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TESIS DOCTORAL

Estudio de potencialidad de las áreas reforestadas en
la provincia de Manabí (Ecuador)

Study of Potential of reforested areas in the province of
Manabí (Ecuador)

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TÍTULO DE LA TESIS: Estudio de potencialidad de las áreas reforestadas en la provincia de Manabí, Ecuador

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INFORME RAZONADO DEL TUTOR

(se hará mención a la evolución y desarrollo de la tesis, así como a trabajos y publicaciones derivados de la misma).

La tesis doctoral presentada por el doctorando Alex Joffre Quimis Gómez con el título “Estudio de potencialidad de las áreas reforestadas en la provincia de Manabí (Ecuador)” corresponde a su trabajo de tesis doctoral realizado bajo nuestra dirección. Consideramos que el doctorando ha cumplido correctamente las etapas implícitas en el desarrollo de la tesis doctoral, lo que ha permitido su correcta formación como investigador. Durante el desarrollo de la tesis doctoral, el doctorando ha desarrollado las destrezas propias del proceso de investigación y ha sabido sobrepasar las dificultades inherentes al iniciarse en la investigación. Creemos que el doctorando tiene la formación necesaria para continuar trabajando en la misma línea de investigación, y desarrollar su carrera investigadora.

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“La gratitud le da sentido al pasado,
trae paz al presente
y crea una visión para el futuro”

Melody Beattie

La huella de nuestro paso por la vida debe ser solidaria con la naturaleza. Los árboles nos protegen, seamos recíprocos.

Alex Quimis Gómez

Dios no te va a usar por tu gran
Currículo, ni por tus enormes cualidades,
Él te va a usar porque ve en ti el corazón
Humilde que se necesita para llevar a cabo
Determinada tarea que Él necesite y tú eres
el indicado para hacerlo.

Anónimo

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Perdón, por mi ausencia, dolor y sufrimientos causados.

En su memoria. Dios la tenga en la gloria.

“Descansen en Paz”

RESUMEN

El Ecuador posee extensas áreas de bosque primario, especialmente ubicadas en la Región Amazónica, en las cordilleras de la región andina y en las zonas húmedas y secas de la región Costa. Siendo estos los principales proveedores de productos forestales como son la madera, frutos, leñas, cortezas, resinas, bejucos, estacas, así como otros productos provenientes de la fauna silvestre. Muchas de estas áreas han sido declaradas parte del Sistema Nacional de Áreas Protegidas principalmente en la región amazónica y andina. El crecimiento excesivo de las ciudades y su expansión representan una grave amenaza para la sostenibilidad de los ecosistemas forestales en la región costera, ya que la madera es explotada para diversos fines, en especial para el comercio. Además, la expansión de la actividad agrícola ha generado una fragmentación de los ecosistemas afectando los hábitats naturales.

El uso y comercio de los recursos maderables y sus derivados son actividades que a lo largo de la historia de El Ecuador han tenido un papel prioritario. El Ecuador ha sido autosuficiente en bienes maderables, debido a una base forestal que en sus comienzos cobijaba alrededor del 80% del territorio nacional. Debido a problemas de sobreexplotación y la tala irracional de bosques primarios, ese porcentaje ha ido revirtiéndose a lo largo del tiempo. Además, debido a la falta de apoyo para actividades de reforestación, la situación se ha ido deteriorando a pasos agigantados. Por lo tanto, el futuro de los ecosistemas forestales dependerá de los esfuerzos que se ejecuten en el bien de la conservación de los bosques, y del uso y manejo sostenible de los recursos naturales en el país.

La investigación tuvo como objetivo principal el estudio de la potencialidad de las áreas reforestadas en la provincia de Manabí en el Ecuador, además se propusieron cuatro objetivos específicos: a) evaluar la idoneidad ambiental de las áreas reforestadas en la provincia de Manabí, b) Caracterizar cómo las nuevas plantaciones forestales de 2008 a 2018, han cambiado la fragmentación del hábitat y la conectividad en la provincia de Manabí, c) evaluar los cambios en la cobertura del suelo y su efecto sobre la fragmentación y la conectividad a través de los paisajes plantados en comparación con los restos de bosques nativos, y d) proponer estrategias que permitan la articulación de las áreas deforestadas para que exista un flujo de transición en la conectividad ecológica entre especies forestales.

De acuerdo con los objetivos planteados la memoria se ha estructurado en 6 capítulos, que se describen a continuación:

En el **capítulo 1**, Introducción General. Se realiza una revisión de los principales Planes de reforestación de Ecuador, con especial incidencia en las especies elegidas, así como el contexto socioeconómico en el cual se han desarrollado dichos programas. Se valora la importancia de la restauración forestal desarrolladas en los últimos años y, finalmente, se analiza el estado del arte respecto a los aspectos en que se centra el presente trabajo.

En el **capítulo 2**, se pretende evaluar la relación entre el hábitat de las especies forestales y su uso en programas de reforestación en la provincia de Manabí en Ecuador. Para ello se estudió la distribución potencial de tres especies de especial importancia en los programas de reforestación en Ecuador, *Triplaris cumingiana* Fisch & C.A. Mey. ex. C.A. Mey., *Prosopis juliflora* (Sw.) DC y *Cordia alliodora* (Ruiz & Pav.) Oken a través de modelos de distribución de especies. Los resultados de estos análisis se compararon con las áreas reforestadas en la provincia de Manabí para comprobar el grado de adecuación de las zonas elegidas para establecer estas especies.

En el **capítulo 3** se estudia el impacto de la deforestación en la fragmentación y conectividad de los bosques en Ecuador, y su relación con las actuaciones de reforestación. Para ello se usan herramientas de análisis espacial a escala de paisaje y de tesela, y la distribución de las plantaciones al interior de la matriz de usos del suelo.

En el **capítulo 4** se analiza, a partir de los resultados de los capítulos 2 y 3, el impacto de los programas de reforestación en la provincia de Manabí, y se determinan, mediante algebra de mapas, las zonas prioritarias de reforestación.

En el **capítulo 5** se procede a la síntesis y discusión general de los resultados obtenidos, incorporando las posibles recomendaciones y mejoras derivadas de este trabajo a los actuales modelos de reforestación en Ecuador.

Finalmente, en el **capítulo 6** se exponen las principales conclusiones del trabajo realizado.

Palabras Claves: Idoneidad del hábitat; restauración forestal; bosque seco; modelos de distribución de especies; programas de reforestación, efectos de borde, gestión del paisaje, conectividad, participación comunitaria; fondo forestal; mecanismo de pago

SUMMARY

Ecuador has extensive areas of primary forest, mainly located in the Amazon Region, in the mountain ranges of the Andean region and in the wet and dry areas of the Coastal region. These are the main suppliers of forest products such as wood, fruits, firewood, bark, resins, vines, stakes, as well as other products from wildlife. Many of these areas have been declared part of the National System of Protected Areas, mainly in the Amazon and Andean region. The excessive growth of cities and their expansion represent a serious threat to the survival of tree populations in the coastal region, since the wood is exploited for various purposes, especially for trade. In addition, the expansion of agricultural activity has generated a fragmentation of ecosystems and has affected natural habitats.

The use and trade of timber resources and their derivatives are activities that throughout history have been part of the economic processes in the country. Ecuador has been self-sufficient in timber goods, due to a forest base that in its beginnings covered around 80% of the national territory. Due to problems of overexploitation of primary forests, this percentage has been reversing over time. Furthermore, the lack of support for reforestation activities has led to a very delicate situation where the situation has been continuously deteriorating. Therefore, the future of the forest ecosystems will depend to the greatest extent on the efforts that are carried out for the sake of forest conservation, and the use and sustainable management of natural resources in the country.

The main objective of the research was to study the potential of reforested areas in the province of Manabí in Ecuador, in addition to four specific objectives: (a) to assess the environmental suitability of reforested areas in the province of Manabí, (b) to characterise how new forest plantations from 2008 to 2018, have changed habitat fragmentation and connectivity in the province of Manabí, c) evaluate changes in land cover and their effect on fragmentation and connectivity across planted landscapes compared to native forest remnants, and d) propose strategies that allow for the articulation of deforested areas so that there is a transitional flow in ecological connectivity between forest species.

In accordance with the proposed objectives, the report has been structured into 6 chapters, which are described below:

In Chapter 1, General Introduction. A review of the main reforestation plans in Ecuador was carried out, with special emphasis on the chosen species, as well as the socioeconomic context in which these programs have been developed. The importance of

forest restoration developed in recent years was valued and, finally, the state of the art regarding the aspects on which this work focuses was analyzed.

In chapter 2, we evaluate the relationship between the habitat of the species and its use in reforestation programs in the province of Manabí in Ecuador. Towards this aim, we studied the potential distribution of three spatially important species in reforestation programs in Ecuador, *Triplaris cumingiana* Fisch & C.A. Mey. ex. AC Mey., *Prosopis juliflora* (Sw.) DC and *Cordia alliodora* (Ruiz & Pav.) Oken by species distribution models. The results of these analysis were compared with the reforested areas in Manabí province to assess the degree adequacy of the areas chosen to establish these species.

Chapter 3 studies the impact of deforestation on the fragmentation and connectivity of forests in Ecuador, and its relationship with reforestation actions. For this, spatial analysis tools were used at the landscape and tile scale, and the distribution of plantations within the land use matrix.

Chapter 4 analyzes, based on the results of chapters 2 and 3, the impact of reforestation programs in the province of Manabí, and determined, through map algebra, the priority areas for reforestation.

In chapter 5 we proceed to the synthesis and general discussion of the results obtained, incorporating the possible recommendations and improvements derived from this work to the current reforestation models in Ecuador.

Finally, in chapter 6 the main conclusions of the work carried out are presented.

