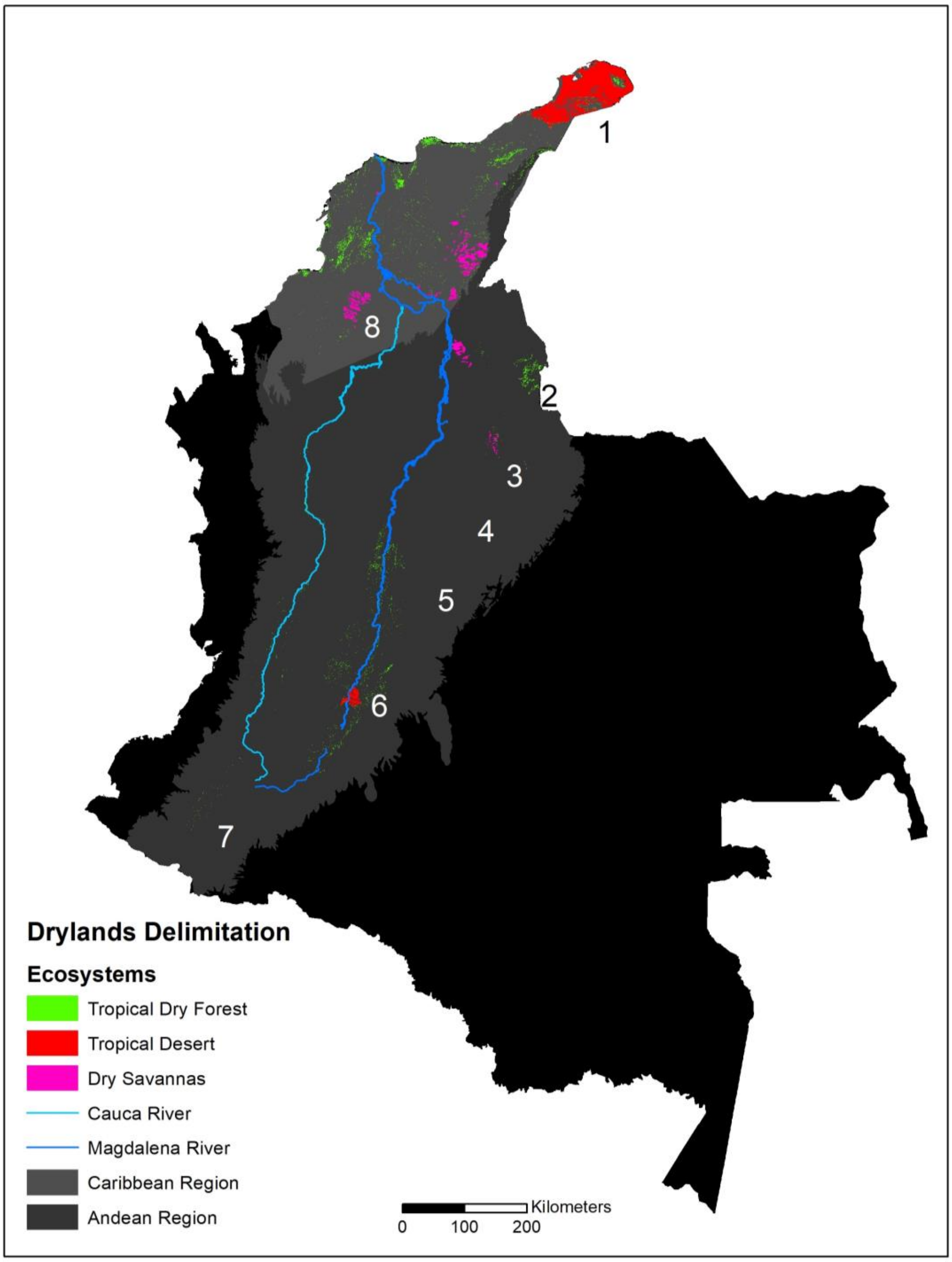


***Figure 2**. Drylands Delimitation. 1 Guajira. 2 Cucuta. 3 Chicamocha Canyon. 4 Villa de Leyva. 5 Bogota. 6 Tatacoa. 7 Patia river valley. 8 Cordoba transition area between Caribbean and Andean regions*

3.2 Drylands area monitoring

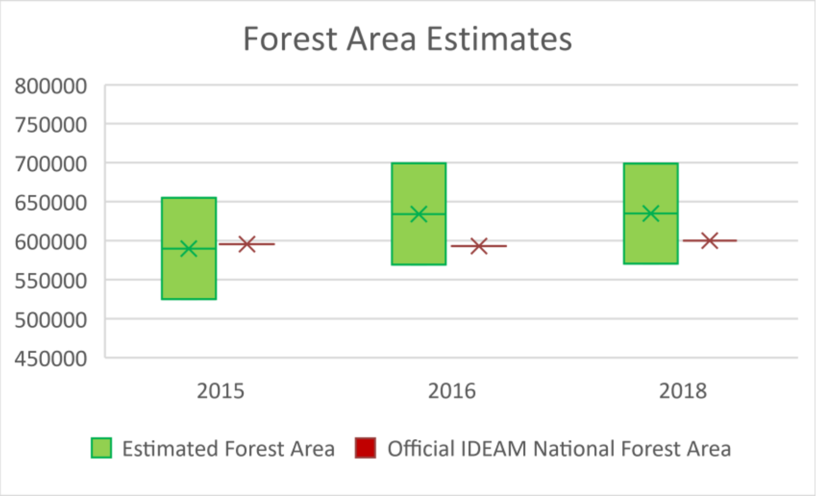
Total area of dry ecosystems based from the classification of sentinel imagery, represents around 3,5% of the national territory, while the tropical desert area is about 1,3 %, tropical dry forest 0,9%, and dry savannas 1,3%. Nonetheless, more accurate comparison is made between the first and last columns, showing a decrease in deserts, forests, and total drylands, although dry savannas have increased between those two periods (table 4).

Additionally, May – Aug. 2019 dry forest area (6772 km^2) is very close to the official national dry forest area (7172 km^2) (Pizano and García, 2014). Moreover, forest assessment resultant areas were 590060, ± 64980 km^2, 634328 ± 65149 km^2, and 634798 ± 64222 km^2 for 2015, 2016, and 2018 respectively, and for all three years the official national forest coverages areas fell within our confidence intervals (figure 2), further proving the areas estimates reliability (figure 3).

Table 4. *Percentages of drylands. The top four rows represent the percentage of each class compared to the national area. The bottom three rows represent the percentage of each dry ecosystem compared to the respective total drylands area. The first and last column represents the corrected estimated area.*

	Sep. - Dec. 2015	Jan. - Apr. 2016	May - Aug. 2016	Sep. - Dec. 2018	Jan. - Apr. 2019	May - Aug. 2019
Tropical Desert National Percentage	2,1	1	0,8	1,3	1,4	1
Tropical Dry Forest National Percentage	0,9	0,7	0,8	1	1,1	0,6
Dry Savanna National Percentage	1	0,7	0,9	1,4	2,1	1,8
Drylands National Percentage	4	2,4	2,6	3,7	4,6	3,3
Tropical Desert Drylands Percentage	52,5	41,7	30,8	35,1	30,4	30,3
Tropical Dry Forest Drylands Percentage	22,5	29,2	30,8	27	23,9	18,2
Dry Savanna Drylands Percentage	25	29,2	34,6	37,8	45,7	54,5

Figure 2*. Forest Area Estimates in km^2. Official national forest coverage compared with the corrected forest area and its confidence interval from the tropical dry forest classifications of 2015, 2016, and 2018.*