Keywords: Habitat suitability; forest restoration; dry forest; species distribution models; reforestation programs, edge effects, landscape management, connectivity, community participation; forest fund; payment mechanism

Tabla de Contenidos

AGRADECIMIENTOS.....	iv
RESUMEN.....	vi
SUMMARY	viii

CAPÍTULO 1

Introducción General.....	1
1. Estudio de potencialidad de las áreas reforestadas en la provincia de Manabí Ecuador	3
1.1. Bosques en el Ecuador	3
1.2. Degradación de los bosques.....	5
1.3. Bosques de la provincia de Manabí.....	6
1.4. Necesidad de restauración.....	7
1.5. Potencialidad y conectividad ecológica	8
2. PLAN NACIONAL DE REPOBLACIONES	9
2.1. Especies elegidas.....	11
2.2. Reforestación en Manabí	12
3. HIPÓTESIS Y OBJETIVOS DE LA TESIS	15
3.1. Hipótesis:	15
3.2. Objetivos:	15
4. REFERENCIAS	16

CAPÍTULO 2

Evaluación de la aptitud de hábitat de especies forestales utilizadas en la restauración de bosques.....	19
RESUMEN.....	21
ABSTRACT	22
1. INTRODUCTION	23
2. MATERIAL AND METHODS	25
2.1. Study area and forest plantations	25
2.2. Species distribution data	26
2.3. Environmental data.....	26
2.4. Statistical analysis	28
2.5. Model projections and outputs	29

3. RESULTS.....	29
3.1. Model selection and fitness	29
3.2. Relative importance of environmental variables	30
3.3. Current and future environmental suitability of forest plantations.....	31
4. DISCUSSION	33
4.1. Relative importance of environmental factors	33
4.2. Current and future environmental suitability projection.....	34
4.3. Applicability to reforestation program	35
5. REFERENCES.....	36
SUPPLEMENTARY MATERIAL 1	39

CAPÍTULO 3

Plantaciones forestales en Manabí (Ecuador): evaluación de la conservación de bosques tropicales secos	43
---	-----------

ABSTRACT.....	45
1. INTRODUCTION.....	46
2. MATERIALS AND METHODS	48
2.1. Study sites.....	48
2.2. GIS sources	49
2.3. Land cover change and fragmentation	50
2.4. Connectivity analysis	52
3. RESULTS.....	54
3.1. Land cover change and fragmentation.....	54
3.2. Connectivity analysis.....	56
4. DISCUSSION	60
4.1. Land uses changes and fragmentation	60
4.2. Connectivity.....	61
4.3. Prioritization of forest plantations to improve connectivity.....	62
5. CONCLUSIONS.....	63
6. REFERENCES.....	64

CAPÍTULO 4

Impactos en los usos de la tierra de los programas extensivos de reforestación en Ecuador: lecciones para el futuro.....	69
---	-----------

ABSTRACT.....	71
1. INTRODUCTION.....	72
2. MATERIAL AND METHODS.....	73

2.1. Study area.....	73
2.2. Selection of reforestation programs	75
2.3. GIS sources	76
2.4. Analytical Framework	78
2.5. Priority areas for reforestation	79
3. RESULTS	80
3.1. Reforested area	80
3.2. Land availability for the purpose of reforestation	80
3.3. Geographic location and territorial impact	81
3.4. Species used in reforestation	81
3.5. Priority areas for reforestation	83
4. DISCUSSION.....	86
4.1. Success of National Reforestation Plan of Ecuador	86
4.2. Analysis to Identify Reforestation Priority Areas	87
4.3. CONCLUSIONS	89
5. REFERENCES.....	90
SUPPLEMENTARY MATERIAL 2	94

CAPÍTULO 5

Discusión general	98
1. Estudio de potencialidad de las áreas reforestadas en la provincia de Manabí Ecuador	100
2. Efecto de los programas de reforestación en la fragmentación y la conectividad de los bosques.....	102
2.1. Fragmentación.....	102
2.2. Conectividad.....	103
2.3. Impactos en los usos de la tierra de los programas extensivos de reforestación en Ecuador.....	104
3. Viabilidad del Plan Nacional de reforestación del Ecuador	105
4. Áreas prioritarias para la reforestación	106
5. REFERENCIAS	108

CAPÍTULO 6

Conclusiones generales.....	110
1. CONCLUSIONES GENERALES	112

Índice de Tablas

Capítulo 1

Table 1. Relación género – bosques.....	11
---	----

Capítulo 2

Table 1. <i>Environmental variables used to calibrate the species distribution models ...</i>	28
---	----

Capítulo 3

Table 1. Classification of Land uses classes of Ecuador.....	51
Table 2. Description of connectivity metrics analyzed according.....	53
Table 3. Fragmentation metrics <i>for native forest</i>	55
Table 4. Connectivity metrics across native forest patches.....	56
Table 5. Number of links, distance in cost and meters of the links generated in the 4 scenarios.....	58

Capítulo 4

Table 1. Suitability, value, classification and source data used.....	78
Table 2. Species used in reforestation.....	82
Table 3. Priority areas for reforestation in Manabí Region (Ecuador).....	84
Table 4. Reforestation priority areas identified through spatial multiattribute.....	85

Índice de Figuras

Capítulo 2

Figure 1. Study area and forest plantations.....	26
Figure 2. Accuracy values (ROC and TSS).....	30
Figure 3. Relative importance of environmental variables.....	31
Figure 4. Current potential distribution of the species under study.....	32
Figure 5. Suitability values in the locations of the plantations.....	33

Capítulo 3

Figure 1. Study sites.....	48
Figure 2. Land cover change and fragmentation.....	55
Figure 3. Current flow metric.....	57
Figure 4. Connectivity of the forest patches.....	58
Figure 5. Corridor in the Land uses scenarios.....	59

Capítulo 4

Figure 1. Location and delimitation of the study area.....	75
Figure 2. Lands cover and roads in the study area.....	87
Figure 3. reforested and afforested tree species.....	83
Figure 4. Priority areas for reforestation.....	84
Figure 5. decrease in reforestation potential values.....	85

Anexos

Capítulo 2

SUPPLEMENTARY MATERIAL 1.....	39
-------------------------------	----

Fig S1. Correlation matrix with Pearson's coefficients across all environmental variables used in the analysis for the three species of the study.

Fig S2. Estimations of temperature seasonality values (BIO4) for two different socioeconomic scenarios (126 and 585) and two temporal periods (2040 and 2060) considering the average of seven different global climate

Fig S3. Estimations of mean annual temperature values (BIO1) for two different socioeconomic scenarios (126 and 585) and two temporal periods (2040 and 2060) considering the average of seven different global climate.

Fig. S4: Current potential distribution of three species in the study area (Triplaris cumingiana (tripla), Prosopis juliflora (prosop) and Cordia alliodora (cordia)) considering the ensemble of six different algorithms.

Fig S5. Estimations of suitability values of Prosopis juliflora for two different socioeconomic scenarios (126 and 585) and two temporal periods (2040 and 2060) considering the average of seven different global climate.

Fig S6. Estimations of suitability values of Cordia alliodora for two different socioeconomic scenarios (126 and 585) and two temporal periods (2040 and 2060) considering the average of seven different global climate.

Fig S7. Estimations of suitability values of Triplaris cumingiana for two different socioeconomic scenarios (126 and 585) and two temporal periods (2040 and 2060) considering the average of seven different global climate.

Capítulo 4

SUPPLEMENTARY MATERIAL 2 94

Figure S2.- Hexagons intersected with natural areas, in red national parks, in yellow protective forest and in blue areas under other conservation figures.

Figure S3.- A) Population density B) and hexagons classification of study area (right). Warmer colors indicate high reforestation interest values and low population densities.

Figure S4.- A) Vulnerable species presence B) hexagons classification of study area . Warmer colors indicate higher values. Dinerstein et al. 2020. A “Global Safety Net” to reverse biodiversity loss and stabilize Earth’s climate. ScienceAdvance. DOI: 10.1126/sciadv.abb2824.

Figure S5.- A) hexagons intercepted with the buffer of infrastructures areas and populated areas B) hexagons intercepted with the buffer of roads. Red colour indicates the 250 m buffer (5) and blue colour indicates the 500 m buffer (-2.5).

Figure S6.- A) Reforestation points analysed to measure connectivity. B) Hexagons with where to reforest increase connectivity, in the red square the most important areas are highlighted. Warm colours indicate more connectivity.

Capítulo 1

Introducción General



"Lo que estamos haciendo a los bosques del mundo no es más que un reflejo de lo que nos hacemos a nosotros mismos y entre nosotros".

- Mahatma Gandhi -

Estudio de potencialidad de las áreas reforestadas en la provincia de Manabí Ecuador

1.1. Bosques en el Ecuador

Los bosques son ecosistemas naturales complejos, donde los forófitos autóctonos y su vegetación acompañante, junto con los animales, hongos y microorganismos del suelo, forman un ecosistema en el que establecen relaciones sostenibles a largo plazo sin la necesidad de la intervención humana. Los bosques proporcionan una multitud de bienes y servicios que son útiles para la sociedad y contribuyen al desarrollo económico. Además de leña y madera, suministran otros productos, como alimentos (bayas, setas), forraje, energía y materias primas renovables (biomasa). Los bosques regulan el ciclo hidrológico y contribuyen a la prevención o atenuación de inundaciones, avalanchas, erosión y sequía. Es importante destacar que estos bienes y servicios también juegan un papel crucial en la reducción del impacto del cambio climático, ya que actúan como sumideros de carbono y pueden ser utilizados como fuente de energía a partir de la biomasa, además, contribuyen a la preservación de la biodiversidad. Estos dos últimos aspectos se consideran claves entre los retos ambientales y socioeconómicos a los que se enfrenta actualmente la sociedad.