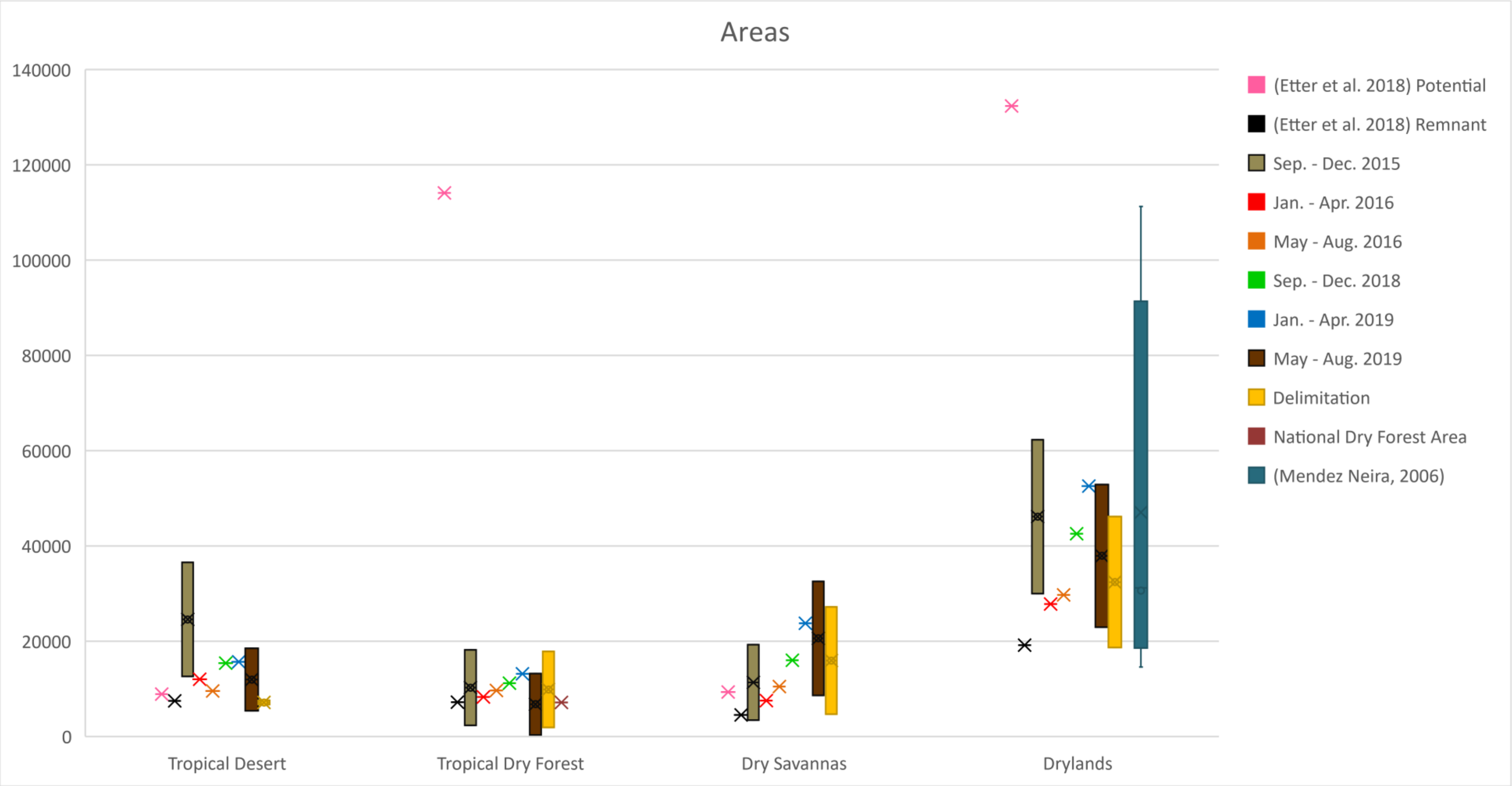


***Figure 3**. Areas. Only the first and last values are corrected and have their respective confidence intervals. The in-between values are not corrected. For comparison purposes it is included the National Dry forest Area, this delimitation area estimates, and drylands area measurements from* (Mendez Neira, 2006). *All the areas are in km*^{2}.

3.3 SDG indicators

Only 790,5 ± 58 km^2 of drylands are within protected areas, representing 2,4% of the total dryland area (figure 4). In particular, 195 ± 43 km^2, 479,6 ± 99 km^2, and 20 ± 14 km^2 of; tropical desert, tropical dry forest, and dry savannas, respectively, are in protected areas accordingly to the area adjustment based on its confusion matrix (table 5). Thus being 2,7%, 4,9%, and 0,12% protected of each ecosystem, respectively. Additionally, according to the official national dry forest area (Pizano and García, 2014), only 390 km^2 of dry forest are within protected areas, this value falls within our confidence interval.

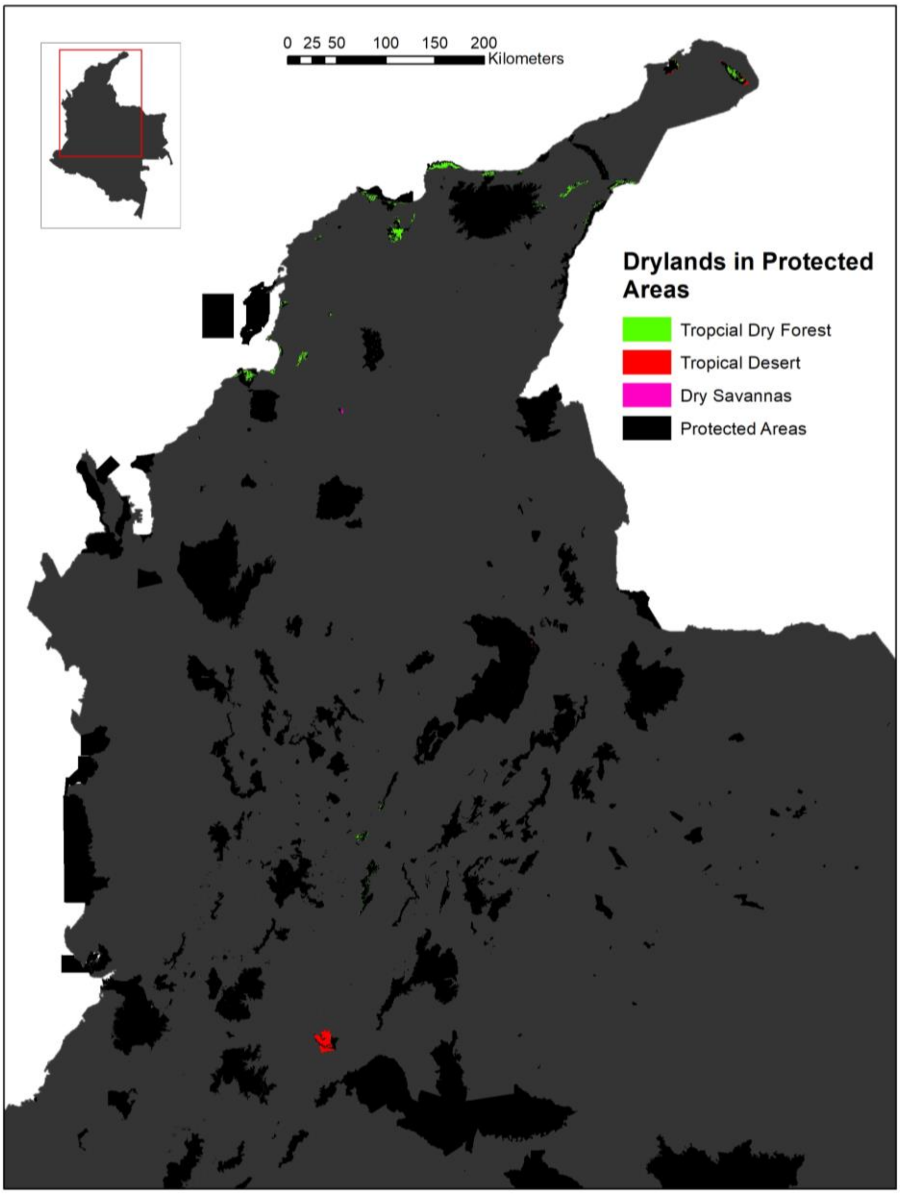
However, based on the May – Aug. 2019 classification, an adjusted protected area was computed, showing that 2985 ± 2500 km^2 or ~7,9% of drylands are protected. In dry ecosystems 698,7 ± 1253 km^2 of tropical deserts, 1303,5 ± 1536 km^2 of tropical dry forest, and 1489,9 ± 1631 km^2 of dry savannas are protected. According to the Aichi targets at least 17% of drylands should be in protected areas, but that goal is not met (figure 5).

Additionally, transformation rates based on the area differences between classified maps (Table 6), showed that on average deserts and dry forest had negative rates, meaning they had lost extension. But dry savannas had positive rates, meaning an increase of area. Drylands overall, however, only had a rate of 1, meaning very little change in the last four years.

Table 5. *Confusion matrix and accuracy for drylands in protected areas map. Top table: drylands separated by dry ecosystems. Bottom table drylands as a whole.*

Considering Only Protected Areas	**Tropical Desert**	**Tropical Dry Forest**	**Dry Savanna**	Non-drylands	**Total Plots**	**Commission Error**	**Users Accuracy**
Total Area (km^2)	259,1	684,1	13	302229,8			
Tropical Desert	35	13	2	0	50	30 %	0,7 ± 0,13
Tropical Dry Forest	1	30	0	19	50	40 %	0,6 ± 0,14
Dry Savanna	0	7	36	7	50	28 %	0,72 ± 0,12
Non-Drylands	0	0	0	467	467	0 %	
Total Plots	36	50	38	493	617		
Omission Error	2,78 %	40 %	5,26 %	5,27 %			
Producers Accuracy	0,92 ± 0,13	0,86 ± 0,06	0,47 ± 0,34				Overall: 0,99 ± 0,0003

Considering Only Protected Areas	**Drylands**	Non-drylands	**Total Plots**	**Commission Error**	**Users Accuracy**
Total Area (km^2)	956,2	302229,8			
Drylands	124	26	150	17,33 %	0,82 ± 0,06
Non-Drylands	0	467	467	0 %	
Total Plots	124	493	617		
Omission Error	0 %	5,27 %			
Producers Accuracy	1 ± 0				Overall: 0,99 ± 0,0002



352 ***Figure 4.*** *Drylands in protected areas*

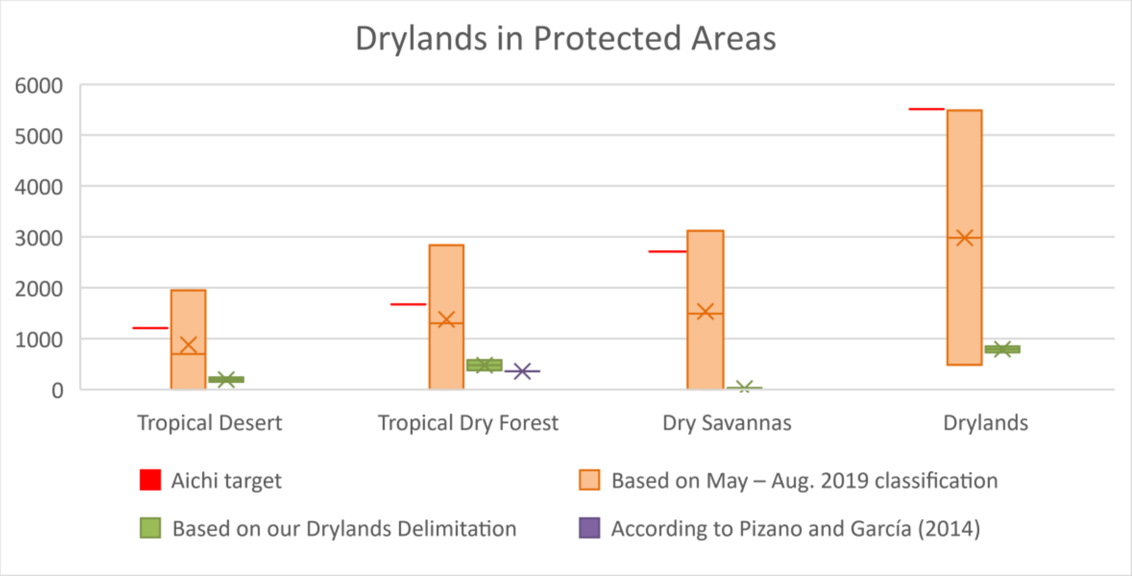


Figure 5. *Drylands in protected areas in km^2. Comparison between estimation made based on the May – Aug. 2019 classification, based on our dryland delimitation, and according to the official national dry forest measurements. It is worth noticing more precise confidence intervals of the estimation based on the drylands delimitation than based on the May – Aug. 2019 classification, therefore being a much more accurate value. Neither drylands (in both estimates) nor each dry ecosystem (estimates based on drylands delimitation) achieves the Aichi target 11.*

Table 6. *transformation (changes) rates, from each classified period to the next one.*

	First-Second	Second-Third	Third-Fourth	Fourth-Fifth	Fifth-Sixth	Average
Desert	-51	-20	61	2	-24	-6
Dry forest	-19	16	16	18	-48	-4
Dry savanna	-34	40	53	48	-13	19
Drylands	-40	7	43	23	-28	1

4. Discussion

4.1 Drylands Delimitation

There are some considerations to be made, firstly it can be problematic to combine geological, climatic and ecological variables into a single map, due to their differences in spatial resolutions, and time scales. However, geological variables in a practical sense are invariable due to its extremely long time scale, and ecological variables because of a lack of maps, we only can use the most recent map, until a better updated version comes out, in practice making it univariable as well. And climatic variables, can be improved if used *in situ* data from the IDEAM, for at least a 30-years lapse. This Is important in order to acknowledge the inherent biases and errors of the model, based on scale issues.