En este contexto, las previsiones existentes sobre el papel que desempeñarán los bosques en los escenarios de evolución futuros confirman su enorme importancia. Según el reciente informe sobre la *Situación de los Bosques del Mundo 2022* (FAO, 2022), los bosques tienen una contribución muy importante en la gestión de la crisis planetaria multidimensional. Específicamente, se ha reconocido el papel de los bosques en la lucha contra el cambio climático y la pérdida de biodiversidad, en el marco de la "Declaración de los Dirigentes" acordada en la reunión de Glasgow sobre bosques y uso de la tierra. En dicha declaración, más de 140 países se comprometieron a eliminar la deforestación para el año 2030, y a apoyar la restauración y actividades forestales sostenibles.

Los bosques secos tropicales en América del Sur están en grave peligro y son considerados uno de los ecosistemas más amenazados del mundo, y sólo queda una pequeña fracción de sus áreas de distribución originales (Pennington et al., 2018). Solo el 2% de los bosques en todo el mundo son clasificados como Bosque Tropical Seco y su principal característica es ser semi o caducifolio (FAO, 2020). Estos bosques albergan altos niveles de diversidad biológica y endemismo. Sin embargo, hay poca información disponible sobre aspectos biológicos básicos como (historia de vida, rango de distribución, ecología y evolución) de las especies que viven en estos ecosistemas frágiles y altamente amenazados (Luzuriaga-Aveiga y Cisneros-Heredia, 2022).

Ecuador es considerado un país de gran diversidad con cuatro regiones bien definidas: la Costa, Sierra, las Islas Galápagos y la Amazonía. Sin embargo, las áreas costeras son las áreas menos protegidas. Esta región está dominada por dos ecosistemas principales: bosque seco y bosque muy húmedo. Según Jones et al (2019), los bosques secos son los ecosistemas tropicales con menos superficie a escala global. Estos bosques se encuentran principalmente en las zonas costeras y se dividen en dos tipos: bosques caducifolios y semicaducifolios. (Rivas Cobo, 2022). Este hecho pone a la mayoría de los bosques secos tropicales de América del Sur en una situación crítica al tener menos estudios científicos que los bosques tropicales húmedos. La situación es similar en Ecuador, donde los bosques secos se encuentran en una situación crítica a pesar de ser parte del “*punto caliente*” global de biodiversidad del Chocó/Darién/Ecuador occidental.

Los bosques secos de la Cordillera de la Costa ecuatoriana han sido identificados como áreas protegidas prioritarias a nivel mundial, principalmente por su alto grado de endemismo. Se estima que una de cada cinco especies de plantas y árboles se encuentran en esta área (Solórzano et al., 2021). Con este antecedente, resulta prioritario desarrollar más estudios orientados a determinar su estructura y vegetación. Menos del 75% de la cobertura original de bosques secos permanecen en Ecuador (Mendoza y Jiménez, 2019). Con esta premisa, hay que tomar la decisión fundamental de qué especies plantar considerando tres aspectos: cuál es el objetivo de la plantación de árboles, que especies se disponen y fundamentalmente cuáles son las características del sitio a plantar (Suárez, 2009).

En concreto, para la provincia de Manabí en Ecuador no existen estudios relacionados con el potencial de especies para la restauración de sus hábitat, así como de los lugares de plantación prioritarios para los programas de reforestación (Bustamante et al. 2019). Esta información es crucial para garantizar la conservación de los sistemas naturales a medio y largo plazo y asegurar una sustentabilidad ecológica de los bosques secos en Ecuador, ya que esto contribuye a reducir el calentamiento global. Por tanto, la presente investigación pretende cubrir esta falta de conocimiento sobre el bosque seco de Ecuador analizando las especies forestadas durante el periodo de estudio 2008 – 2018, con el objetivo de comprender la idoneidad de las plantaciones, su efecto en la fragmentación, así como mejorar la contribución de nuevas plantaciones a la conservación y sustentabilidad de los bosques secos.

1.2. Degradación de los bosques

Los bosques secos tropicales se han reconocidos como uno de los ecosistemas más importantes a escala global, pero están expuestos a muchas amenazas, incluida la deforestación, la fragmentación, el pastoreo excesivo, los incendios, la conversión a la agricultura, y la sequía (Reiche et al., 2018). son algunos de los principales factores que han contribuido a la pérdida de especies y la reducción de la variabilidad genética en los bosques secos tropicales. El futuro de los bosques secos ha despertado grandes preocupaciones debido a que son muy accesibles, y presentan condiciones topográficas y climáticas para su transformación a otros usos del suelo, lo que los convierte en blancos fáciles para la expansión de la agricultura (en particular la intensiva), lo que favorece su pérdida de diversidad funcional (homogeneización), que reduce la variabilidad genética tanto dentro de las especies como entre poblaciones (Cueva Ortiz et al., 2019).

Durante el cambio de siglo, Ecuador ha presentado una de las tasas de deforestación más elevadas de América del Sur, con las consiguientes amenazas a la provisión de servicios ambientales esenciales para la vida (Mohebalian y Aguilar, 2016). Esto coincide con lo expuesto por Rivas Cobo (2022), que indica que, la tasa de deforestación en Ecuador durante el periodo de 1990 a 2010 ha sido muy alta, lo que ha resultado en una importante fragmentación de los ecosistemas de bosque seco en el país. Esta fragmentación es una de las principales amenazas que enfrentan los bosques secos ecuatorianos (Luzuriaga Aveiga y Cisneros Heredia, 2022). La fragmentación de los bosques tiene como consecuencia una serie de cambios rápidos en los ecosistemas. Uno de los primeros resultados de la fragmentación del hábitat es el aumento de los efectos de borde que podrían tener una influencia en los procesos de los ecosistemas locales, como los efectos microclimáticos, cambios en la abundancia y distribución de especies, y cambios en las interacciones entre especies. (González et al., 2018).

Los autores Castro et al. (2013), mencionan que entre 1990 y 2008, en Ecuador se perdieron cerca de 19000 km² de bosque natural. En 1990, la cobertura de bosque en Ecuador representaba el 69,6% de la superficie forestal potencial del país, sin embargo, para el año 2008, esta cifra se había reducido al 60,7%. Cerca del 70% de la deforestación ocurrió en la década de los años 1990. Luego, un aparente pero significativo incremento de la regeneración de bosques acentuó la caída de la deforestación neta total. Entre 1990 y el 2000 se regeneraron 0,3 ha de bosque por cada hectárea deforestada, mientras que entre el 2000 y el 2008 se regeneraron 0.47 ha de bosque por cada hectárea deforestada; 50% más que en periodo anterior (Sierra, 2013).

En Ecuador, la principal causa de la deforestación es la expansión de la frontera agrícola (Sierra, 2013). Durante el período de 1990 a 2000, el 99,4% del área deforestada en Ecuador fue convertida en áreas agropecuarias, el 0,14% en infraestructuras como zonas urbanas y asentamientos rurales densos, y el 0,46% en otros tipos de cobertura. Mientras que entre 2000 y 2008, el 99,4% del área deforestada fue transformada a áreas agropecuarias, el 0,23% a infraestructuras, principalmente áreas urbanas y asentamientos rurales densos, y el 0,37% a otros usos. Visto de otra manera, en los periodos de 1990 a 2000 y 2000 a 2008, la expansión del área agropecuaria en Ecuador estuvo estrechamente ligada a la deforestación, siendo alrededor del 97,5% y el 95%, respectivamente, el incremento del área agropecuaria generado a partir de la transformación de áreas de bosque nativo en cultivos y pastos. La única diferencia entre ambos periodos fue que en el segundo hubo una mayor transformación de vegetación arbustiva y herbácea, principalmente en la región de la Sierra. El área absoluta deforestada a nivel nacional para crear infraestructura, y especialmente asentamientos, decreció un 30% entre los dos periodos. Sin embargo, el área urbana total se duplicó mediante la transformación de áreas agropecuarias (Sierra, 2013).

1.3. Bosques de la provincia de Manabí

La zona centro de la provincia de Manabí agrupa a 20 cantones y a la zona no delimitada de la Manga del Cura. Se caracteriza por tener una reducción en la tasa de deforestación que pasó a convertirse en regeneración de bosque, de -5,33% en el período 1990-2000 a +1,57% en 2000-2008. Es la única zona que exhibe una recuperación de bosque en lugar de pérdida de cobertura en Ecuador. Sin embargo, apenas un 8,3% de la superficie de Manabí es bosque. El principal uso del suelo son los pastizales que representan el 62% de la superficie agrícola, que fueron la superficie con mayor crecimiento entre 2000 y 2008. Los productos agropecuarios con mayor expansión de superficie fueron la leche, la carne, el cacao y el plátano; y se destinaron mayoritariamente al consumo nacional. La zona muestra una flexibilidad media para la expansión agrícola ya que el 5% de la superficie agrícola se encuentra bajo descanso, ligeramente superior a la proporción nacional del 4%. Para esta zona, los modelos de predicción sobre los bosques proyectan un incremento del área forestal, debido principalmente a una redistribución de la población (Castro et al., 2013).

1.4. Necesidad de restauración

La reforestación, de acuerdo con Wightman (2003) es una actividad forestal crucial para recuperar y hacer productivas las zonas que han sido deforestadas o degradadas. En muchas partes del mundo la reforestación ha sido ampliamente adoptada para aumentar el secuestro de carbono terrestre y mejorar la preservación del agua y el suelo (Hong et al., 2018). Otros estudios indican que, las actividades de reforestación han generado un conjunto de impactos no deseados como la propagación de enfermedades y plagas, tanto en los bosques como entre los humanos, disminución de las precipitaciones, aumento de las temperaturas locales, erosión del suelo y disminución de la biodiversidad (Malkamäki et al., 2018). A pesar de ello, las plantaciones de árboles siguen formando parte de la gobernanza ambiental (Davis y Robbins, 2018). Sin embargo, y a pesar de todos los esfuerzos por parte de los sectores públicos y privados, los resultados de las políticas de reforestación no han sido del todo alentadores, ya que el avance de la deforestación constituye uno de los males que, con mayor impacto y menor grado de atención, aflige a los países latinoamericanos y del resto del planeta (Herrera, 2016); por lo que algunos autores recomiendan reducir las áreas de plantación, favoreciendo las actuaciones de mayor calidad ecológica (Villar Salvador, 2016). Un paso importante para minimizar los impactos, y aprovechar lo positivo de las actuaciones de plantación forestal, es determinar los posibles impactos del cambio climático sobre las áreas aptas para las especies usadas en plantaciones forestales.

Los principales programas de forestación y reforestación que se han ejecutado en el Ecuador fueron realizados por el Ministerio de Agricultura, a través de proyectos como: Plan Bosque; Proyecto BID 808 y Proforestal, con un total de 107.500 ha (Ministerio del Ambiente Ecuador 2013). La pérdida de la cubierta forestal en la costa genera fenómenos de erosión que vuelven deficiente la productividad de los suelos. En este caso se registró, en el período 2012-2013, una superficie total de 7.303.674 ha, de labor agrícola, según reveló el resultado de la encuesta de superficies de producción realizada por el Instituto Nacional de Estadísticas y Censos citados por (Pérez-Leira et al., 2018). Además, manifiestan que las provincias con mayor superficie de labor agrícola son Manabí (15,48%), Guayas (11,26%), Loja (7,64%), Los Ríos (7,25%) y Esmeraldas (7,11%). Manabí posee una superficie general de área agrícola de alrededor de 1.894.000 ha, es la provincia con mayor superficie agropecuaria con 1,2 millones de hectáreas, es además una provincia especializada en agricultura, en relación con el resto del país, lo que indica que su campo agrícola tiende a la expansión generando deforestación y problemas antes citados.

En Ecuador, se ha reforestado con especies nativas en áreas específicas como la Región Amazónica, las áreas montañosas que bordean las cordilleras de la región andina y las zonas costeras secas y húmedas (Zúñiga Suárez 1999), en las estribaciones externas de las dos cordilleras de la región andina y en zonas secas y húmedas de la Costa. Con estos antecedentes actualmente, en el plano académico e institucional, está extendida la importancia de recuperar no sólo especies y hábitats, sino también la biodiversidad y las funciones de los ecosistemas (Navarro Cano et al., 2019). Por otro lado, Navarro Cano et al. (2019) recomiendan favorecer la variabilidad genética dentro de una única especie (intraespecífica), ya que esto induce cambios en la composición taxonómica de las comunidades con las que interactúa, y eventualmente puede determinar funciones ecosistémicas claves.

La incorporación en los diferentes programas de reforestación de especies nativas como Fernán Sánchez (*Triplais cumingiana* Fisch & C.A. Mey. ex. C.A. Mey), Algarrobo (*Prosopis juliflora* Sw. DC), Laurel (*Cordia alliodora* (Ruiz & Pav.) Oken) entre otras, proporcionan múltiples bienes y servicios (Campos y Vélez, 2015). Estas especies sufren actualmente una fuerte retracción debido a un uso histórico extractivista, por lo que se hace necesario promover la conservación y el manejo sostenible de los bosques donde aparecen a escala de ecosistema. De acuerdo con SENPLADES (2017), el Consejo Sectorial Hábitat, Infraestructura y Recursos Naturales coinciden en destacar que los problemas prioritarios que se presenta en la provincia de Manabí para atender las necesidades de agua para el consumo humano y el sector agropecuario, dado el fuerte impacto de las prácticas agropecuarias. Por otro lado, se han realizado estudios en el cantón Jipijapa y la zona sur de Manabí, según la investigación de Indacochea Ganchozo et al. (2017) debido a la amplia gama de especies de madera que se encuentran en los bosques primarios y las áreas protegidas, ha habido una deforestación descontrolada de estos bosques para utilizar esta materia prima en la fabricación de artesanías, muebles y para la exportación a través de los puertos de Guayaquil y Manta.

1.5. Potencialidad y conectividad ecológica

Cuando se habla de este tema, se refiere a la potencialidad ecológica o la capacidad que tiene un área determinada para mejorar su estructura ecosistemática, la cual está influenciada de una serie de factores que permiten su desarrollo en este proceso. Cuando se aborda este tema siempre se habla principalmente o se hace referencia al paisaje, aunque en este caso se aluce al sistema o capacidad que tiene la provincia de Manabí para ser forestada o reforestada por sus condiciones geográficas,

meteorológicas, geológicas que permiten un adecuado proceso para su restauración sin la intervención de factores externos que puedan comprometer su integridad y capacidad.

Por otro lado, la conectividad ecológica es la articulación que permite que exista un enlace entre especies sin que se pierda contacto, en algunos lugares se les puede encontrar formando corredores ecológicos, en otras líneas de árboles en linderos de fronteras agrícolas o silvopastoriles; lo que hace que no se corte la conexión permitiendo a los organismos moverse entre los diversos parches ecosistemáticos o hábitats.

El desafío más grande que existe actualmente está en frenar la expansión de la frontera agrícola, la cual trae desventajas potenciales para crear una conectividad exitosa, la misma que está influenciada por factores tan sencillos como complejos, a lo que se podría citar, el desconocimiento que tienen los agricultores de las ventajas de cercas vivas en los linderos o la necesidad de mantener árboles para protección de los suelos. Los programas de forestación a nivel de parroquias rurales en los últimos años han permitido que haya una mejor interrelación ecosistemática, permitiendo la transferencia de flujo ecológico a través de estos nuevos corredores.

2. PLAN NACIONAL DE REPOBLACIONES

En el Ecuador cada gobierno ha establecido sus políticas en relación con el desarrollo forestal, las mismas que se dan inicio desde el 2007, dentro del Plan Nacional de Desarrollo. El Ecuador ha priorizado una estrategia de Reducción de Emisiones por Deforestación y Degradación (REDD+) y así, aunar esfuerzos a nivel global para mitigar el cambio climático. A través de ello ha realizado acciones para promover la conservación, el manejo forestal sostenible y el incremento de reservorios de carbono forestal. La Estrategia Nacional REDD+ del Ecuador y el Plan de Acción REDD+ (Ministerio del Ambiente Ecuador 2016) son los referentes sobre los cuales el país se ha vinculado a esta propuesta global. Para una evaluación que permita determinar el aporte que diferentes programas que se acogen al mecanismo REDD+ no sólo a corto plazo, sino también a mediano y largo plazo, se ha considerado la necesidad de evaluar el impacto, la eficacia y la eficiencia de tres programas: Socio Bosque, Agenda de Transformación Productiva Amazónica (ATPA) y Fondos de Agua cuyos principios rectores y trayectoria permiten operacionalizar los componentes estratégicos del PA REDD+ (Programa de las Naciones Unidas para el Desarrollo (PNUD) Earth Innovation Institute y Ministerio del Ambiente Ecuador 2019).

La biomasa forestal del Ecuador al año 1990 cubrió aproximadamente el 69,6% del territorio, disminuyendo a 61,7% para el año 2008. De los cuales se estima que el 80% se encuentra en la región Amazónica, el 13% en la Costa, y el 7% restante en la Sierra. Se estima además, que apenas 164 mil ha son bosques plantados para usos comerciales, la distribución por regiones es la siguiente: Sierra 90 mil ha, donde existen principalmente árboles de pino y eucalipto; Costa, 50 mil ha, (20 mil ha de teca, 10 mil ha de balsa y 20 mil ha de maderas tropicales -caoba, cedro, palo de rosa-); y, Amazonía, alrededor de 25 mil ha, en esta región predomina el cultivo de árboles en sistemas agroforestales (Sánchez, 2015).

El Plan Nacional de desarrollo “Toda una vida” 2017 – 2021 (Consejo Nacional de Planificación, 2018), establece que el Programa Nacional de Reforestación para la conservación ambiental, este enfocada a la protección de cuencas hidrográficas y los beneficios alternativos. El Gobierno Central, a través del Ministerio del Ambiente (MAE), asume la responsabilidad ambiental y crea el Programa Nacional de Reforestación en 2014 para resolver los problemas causados por la degradación ambiental (Ministerio del Ambiente, 2021). En 2016, tras el terremoto que afectó al país, el gobierno decidió priorizar el Programa Nacional de Reforestación en las zonas más afectadas, especialmente en las áreas más afectadas. El objetivo del programa era atender la necesidad de restauración de la vegetación en todo el Ecuador continental, de acuerdo con los principios de la Constitución, el Plan Nacional de Desarrollo 2017-2021 y el Programa "Ecuador Verde". El modelo de gestión del programa se basó en una visión holística de la restauración de ecosistemas, lo que implica que varios niveles de actores públicos y privados trabajaran juntos para formar una alianza que permitiera el logro de las metas nacionales. El programa fue operando entre 2014 y 2021 (Ministerio del Ambiente, 2021).

Por otro lado, la degradación y deforestación tienen efectos significativos en la economía de la población rural, y esto tiene un impacto social importante, especialmente en lo que se refiere al género. A lo largo de la historia, hombres y mujeres se han beneficiado de los bosques de manera diferente, y esto ha tenido consecuencias en términos de igualdad de género (Tabla 1).

Tabla 1. Relación género – bosques

Variable	Hombres	Mujeres
Recurso Extraído	Madera	Leña, hongos, plantas, agua, hojas, cortezas y látex.
Beneficio	Económico	Satisfacción de necesidades para subsistencia familiar

Nota. Beneficios que da el bosque para satisfacción de necesidades familiares. Datos obtenidos del ministerio del ambiente, 2017.