This delimitation estimates a much smaller drylands area than the current official map (Ministerio de Ambiente y Desarrollo Sostenible, 2005), with a difference from 21% to 2,8% of the national territory. This difference likely occurred as a result of the official map only taking into account the CCD index to determine drylands (P/EVP <0,65). This could explain since, precipitation is not the only water source for ecosystems, therefore some might have low precipitation with other water sources (like discharge or glaciers melt) (MINAMBIENTE; IDEAM, 2015), that excludes this systems for being considered drylands.

This was one of the reasons this why this study tried to incorporate different information sources that complement the CCD index criteria and enhances the delimitation.

However, by comparing with the remnants ecosystems from the Red List of Colombian Ecosystems (Etter et al., 2018), our delimitation showed consistency. Our overall drylands minimum estimated area is close to the reported by Etter et. al. 2018 having just 498 km^2 of difference, deserts had a difference of 358 km^2, dry forest -2679 km^2 of difference and dry savannas minimum estimated area had a -183 km^2 difference. Meaning in general, our delimitation estimates areas close to the expected values, but having an apparent overestimation of dry forest and savannas. Dry savannas and drylands overall areas apparently are closer to the minimum estimated area within their respective confidence intervals.

Nevertheless, this map shows to have good user accuracy in both stages, drylands as a single category, and dry ecosystems separated, meaning that not many non-drylands areas where mapped as drylands. But producer accuracy is still insufficient, in drylands as a whole as in tropical dry forest and dry savannas but not for tropical desert which is actually very good, given that the omissions of Sabrinsky desert and Candelaria desert, might, be due to its closeness to urban areas, therefore being confused with transformed areas. Furthermore, those omissions are undetected, so the deserts adjusted area might be underestimated.

The Orinoquia region was initially thought to have some dry savannas, but after further analysis, its shown that those are commissions, because those savannas are far too humid to be considered drylands, and are seasonal wetlands or flooded savannas (IDEAM et al., 2017; Jaramillo et al., 2015). However, there are some small tropical dry forest in the northeast piedmont of the Andes, and a narrow area along the Orinoco river in the Colombia – Venezuela border, but those forest are dry not because low precipitations, but rather because of soils conditions that have low water retention, therefore restricting available water (Pizano and García, 2014). Even so, this delimitation failed to map these forests, thus explaining some of the tropical dry forest omission error. Nonetheless, tropical dry forest delimitation and area, seems to be coherent and close to the national delimitation and area from the national tropical dry forest map (Pizano and García, 2014), where both maps, displays dry forest along the Patia river valley, Cauca river valley, Magdalena river valley, Caribbean Region, and northeast of the Andean region, and shows an area difference is of 2691 km^2 (this delimitation estimating a larger area).

The omissions, due to the nature of the map presented here (some rare and small classes within a very large and common cone) could overestimate the omission error, and consequently enlarge the confidence interval (Perilla and Mas, 2019).

Additionally, there are over 30 different aridity indices, and most of them are measurable with IDEAM data, so we strongly recommend to include in future studies, additional indices, from *in situ* data, that ideally will enhance the performance evaluation of the model. However, we tired comparing our delimitation against drylands estimates from other climatic indexes (Lang, United Nations Environment Programme UNEP, Thornwaite and Martonne) measured by Mendez Neira (2006), it is noticeable that our area calculations and its confidence intervals are within the expected variability. Even more, our estimations (32416 km^2) are close to the UNEP (30638 km^2) and Thornwaite (31183 km^2) approximations, this could be interpreted as a proxy of the accuracy of our delimitation as a generally trustworthy one. Moreover, five of the six area estimates (excluding the one of Sep. – Dec. 2018) are within the drylands delimitation confidence interval, and considering that those estimates were resulting from different methodologies (delimitation and Sentinel-2 classifications), it could be considered as a mean to determine the accuracy of the delimitation area estimated.

For future improvements on drylands delimitations, should be minimized the omissions (mainly dry savannas and forest ones). To achieve this, we suggests the inclusion of other climatic data as temperature, and/or, if possible, moisture (soil and atmospheric) (Safriel and Adeel, 2005), in addition of field data for both, delimitation and accuracy assessment might improves the delimitation and area estimates.

Ergo, our delimitation should be interpreted as an alert to increase the urgency to protect, manage sustainably and research drylands, since it shows a worse panorama than previously thought in terms of total area.

4.2 Drylands Area Changes from 2015 to 2019

The way our 4-months periods were selected, was arbitrary in order to maximize the available imagery, however different 4-month periods could change and even improve the results, for example if are based on precipitation seasonality in drylands.

This work attempted to evaluate for the first time Colombian drylands extension changes. Thus, helping to assess the nation performance towards achieving acquired international goals and targets. However, we did not estimate drylands extension for the period Sep. 2016 – Aug. 2018, therefore, missing 2 years of data, to completely asses the changes since 2015. Nonetheless, our results help to fulfil missing information to evaluate currently overlooked goals and targets concerning drylands.

Additionally, because there are not landcover or ecosystems maps, that match the “in-between” time periods (Jan. - Apr. 2016, May - Aug. 2016, Sep. - Dec. 2018, and Jan. - Apr. 2019), for those classifications the accuracy assessment and the area estimates could not be performed, therefore, the respectively area measurements, should be carefully examined. By comparing those estimates with the ones from Sep. – Dec. 2015 and May – Aug. 2019 periods, including their confidence intervals, is clear that all estimates are within the expected variability, and none of them are extreme values outside the confidence intervals.