2.1. Especies elegidas

El género *Prosopis* (*Fabaceae*) comprende 44 especies y numerosos híbridos (Hunziker et al., 1975), comúnmente llamados “algarrobos” o “mesquites”. Cuarenta de estas especies son originarias de las regiones áridas y semiáridas del continente americano, dentro de su rango de distribución natural los algarrobos son considerados “especies clave”. Son especies esenciales de los ecosistemas en los que aparecen, tanto para la comunidad vegetales y animales, como para la subsistencia de numerosos grupos humanos ancestrales y actuales. En Ecuador, esta especie se encuentra distribuida en diferentes hábitats, en particular en planicies y laderas del bosque seco, a altitudes que oscilan entre los 0 y los 500 metros sobre el nivel del mar. Se pueden encontrar en varias provincias del país, entre ellas Esmeraldas, Galápagos, Guayas, Loja y Manabí (Jorgensen y León Yáñez, 1999). En concreto, se encuentra en los tipos de bosque seco pluvio estacional y bosque seco andino. Dentro de sus usos, la madera se emplea para postes, carpintería, parquet, leña y carbón. Las hojas molidas se cocinan y, previo colado, se aplican en gotas para la irritación de los ojos. El uso más importante es la cocción de los frutos para obtener la algarrobina. Es una especie apta para Sistemas Agroforestales (SAF) y repoblación forestal (Ministerio del Ambiente Ecuador, 2012).

El Fernán Sánchez es una especie perteneciente a la familia Polygonaceae, que se encuentra distribuida en varias regiones del Ecuador, incluyendo las Islas Galápagos, la Costa y la región Andina, específicamente en las provincias de Bolívar, Chimborazo, El Oro, Esmeraldas, Galápagos, Guayas, Loja, Los Ríos, Manabí, Morona Santiago y Pichincha, en altitudes que van desde 0 hasta los 1500 metros sobre el nivel del mar. Esta especie se puede encontrar en laderas de bosques secos y premontanos, y habita en diferentes tipos de bosques como el bosque seco pluvial estacional, bosque seco andino y bosque siempre verde de tierras bajas de la Amazonía (Ministerio del Ambiente Ecuador, 2012). Se describe como un árbol de 17 metros de altura que tiene una copa

frondosa e irregular. Tiene raíces profundas que a veces parecen tablones, pero en realidad son engrosamientos superficiales en el tallo hasta 0,40 a 0,50 m sobre el suelo. El tronco es recto con hendiduras y una corteza externa grisácea e interna café claro que se descascara en láminas. Las hojas son simples, alternas, oblongas y de borde entero. Tienen un color verde mate en el haz y verde grisáceo en el envés, con nervaduras pinnatinervadas, ápice redondeado y base obtusa. Las flores son dioicas, con las masculinas de color cremoso blanquecino y las femeninas de color rosado. El fruto es una nuez seca e indehiscente con una sola semilla, de color café lustroso con tres alas pequeñas y ligeras en consistencia (Aguirre et al., 2015).

El laurel costeño es una planta perteneciente a la familia Boraginaceae, que se encuentra en las Islas Galápagos, la costa y la selva amazónica, en diversas provincias de Ecuador, entre altitudes de 0 a 1000 metros sobre el nivel del mar. Se puede encontrar en bosques, laderas, potreros y cultivos de la provincia de Manabí. Es comúnmente encontrado en los bosques secos estacionales y andinos (Ministerio del Ambiente Ecuador, 2012). Se trata de un árbol que alcanza los 19 metros de altura, con una copa de tamaño reducido y con el follaje esparcido (Aguirre et al., 2015).

El árbol presenta un tronco recto y cilíndrico, sin ramas hasta su mitad, y su corteza externa es de color blanco grisáceo. Sus hojas son simples, alternas y tienen una textura áspera en el haz, mientras que en el envés presentan pelos estrellados. Son ovado-lanceoladas o elípticas, con ápice agudo, bordes enteros u ondulados y una base obtusa o desigual. El pecíolo es pubescente y áspero al tacto. Las flores son blancas y fragantes, y las inflorescencias surgen de los engrosamientos de las ramas. Su fruto es una nuez con una sola semilla, y estas son dispersadas por el viento y los animales. Según las conclusiones obtenidas por (Aguilera Peña y Jalón de Torbay, 2018) Para llevar a cabo la repoblación forestal, es necesario en primer lugar identificar los territorios que cumplan con los requisitos fundamentales para esta actividad.

2.2. Reforestación en Manabí

Dentro de los Programas de Reforestación en la provincia de Manabí, se han considerado la extensión del territorio, su diversidad cultural y sus recursos valiosos. Se han propuesto cuatro Operaciones Estratégicas Territoriales que involucran la costa, el interior rural y las ciudades más pobladas, cada una con características demográficas y particulares que las distinguen. Cada operación tiene su propio carácter y objetivos específicos (Consejo Provincial de Manabí, 2021) y se presentan a continuación:

- Operación Pacífico Ecuatorial: Costa: Jama, Pedernales, Cojimíes Valles de Jama y Coaque – Pedernales, Jama, San Jacinto, Bahía de Caráquez, San Vicente, Canoa y la conexión con El Carmen.
- Operación Agrópolis de Manabí: - Valles de Chone y Carrizal. Aglomeración Chone Tosagua – Calceta y Junín. Nodos complementarios en EL Carmen, Portoviejo y Jipijapa.
- Espacio Metro rural “Eloy Alfaro”: Portoviejo - Rocafuerte – Santa Ana | Manta Jaramijó – Montecristi. Costa San Lorenzo, Pacoche, Manta, Crucita y conexión con Pichincha y Olmedo.
- Operación Manabí Sur: Jipijapa, Paján, Puerto López, Puerto Cayo y Parque Machalilla Valles del Puca y Colimes.

El Consejo Provincial de Manabí (2021) tiene previsto implementar un programa de reforestación en el eje Hipijapa-Paján, que se ubica en la sierra seca costera y en los bosques semidecíduos del interior, como parte de la Operación Manabí Sur. Estas áreas pertenecen a las cuencas de los ríos Hipijapa, Colimes y Guanabano, muy relacionadas con el incremento de la producción de café en las provincias de Hipijapa, Padang y 24 de mayo en los últimos años. Es necesario fortalecer las rutas agroecoturísticas de café, cacao y ceibo en estas áreas, y se espera aumentar la productividad, regenerar suelos degradados, implementar procesos de forestación, instalar sistemas de riego, brindar asistencia técnica, financiamiento, etc.

El programa "Manabí Verde, Ocre y Azul" tiene como objetivo principal la reforestación y conservación de áreas con alta vulnerabilidad ecosistémica en la provincia de Manabí, minimizando el deterioro ambiental y promoviendo el desarrollo sostenible y equitativo de la región. Por ello, se propone desarrollar programas de reforestación anuales en zonas rurales sensibles, priorizando las plantaciones en corredores ecobiológicos costeros y continentales y reservas de agua. cuencas y microcuencas. Todo esto ocurre en el contexto de fortalecer el crecimiento regional y el desarrollo sostenible y equitativo (Consejo Provincial de Manabí 2021a), el programa cuenta con 5 objetivos y se detallan a continuación:

- Incentivar la plantación de especies que contribuyan a un mejor balance ambiental en las Áreas de Conservación Provincial.
- Incentivar la plantación de especies con marcado carácter comercial en zonas estratégicas del territorio, que contribuyan a disminuir las presiones forestales sobre las Áreas de Alto Valor Natural.

- Propiciar las condiciones logísticas y estratégicas para la producción sostenida de plantas.
- Motivar a otros actores territoriales sobre la importancia de la reforestación y forestación en zonas de protección hídrica de cuencas y microcuencas, así como en los biocorredores ecológicos.
- Impulsar un aprovechamiento sostenible y balanceado del medio físico litoral, desde una intervención articulada y horizontal entre distintos niveles de gobierno y actores territoriales.

El área de influencia de implementación de este programa aplica para toda la provincia, con un presupuesto alineado durante el proceso de actualización (2019 -2020), de \$ 1.934.071,31 USD y un presupuesto referencial para el programa (2021 - 2023), de \$ 4.150.000,00 USD.

3. HIPÓTESIS Y OBJETIVOS DE LA TESIS

3.1. Hipótesis:

La hipótesis de esta tesis es que los trabajos de reforestación impulsados por el Gobierno de Ecuador, y por el Gobierno de la provincia de Manabí utilizan especies y criterios de establecimiento que no tienen en cuenta la adecuación del programa a criterios de potencialidad y conectividad de los ecosistemas forestales. Partiendo de esta hipótesis, la metodología de la tesis integra modelos de predicción de especies, análisis de fragmentación y conectividad, y Sistemas de Información Geográfica para evaluar los programas de reforestación en la provincia de Manabí. En este sentido la investigación y el documento de tesis doctoral pretende ser un elemento de análisis crítico de estos programas, con el objeto de mejorar las actuaciones de restauración de ecosistemas forestales en Ecuador bajo escenarios del cambio climático.

3.2. Objetivos:

El objetivo principal de la tesis es el de estudiar la potencialidad de las áreas reforestadas en la provincia de Manabí en el Ecuador, se concreta mediante la definición de una serie de objetivos específicos:

- Evaluar la idoneidad ambiental de las áreas reforestadas en la provincia de Manabí.
- Caracterizar cómo las nuevas plantaciones forestales de 2008 a 2018, han cambiado la fragmentación del hábitat y la conectividad en la provincia de Manabí.
- Evaluar los cambios en la cobertura del suelo y su efecto sobre la fragmentación y la conectividad a través de los paisajes plantados en comparación con los restos de bosques nativos.
- Proponer estrategias que permitan la articulación de las áreas deforestadas para que exista un flujo de transición en la conectividad ecológica entre especies forestales.