Moreover, when comparing these area estimates with the area estimate from the dryland delimitation, with the exception of desert, dry ecosystems and drylands, have similar size and overlapping confidence intervals, and adjusted areas. On the other hand, deserts area from the dryland delimitation, besides overlapping, have much more reduced confidence intervals, and less area estimated, than the ones from the triannual classifications. on the other hand. Though, it is worth to remember that the drylands delimitation had some undetected desserts omissions (Sabrinsky and Candelaria deserts), meaning that that area estimate might be underestimated. Also, when comparing actual (May – Aug. 2019) dry forest coverage estimate against the national dry forest area (Pizano and García, 2014), the closeness of both values suggest a high accuracy of the adjusted area.

Similarly, when estimating total national forest (dry or not) from the 2015, 2016 and 2018 classifications, it must be considered that our classification have many omission (all non-dry forest), and that the periods do not match perfectly. For 2015 and 2018 our data merely shows information for the last four months of the year while the national forest coverage consider the whole year (IDEAM, 2019, 2016), likewise for 2016 our data only represents the first eight months of the year. All of these issues, explain the big confidence intervals for those estimations, however its worth noticing that all three IDEAM (2019a, 2018, 2016) forests measurements are within our confidence intervals, thus suggesting that our dry forest adjusted area is reliable, and secondly that this study methods are able to detect changes during the examined time period. Having these results for one dry ecosystem might suggest a similar accuracy on the other two ecosystems, and drylands as a whole, nonetheless further research and studies should be made to support or disprove this hypotheses.

Having said that, drylands extension from 2015 to 2019, apparently have had a slight reduction, but still is not statistically significant, because of the overlapping confidence intervals. Similarly, average transformation rate is merely at 1. Detail consideration of the dry ecosystems show that:

Deserts seem to not have had strong extension changes between 2015-2019, thought the first area estimate (Sep. – Dec. 2015) appears to be over-estimating deserts, due to being a rare class with relatively low commission errors but happening in the non-drylands class (a big, common and dominant class), thus resulting in a possible overestimation (Perilla and Mas, 2019). However, when comparing against the potentially original extension of ecosystems from the Red List of Colombian Ecosystems (Etter et al., 2018), our deserts estimations clearly seems to be overestimated then its area is oscillating around 11000 km^2, but closer to 7500 km^2, with a slight reduction displaying an average transformed rate of -6%.

Dry savannas have shown a slight growth over the last four years with and average transformed rate of 19%, but still, due to the overlapping of confidence intervals, it is not be statistically significant, and similarly its area fluctuates around 15500 km^2. However, this growth, might be explained by the commission errors that misclassified humid savannas, of the Orinoquia region, with dry savannas (Huete, 2012). Even so, this increase can also be explained by the degradation of land, agricultural frontier expansion, and/or desertification of other ecosystems thus becoming spectrally similar to savannas (Ferreira et al., 2013), thus inducing commission errors.

Tropical dry forest, similarly, appear to do not have strongly changed in the last 4 years with an average transformed rate of -4%, being more or less stable around 9300 km^2, however tropical dry forest are the most endangered tropical ecosystem (Janzen, 1988), and the most threatened in Colombia (Aldana-Domínguez et al., 2017), due to its high level and rates of transformation (Etter et al., 2018). Therefore, requiring an even more specialized attention, hence the recommendation to expand research on tropical dry forest area changes, urging to develop an area monitoring exclusively to dry forest with higher accuracy and smaller confidence intervals.

The results shown here should also take into account that Colombia in 2016 had an ENSO (El Niño-Southern Oscillation) year (IDEAM, 2019b), meaning low precipitations and severe drought nationwide. Hence, not all evaluated years had the same climatic conditions, therefore hindering the analysis. However, our data did not show evident differences in extension from years with or without ENSO events, but further analysis over longer periods should be made.

Monitoring drylands with multispectral imagery allows to have periodic reliable and possible free data, consistently high-resolution results, and easily comparable, that can be disaggregated to smaller scales (Mas, 1999); having a national indicator with relevant information at subnational scales. Ergo, this methodology can help to address the performance towards achieving SDG and/or Aichi targets. This methodology has potential to become a monitoring system, however, at this stage it still lacks data to assess for longer periods (it is suggested at least 3 decades, because climate plays a crucial role in land covers, and climate is evaluated in periods of at least 30 years (IPCC, 2014)), and a more thorough accuracy assessment ideally from field data (Dawelbait and Morari, 2008).

Should also be taken into account that drylands, as a single category is very spectrally variable, and even each dry-landcover is not spectrally distinctive (Dawelbait and Morari, 2008), having spectral confusion with urban areas, paramos, bare soils, agriculture, pasture lands, tropical humid forest (pers. obs.).

All of the above affects the proposed drylands classifications, and subsequently it area change assessment, making it still not as precise, having yet significant confidence intervals, and substantial commission an omission errors that fortunately the area adjustment rectifies. Even so, once the area is corrected, it appears that the estimation match the reality, as it can be evidenced with the forest assessment, where the official forest area falls within the confidence interval of the estimated area, thus, suggesting that independently on the quality of the four-month classifications, the corrected areas are reliable (within the confidence intervals).

Ideally, this methodology would be used as a first draft of national drylands, and successively be treated as initial input for refined subnational and local monitoring. In turn, this would ultimately enhance a future national drylands monitoring. In order to improve it, we suggest additionally to the multispectral data, to include a mask based on high-resolution digital elevation model, since dry ecosystems are specific for certain elevations (Etter et al., 2018), and other climatic mask mainly moisture, temperature, precipitation and evapotranspiration that helps to discriminate drylands (Safriel and Adeel, 2005), thus, reducing the total misclassified area of classification, ultimately lowering the spectral variability.

Those improvements certainly would greatly enhance a monitoring system, because this methodology at its current state, still manages to overcome the main problems that national indicators carry on (Congreso de Colombia, 2019), like lack of data (this study used more than 8000 satellite images), low quality of data (Sentinel-2 imagery is high resolution and have widespread used for monitoring landcovers (Mas et al., 2016)), difficulty for disaggregate and compare indicators through scales, and associated high cost regarding tools for measurement and monitoring (GEE capacity allows to easily make maps at large scales with high resolution, free of charge for research and nonprofit purposes (Gorelick et al., 2017)). Also, it produces in almost real-time, necessary information to overcome the struggle of slow data updating, that delay effective action concerning landscape management, territorial development planning, and rapid responses (Shimabukuro et al., 2011), Accomplishing one of the nation goals to implement big data processing as a strategy to strengthen the SDG national agenda (DEPARTAMENTO NACIONAL DE PLANEACIÓN, 2018).

4.3 Global targets assessment

The drylands delimitation and its area change assessment have the potential to be used as a SDG indicator for the target 15.3, which Colombia has yet to improve upon. A possible national 15.3 target could be as follows: *"by 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought, and floods, and strive to achieve a land degradation neutral world".* Because drylands are the most affected by desertification, land degradation, and drought, an indicator "15.3.2" for that target could be: *“number of square kilometers of drylands”*. By doing so Colombia would be able to monitor drylands changes, and with the proper research, find out the causes of those changes either desertification, land degradation, drought or floods. It would also be desirable to set a performance goal of the indicator to at least **preserve the remnant drylands area**; maintaining the 2015 remaining dry forest, tropical desert, and natural dry savannas. For assessing this indicator, we took as original values the minimum possible adjusted area from our drylands delimitation, except for dry forest, where the official dry forest estimates (Pizano and García, 2014) were took instead. And the current value were the minimum possible adjusted areas from the May – Aug. 2019 classification, except for dry forest for which we took as current value the medium adjusted area of the same classification. By doing so, the country could reach the two objectives of the Sustainability Pact of National Development Plan, regarding implementation of climate change initiatives that reduces the effects of drought in the territories, and carry out natural phenomena studies to improve land planning and use (Congreso de Colombia, 2019).

Consequently, and taking into account the potentially originally extension of drylands (Etter et al., 2018), **Colombia is not reaching the SDG target 15.3**. decreasing the deserts and dry forest extension, and dry savannas that apparently have increase, it more likely due to degradation, expansion of cropped areas, and/or commission error. Regarding the Aichi target 5 transformation rates in drylands are not 0, therefore, that goal is not been reached either.

Colombia already adopted the target 15.1 and its indicator is number of hectares in protected areas. But its goal is to reach 30000 ha of protected areas by 2030, a goal that currently have been reached. However, this might be an insufficient indicator of the target, because it does not discern between drylands and other ecosystems. It could further be complemented disaggregating this indicator in protected area per each ecosystem, and with that addition, improve the performance evaluation towards achieving the national target 15.1. and its complement the Aichi target 5.

According to PNN (2019), drylands are among the ecosystems with the lowest representativeness in the national protected areas, being at best at underrepresented levels (1%-17% of area), therefore, a minimum performance goal of the indicator, should be set by the Aichi target 11 assuring at least a conservation of 17% of drylands.

Unfortunately, drylands in protected areas according to this study delimitation only reach 2,4%; deserts have 2,7%; dry forest 4,8%; and dry savannas 0,1%, still being dangerously underrepresented, and therefore failing to meet the Aichi target. Additionally taking into account the user and producer accuracy, for both drylands as a whole and dry ecosystem separately, all are over 0,7 except the producer accuracy of dry savannas at 0,47. Meaning, that this estimation is highly accurate (but due to its methodology it cannot be periodically repeated to show changes).

In contrast drylands in protected areas according to the May – Aug. 2019 delimitation (following the proposed methodology that can be periodically repeated and show changes), shows that drylands representativeness is 7,8 %, and dry forest is the only dry ecosystems that surpass the 17% threshold reaching 19,25% of protected area but desert (5,8%) and dry savannas (7,2%) still are under the Aichi target, however the large confidence intervals of this estimations made this percentages highly uncertain. Nonetheless, even with a large confidence interval it can be totally assured that **Colombia is failing to meet**

the Aichi target 5 considering drylands as a whole, because its maximum possible area estimate only reaches 16%.

Similarly, SDG target 13.2 was adopted by Colombia with its indicator 13.2.2 and by 20130 it is expected that 100% of municipalities and departments will incorporate the climate change component in their respective territorial arrangement plans by 2030. In this case, drylands, which are one of the most affected ecosystems by climate change, can be monitored as a proxy for an early warning of climate-related detrimental consequences. Ergo, drylands monitoring has the potential use of becoming an input that helps local governments (municipal and departmental), to develop and follow through climate change-related policies introduced in their respective territorial arrangement plans.

Currently only 0,1% of municipalities and departments have incorporated climate change component in their territorial arrangement plans (Comision ODS, 2015), failing to reach the target, and falling far behind the expected performance to successfully accomplish this goal by 2030.