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Capítulo 2

Evaluación de la aptitud de hábitat de especies forestales utilizadas en la restauración de bosques secos nativos en Ecuador

Assessment of the habitat suitability of forest species used in the restoration of native dry forests in Ecuador



Sólo una ciudad perdida entre los bosques es una ciudad de verdad.
Mehtmet Murat Ildan

RESUMEN

La restauración de los ecosistemas permite recuperar su función ecológica, mismo que conlleva un proceso que implica tres partes, i) técnica; ii) política y iii) social, estas responden a la necesidad de devolver las características naturales y servicios ecosistémicos al área, y mejorar las condiciones de vida de sus poblaciones, de esta manera, las actividades de reforestación se han adoptado ampliamente y los programas de reforestación son idóneos ante una variedad de problemas ecológicos, mismo que incluyen la erosión de suelo y la pérdida de biodiversidad. El área de estudio comprende plantaciones forestales de las especies nativas *Triplaris cumingiana*, *Prosopis juliflora* y *Cordia alliodora*, en la zona sur de Manabí. Para el estudio se realizaron análisis estadísticos, recopilando los registros disponibles a nivel mundial para las tres especies focales en el Servicio de Información sobre Biodiversidad Global, además de información climática de la base de datos WorldClim y un conjunto de variables ambientales, un paquete biomod2 para implementar los modelos de distribución de especies, valores de idoneidad por especie en cada una de las localidades de plantaciones forestales y se desarrolló proyecciones futuras de la distribución potencial de cada especie. Los resultados mostraron que los algoritmos más precisos para estimar la distribución de las tres especies fueron *Random Forest (RF)* y *Generalized Boost Models (GBM)*; además se demostró que las especies estudiadas tuvieron alta sensibilidad ante estacionalidad de la temperatura y se destacó que, todas las variables ambientales son importantes sin embargo estas varían según las especies. Por su parte, el análisis de idoneidad mostró que los valores estimados en el área de estudio fueron relativamente altos para las tres especies, y las proyecciones revelaron que la idoneidad del hábitat parece aumentar para todas las ubicaciones de las especies *Triplaris* y *Cordia*; sin embargo, para *Prosopis* disminuye, esto se debe principalmente a las ubicaciones de plantación en la parte este del área de estudio.

Keywords: habitat suitability; forest restoration; dry forest; species distribution models; reforestation programs

ABSTRACT

The restoration of ecosystems allows the recovery of their ecological function, which entails a process that involves three parts, i) technical; ii) political and iii) social, these respond to the need to return the natural characteristics and ecosystem services to the area, and improve the living conditions of its populations, in this way, reforestation activities have been widely adopted and conservation programs reforestation are suitable for a variety of ecological problems, including soil erosion and loss of biodiversity. The study area includes forest plantations of the native species *Triplaris cumingiana*, *Prosopis juliflora* and *Cordia alliodora*, in the southern area of Manabí. For the study, statistical analyzes were carried out, collecting the records available worldwide for the three focal species in the Global Biodiversity Information Service, as well as climate information from the WorldClim database and a set of environmental variables, a biomod2 package for implement species distribution models, suitability values per species in each of the forest plantation locations, and future projections of the potential distribution of each species were developed. The results showed that the most accurate algorithms to estimate the distribution of the three species were Random Forest (RF) and Generalized Boost Models (GBM); In addition, it was demonstrated that the studied species had high sensitivity to seasonality of temperature, and it was highlighted that all environmental variables are important, however, they vary according to the species. For its part, the suitability analysis showed that the estimated values in the study area were relatively high for the three species, and the projections revealed that habitat suitability seems to increase for all locations of the *Triplaris* and *Cordia* species; however, for *Prosopis* decreases, this is mainly due to planting locations in the eastern part of the study area.

Keywords: habitat suitability; forest restoration; dry forest; species distribution models; reforestation programs

1. INTRODUCTION

Ecosystem restoration is a cost-effective and efficient strategy for mitigating biodiversity loss and climate change (Strassburg et al., 2020). One approach that has been suggested to be important in achieving this objective is the restoration of forest ecosystems through the planting of trees or the promotion of the spontaneous regeneration of woody species (Uriarte and Chazdon, 2016). Reforestation is a forestry activity of great importance in degraded areas to restore ecosystem functions and landscapes (Jones et al., 2018). Reforestation activities have been widely adopted to increase terrestrial carbon sequestration and improve soil and water preservation (Hong et al., 2018). Furthermore, reforestation programs have been viewed as a panacea for a variety of ecological, social, and economic problems, including poverty, decreased rainfall, warming temperatures, soil erosion, and the decline of biodiversity. As a result, forest plantations, despite their several complexities, have flourished as an art of environmental governance (Davis and Robbins, 2018). However, those public and private reforestation programs have frequently resulted in major failures due to inadequate technical and social implementation, combined with the real threat of deforestation continues affecting particularly Tropical regions (Choi et al., 2022). An important step to minimize these negative aspects is to determine the possible impacts of climate change on habitat suitability for the species used in forest plantations (Duque-Lazo et al., 2018).

A relevant study case to evaluate the effectivity of reforestations is Ecuador, where there has been a large effort in the last decades to revert deforestation trends with widespread national reforestation programs. The main reforestation programs carried out in Ecuador were promoted by the Ministry of Agriculture, through projects such as: Forest Plan; BID 808 and Proforestal Project, with a total of 107,500 ha (Ministerio del Ambiente Ecuador 2013). One of the most relevant ecosystems targeted by these programs was the dry forests of Coastal Cordillera. This ecosystem has been identified as priority areas for conservation worldwide, mainly due to their high level of endemism since it is estimated that one in five species of plants and trees are endemic (Jadán et al., 2022). Those forests are unique of the Ecuadorian coast, but they are affected by severe deforestation process (Kleemann et al., 2022; Rivas et al., 2021a; Tapia-Armijos et al., 2015). Furthermore, only two percent of world forests corresponds to Tropical Dry Forests (Pennington et al., 2018).

The reforestation programs in Equatorial dry forest have focused mainly in three native tree species: *Triplaris cumingiana* Fisch & C.A. Mey. ex. C.A. Mey., *Prosopis juliflora* (Sw.) DC *Cordia alliodora* (Ruiz & Pav.) Oken. These species provide multiple goods and services (Sánchez et al., 2006) but have been threatened by a strong retraction due to an historical intensive use. Furthermore, there is a lack of understanding of the effect of climate change on future sustainability of these forest plantations. In fact, although there is an extensive and growing literature regarding the impacts of climate change on the abundance and distribution of species, there is little experience on its effect on forest plantations in Central America (Leguía et al., 2009). Despite the efforts to replant these species, we do not have a clear understanding of the habitat suitability of these species at regional scale which is of the uttermost importance to guarantee the ecological sustainability of dry forests reforestation activities. Therefore, it is important that forest restoration considers the promotion of landscape heterogeneity and biodiversity (Brancalion and Chazdon, 2017).

When forests are restored, just a few quickly growing tree species are frequently chosen, which leads to reduced survival rates, less tolerance to diseases and harsh weather, decreased biodiversity, and increased fragmentation compared to the natural forests they replace. In order to reduce the effects of climate change and restore biodiversity and ecosystem services, several studies have recently emphasized the need of planting various native species in reforestation operations (Brancalion and Chazdon 2017; Navarro-Cano et al., 2017). However, species selection in reforestation programs is still one of the most difficult challenges in ecosystems restoration (MacKenzie y Mahony, 2021). Species distribution models (SDMs) have been used over the past two decades to assess individual and multiple-species habitat modelling (Chapman et al., 2019a; Elith et al., 2010; Sillero et al., 2021). However, previous applications of SDMs have mostly focused on how well SDMs predict occurrences at the species level, but there is still a need for widely using those models to species selection and assessment in forest plantations (Duque-Lazo et al., 2018; Hu et al., 2020). Therefore, it is essential to learn how well SDMs can orient this species selection and environmental conditions suitability in National Reforestation Programs.

To accommodate species selection to bio geoclimatic and tree species feasibility ratings for Ecuador we used a species distribution model approach to project a range of future spatial distributions of three tree species based on an ensemble of downscaled global climate models. We applied the state of the art species distributions models (Sillero et al., 2021) to make spatial explicit predictions of the distribution of our focal species as

an informative means of looking for relationships between groups of environmental variables and the occurrence of species under current and future climate scenarios. From these premises arise our main research aims a) to characterize the environmental suitability of the three main species used in reforestation programs of the Equatorial dry forest and b) assess the sustainability of the plantations carried out in a climate change scenario. Our results intent to facilitate integration of climate change into the existing reforestation policy in Ecuador.

2. MATERIAL AND METHODS

2.1. Study area and forest plantations

The study area includes forest plantations of native species *Triplaris cumingiana*, *Prosopis juliflora* and *Cordia alliodora*, in the southern area of Manabí, which includes the Jipijapa, Paján, Puerto López and 24 de Mayo cantons (Fig. S1). With an approximate surface of 3335.46 km², inserted in a wide mountain range (mountainous system of Manabí) with elevations between 100 and 800 meters above sea level and with a dry tropical climate. Manabí is located in the centre of the coastal region of Ecuador and in the most west-ern part of the South American continent, on the margins of the Pacific Ocean. in the biogeographical region of Ecuador Coast. Five types of ecosystems are found in this area: low deciduous forest, deciduous scrub and grass-land, deciduous forest, semi-deciduous forest, and seasonal evergreen forest (Ministerio de Ambiente Agua y Transición Ecológica, 2013), To obtain the geographical location of the reforested areas, we obtained the coordinates and surface of all reforested plots from the Department of Environmental Management of the Provincial Government of Manabí, for the period 2008 - 2018.

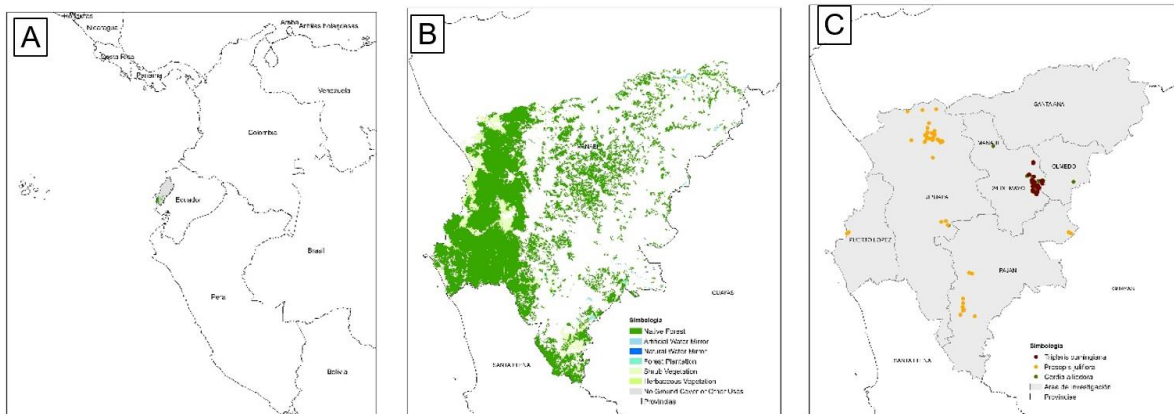


Figure 1. Study area and forest plantations

Note. A) Study area in Ecuador. B) Ecosystems in the study area. C) location of plantations per species. 2023.

2.2. Species distribution data

We collated all records globally available for the three focal species in Global Biodiversity Information Facility (www.gbif.org) on December 5th, 2022: *Prosopis juliflora* (6874 records, <https://doi.org/10.15468/dl.x3pgwe>), *Triplaris cumingiana* (21411 records <https://doi.org/10.15468/dl.pbwedh> and *Cordia alliodora* (19945 records, <https://doi.org/10.15468/dl.c2m5df>). We used the Coordinate Cleaner package (v 2.0 – 20) to conduct an automated correction of GBIF downloaded records (Zizka et al. 2019). Specifically, we carried out an analysis per species excluding occurrences with coordinates on country capitals, country centroids, absolute longitude and latitude, GBIF headquarters, biodiversity institutions, plain zeros, equal longitude and latitude, countries, duplicates, and sea locations. We also removed records older than 1945 to avoid inaccurate locations. Finally, we reduced sampling bias keeping only one record per species in each 2.5 arc-min grid using the function `gridSample` from R package `dismo` (Hijmans y Elith s. f.), resulting in 1329 records for *Prosopis*, 191 records for *Triplaris* and 1521 records for *Cordia*.

2.3. Environmental data

Climate information was extracted from WorldClim database (Fick and Hijmans, 2017) which reports gridded mean climate values from baseline period of 1970-2000. The dataset was downloaded at 2.5 arc-min spatial resolution (~21.5 km²). Outputs from

circulation models of the Coupled Model Inter-Comparison Project Phase (CMIP6) were used to assess projected changes in future climate. Downscaled monthly future climate data from CMIP6 is available in GeoTiff files for seven global climate models (GCMs): BCC-CSM2-MR, CNRM-CM6-1, CNRM-ESM2-1, CanESM5, IPSL-CM6A-LR, MIROC-ES2L, MIROC6, and four Shared Socio-economic Pathways (SSPs). The monthly values were averages over 20-year periods (2021-2040, 2041-2060, 2061-2080, 2081-2100). For future projections and for providing plausible scenarios for management, we selected two contrasting SSPs scenarios (i.e., SSP126 and SSP585), and the two first periods (i.e. 2021-2040, 2041-2060). In the relatively sustainability-focused SSP126, emissions peak between 2040 and 2060 – even in the absence of specific climate policies, declining to around 22 to 48 gigatons of CO₂ (Gt CO₂) per year by 2100. This results in 3-3.5C of warming by 2100. The high-growth energy-intensive SSP585 shows the most overall emissions of any SSP, ranging from 104GtCO₂ to 126GtCO₂ in 2100, resulting in warming of 4.7-5.1C. Soil data was extracted from SoilGrids database (<https://soilgrids.org/>), which provides maps for ten different soil properties at six different depths. In this work, we used the 5 km resolution files (<https://files.isric.org/soilgrids/> retrieved on 12th January 2023) and an average of soil values from 30 to 100 cm which is relevant for forest tree species. Soil data was reprojected to 2.5 arc-min to keep the same resolution across environmental data. All GIS processing was carried out with R packages raster (Hijmans, 2023) stars (Pebesma, 2018, 2022). We carried out a multicollinearity test estimating pair-wised Pearson's correlation coefficients using corrplot package (Taiyun Wei and Viliam Simko, 2021) to identify a set of low correlated variables per species (Fig. 1). The final set of environmental variables selected across the three species were (Table 2): Annual Mean Temperature (bio1), Mean Diurnal Range (Mean of monthly (max temp - min temp)) (bio2), Temperature Seasonality (standard deviation ×100) (bio4), Annual Precipitation (bio12), Precipitation Seasonality (Coefficient of Variation) (bio15), Precipitation of Warmest Quarter (bio18), Cation exchange capacity at pH 7 (cec), Coarse fragments volumetric (cfvo), nitrogen content (nitrogen), Sand content (sand) and Soil organic carbon content (soc).

Table 1. Environmental variables used to calibrate the species distribution models.

Variable	Code	Units
Annual mean temperature	BIO1	°C
Mean Diurnal Range (Mean of monthly (max temp - min temp))	BIO2	°C
Isothermality (BIO2/BIO7) (×100)	BIO3	
Temperature Seasonality (standard deviation ×100)	BIO4	
Max temperature of warmest month	BIO5	°C
Min Temperature of Coldest Month	BIO6	°C
Temperature annual range (BIO5 – BIO6)	BIO7	°C
Mean Temperature of Wettest Quarter	BIO8	°C
Mean Temperature of Driest Quarter	BIO9	°C
Mean Temperature of Warmest Quarter	BIO10	°C
Mean Temperature of Coldest Quarter	BIO11	°C
Annual precipitation	BIO12	mm
Precipitation of Wettest Month	BIO13	mm
Precipitation of driest month	BIO14	mm
Precipitation Seasonality (Coefficient of Variation)	BIO15	mm
Precipitation of Wettest Quarter	BIO16	mm
Precipitation of Driest Quarter	BIO17	mm
Precipitation of Warmest Quarter	BIO18	mm
Precipitation of Coldest Quarter	BIO19	mm
Bulk density	bdod	Cg/cm ³
Clay content	clay	g/kg
Sand	sand	g/kg
Silt	silt	g/kg
Cation exchange capacity (at ph 7)	cec	Mmol(c)/kg
Nitrogen	nitrogen	Cg/kg
pH	phh2o	pH*10
Soil organic carbon content in the fine earth fraction	soc	dg/kg
Volumetric fraction of coarse fragments (> 2 mm)	cfvo	cm ³ /dm ³

Note. In bold selected variables after multicollinearity analysis. 2023.

2.4. Statistical analysis

We used the package biomod2 package (Thuiller et al., 2022) to implement the species distribution models considering six widely used algorithms: Generalize Lineal Models (GLM), Generalize Additive Models (GAM), Artificial Neural Networks (ANN), Generalised Boosted Models (GBM), Random Forest (RF), and MAXENT (Chapman et al. 2019b). Occurrence data per species was split between 70 % of the occurrences for

calibration and 30% for testing. We carried out a 10-fold-cross-validation procedure for each of the species and algorithm (10 data split-repetitions per combination). We estimated five random sets of pseudoabsences per combination in order to reduce uncertainty in previous research (Sillero et al., 2021). Pseudoabsence selection was estimated randomly as equal number of records than presences. Each model was assessed in terms of the following metrics: True Skills Statistics (TSS), Receiving Operation Curve (ROC) and Kappa. We also developed ensemble combinations of the best algorithms per species considering a weighted average approximation. This is a widespread procedure since considers the contribution of each model based on its quality (Hao et al., 2020). The metric quality threshold was set in 0.7, so models with less quality were not included in ensembles. The significance level to estimate the confidence interval around the probability mean was set to 0.05. Finally, we estimated the importance of variables with three permutations.

2.5. Model projections and outputs

Ensemble models were projected across the study area. We analysed the suitability values per species in each of the forest plantation locations. We also developed future projections of potential distribution of each species following the ensemble modelling approach indicated above. Algorithms per species calibrated with current climate were projected into future climate scenarios according to seven GCMs and two SSPs (i.e., SSP126 and SSP585) to predict the distribution of suitability by the 2021-2040 and 2041-2060 periods.

3. RESULTS

3.1. Model selection and fitness

Most accurate algorithms to estimate the distribution of the three species were Random Forest (RF) and Generalised Boosted Models (GBM) (Fig. 2). These two algorithms showed TSS and ROC values close to 0.9. The algorithms ANN, GAM, GLM and MAXENT were not considered optimal for the distribution of the species in the present analysis. Across the three species, *Triplaris* showed the highest scores in terms of TSS and ROC, while *Prosopis* showed the lower scores (Fig. 2).

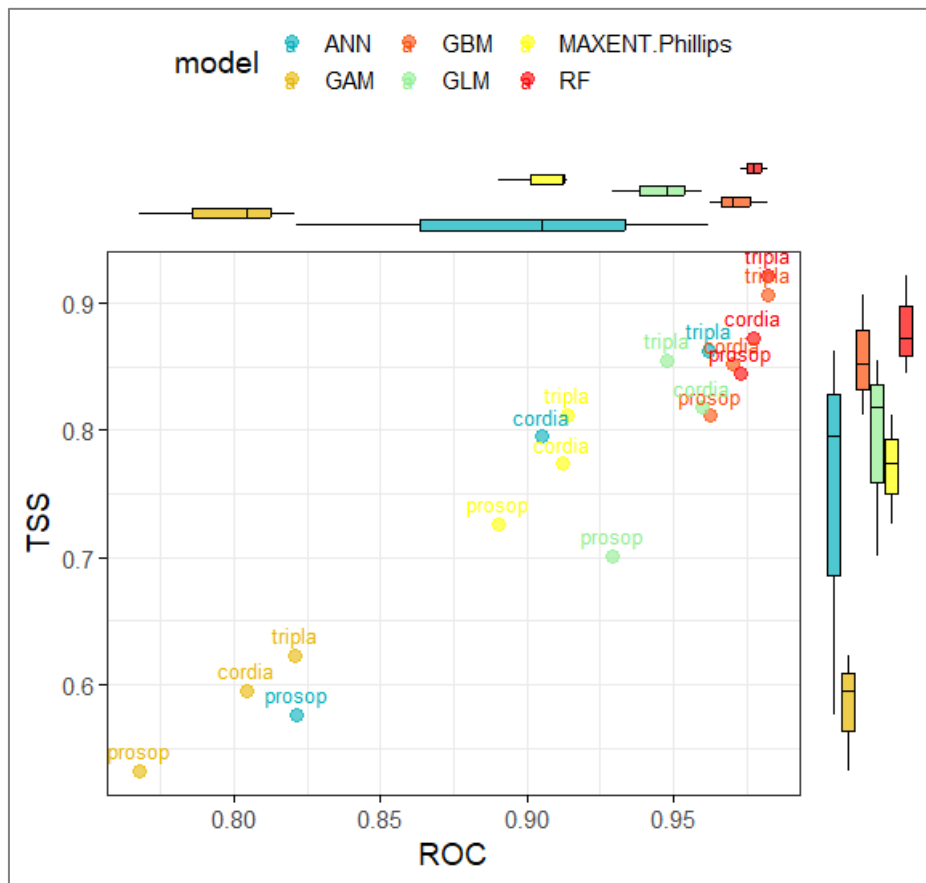


Figure 2. Accuracy values (ROC and TSS)

Note. **Boxplot** used for the distribution models of three species *Triplaris cumingiana* (tripla), *Prosopis juliflora* (prosop) and *Cordia alliodora* (cordia) considering six different algorithms. 2023.