4.4 Considerations

This work is one the first studies employing GEE in Colombia (Kumar and Mutanga, 2018), and most likely is one of the firsts studies to use that many available Sentinel-2 atmospherically corrected imagery (8189), because the SIAC tool was available only until mid-2019 (Yin, 2019), and this tool is one of the first publicly available that allows atmospheric correction directly in GEE cloud (pers. obs). Ergo, there will be hopefully in the near future, better approaches and improvements over the proposed methodologies and analysis (e.g.: better assessment to temporal and spatial scales variations and use of *in situ* climatic data, instead of satellite one); therefore, ideally, this work will promote drylands and landcover monitoring with big data research.

5. Conclusions

Drylands delimitation while difficult is possible and urgent. Even considering the limitations of the map generated in this study, it could be a great input of drylands delimitation available for the nation. Ideally, this would help to overcome the knowledge gaps concerning drylands, and subsequently, improves its management. Nevertheless, it is still urgent to work towards improvements on drylands delimitation.

Regarding assessing area changes, there is room for improvement, showing that multispectral data is not sufficient to monitoring drylands, and should be complemented with other variables to further reduce he confidence intervals, hence increasing the accuracy. Nonetheless, our results should value since, while is true that the confidence intervals are big, it certainly gives a first draft of the Colombian drylands panorama, and their broad (unfavorable) trends, urging to complete the missing data for the period Sep. – Dec. 2016 and Jan. 2017 – Aug. 2018. Also, it provides the first inputs to assess some of the global targets, from which Colombia has agreed upon to but have not been addressing. Furthermore, it also, depicts some struggles towards drylands monitoring, thus hopefully encouraging near-future improvements in this topic.

On the subject of SDG drylands targets assessment, in spite of the big confidence intervals this work has shown, that currently Colombia is failing to achieve the targets, and should increases its conservation, restauration and research efforts in order to achieve them by 2030, as expected. Additionally, a this assessment and future monitoring would help to identify accomplishments and failures, that can be replicated or avoided in other regions of the world, ultimately helping globally achieving the SDG agenda by 2030.

With GEE huge capacity, potential uses are still been explored in studies like this one. Hopefully, regardless of its limitations, useful information can be produced, at high resolution, with low-cost in almost near real-time, improving the response and adaptation to climate change and landscape management, towards more sustainable practices, that ultimately enhances the natural and social conditions in such vulnerable regions like drylands.

Declarations of Competing Interest

No potential conflict of interest was reported by the author

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ECOLOGICAL INDICATORS

Integrating Sciences for Monitoring, Assessment and Management

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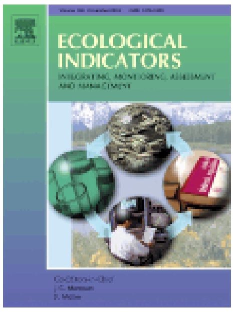

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DESCRIPTION

The ultimate aim of *Ecological Indicators* is to integrate the **monitoring** and **assessment** of **ecological** and **environmental indicators** with **management** practices. The journal provides a forum for the discussion of the applied scientific development and review of traditional indicator applications as well as for theoretical, modelling and quantitative approaches such as index development. Research into the following areas will be published.

- All aspects of ecological and environmental indicators and indices.
- New indicators, and new approaches and methods for indicator development, testing and use.
- Development and modelling of indices, e.g. application of indicator suites across multiple scales and resources.
- Analysis and research of resource, system- and scale-specific indicators.
- Methods for integration of social and other valuation metrics for the production of scientifically rigorous and politically-relevant assessments using indicator-based monitoring and assessment programs.
- Approaches on how research indicators can be transformed into direct application for management purposes.
- Broader assessment objectives and methods, e.g. biodiversity, biological integrity, and sustainability, through the use of indicators.
- Resource-specific indicators such as landscape, agroecosystems, forests ecosystems, aquatic ecosystems, wetlands, etc.

The journal seeks innovative papers which provide new developmental and methodological steps for environmental indication. Submissions of results from simple monitoring programs or single case studies, resulting in descriptive approaches without any exploration from the theory of indication, from the methodology of indication, or from the management points of view are not considered suitable for publication in Ecological Indicators.

The following contributions will be accepted:

Original research papers;
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Short notes and case studies;
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INTRODUCTION

The journal is concerned with the development and application of ecological indicators, from the molecular to the ecosystem and landscape level, in the scope of environmental quality assessment and management towards sustainability.

Human activities and well-being depend on our capability to develop proper tools to evaluate and help acting upon ecosystems ecological conditions and long term trends. Ecological and environmental indicators and indices play an essential role with regard to this endeavour and must have biological, methodological, and social relevance: they are expected to extract information from raw data in a very condensed form that is of significance to scientists, decision makers, resource managers, and general public.

From a management point of view, a good ecological indicator should be a) simple to apply and easily understood by laymen, b) relevant in the context, c) scientifically justifiable, d) quantitative, e) acceptable in terms of costs, f) covering all relevant and actual problems, and g) sensitive to possible changes. On the other hand, from a more scientific perspective, it should have h) handling easiness, i) sensibility to small variations of environmental stress and/or ecological conditions, j) independence of reference states, k) applicability in extensive geographical areas and in the greatest possible number of communities or ecological environments, and l) possible and reliable quantification. Ecological Indicators can be applied to a wide range of topics going from basic ecology to human ecology and socio-ecological systems, and the journal welcomes research articles, review articles, short notes and studies, viewpoint articles, letters to the Editor, and book reviews. The journal also publishes Special Themes Issues.

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Types of papers

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