3.2. Relative importance of environmental variables

All species showed high sensitivity in their distribution to the seasonality of the temperature (bio4) (Fig. 3). However, the relative importance of the remaining environmental variables varied across *Triplaris*, *Cordia* and *Prosopis* species (Fig. 3). It is denoted that the average annual temperature (bio1) had a greater influence on the distribution of the *Prosopis* and *Cordia* species, and a lesser influence on the *Triplaris* species. *Prosopis* showed a contrasting difference in the relative importance of variables compared to the other species, with annual rainfall (bio12) and the precipitation of the warmest quarter (bio18) with greater influence on the distribution of the *Prosopis* species, unlike *Cordia* and *Triplaris*. Rest of climatic variables and edaphic variables (e.g., the seasonal variables of rainfall; coarse fraction, nitrogen, soil organic carbon content and cation exchange capacity) did not show a major influence on the distribution of the species studied.

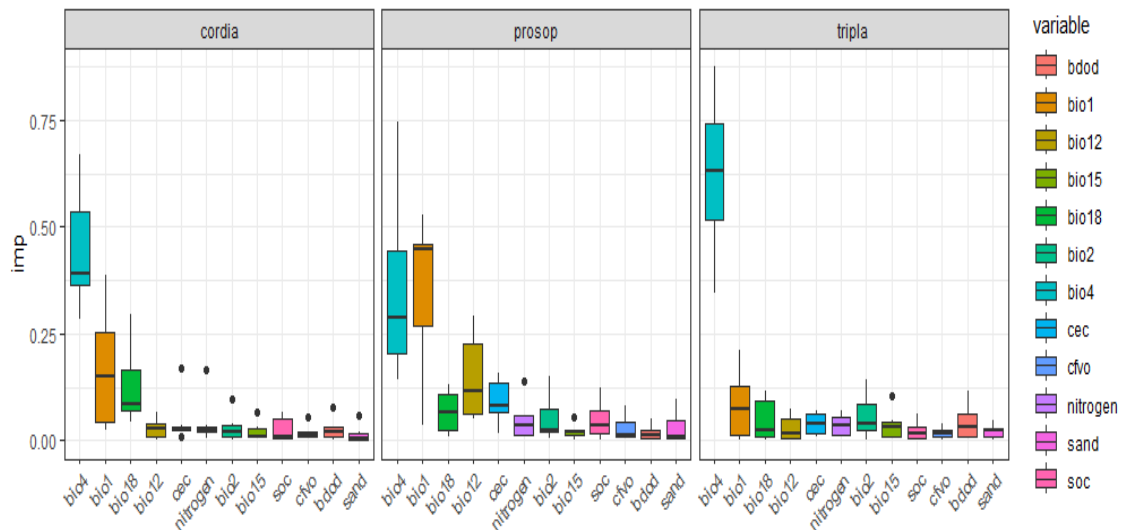


Figure 3. Relative importance of environmental variables

Note. Explain the distribution of three species *Triplaris cumingiana* (tripla), *Prosopis juliflora* (prosop) and *Cordia alliodora* (cordia) considering six different algorithms. 2023.

3.3. Current and future environmental suitability of forest plantations

The analysis of mean ensemble distribution for the species *Triplaris* showed large suitable areas across all the study area with only a minor reduction in the higher elevation areas (Fig. 4). The ensemble potential distribution of *Cordia* showed also a similar suitable area but with overall lower scores. (Fig. 4). *Prosopis* showed higher habitat suitability values on the Western area of Ecuador, corresponding to the coastal areas, and with suitability values extremely low on the Eastern side of the study area (Fig. 4).

Uncertainty in the potential distribution projections (i.e., CV) varied also across species and followed similar pattern than the ensemble mean projection. The species *Triplaris* and *Cordia* showed lower uncertainty on higher elevation areas (Fig. 4). The analysis of the species *Prosopis* showed that there is greater uncertainty that this is present in the study scenario due to environmental factors, particularly in the Eastern part of the study area (Fig. 4).

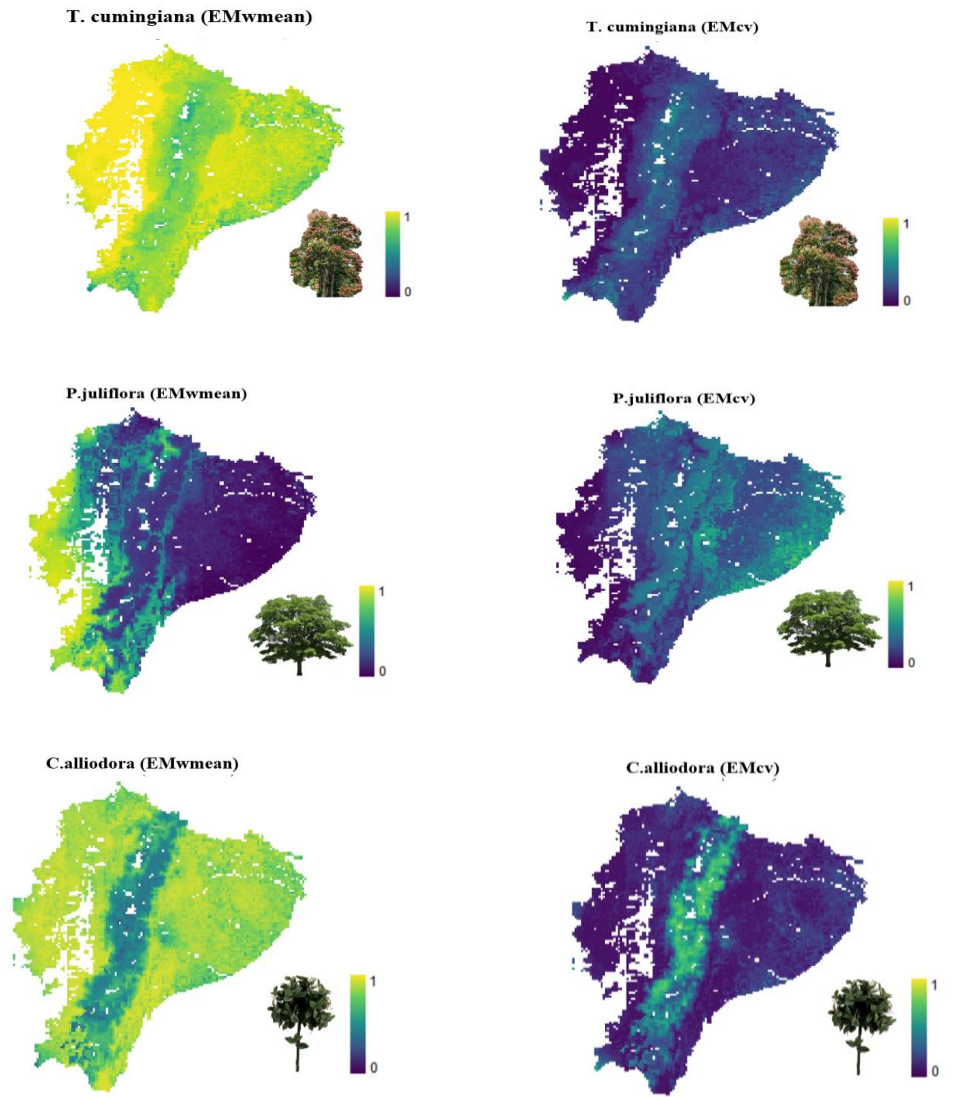


Figure 4. Current potential distribution of the species under study

Note. The species the study are *Triplaris cumingiana* (tripla), *Prosopis juliflora* (prosop) and *Cordia alliodora* (cordia). In Ecuador based on ensemble species distribution models considering six different algorithms. Each row corresponds to a different species, while left shows mean predictions (Emwmean) and the right image the uncertainty in terms of the coefficient of variance (Emcv). 2023.

Suitability values for current climatic conditions estimated for the locations of the plantations in the study area were relatively high for the three species, particularly for *Prosopis* (Fig. 5, Fig. S4). Projections of for future climatic conditions in the plantations locations revealed that habitat suitability seems to increase for all locations of *Triplaris* and *Cordia* species (Fig. 5). The future projection for these species across SSP scenarios and periods is rather homogeneous (Fig. 5, Fig. S6 and S7). However, for *Prosopis* the habitat

suitability seems to decrease, particularly for the worst SSP scenario and the period 2040-60 (Fig. 5). This drastic reduction corresponds mainly to the plantation locations in the Eastern part of the study area (Fig. S4 and Fig. S5).

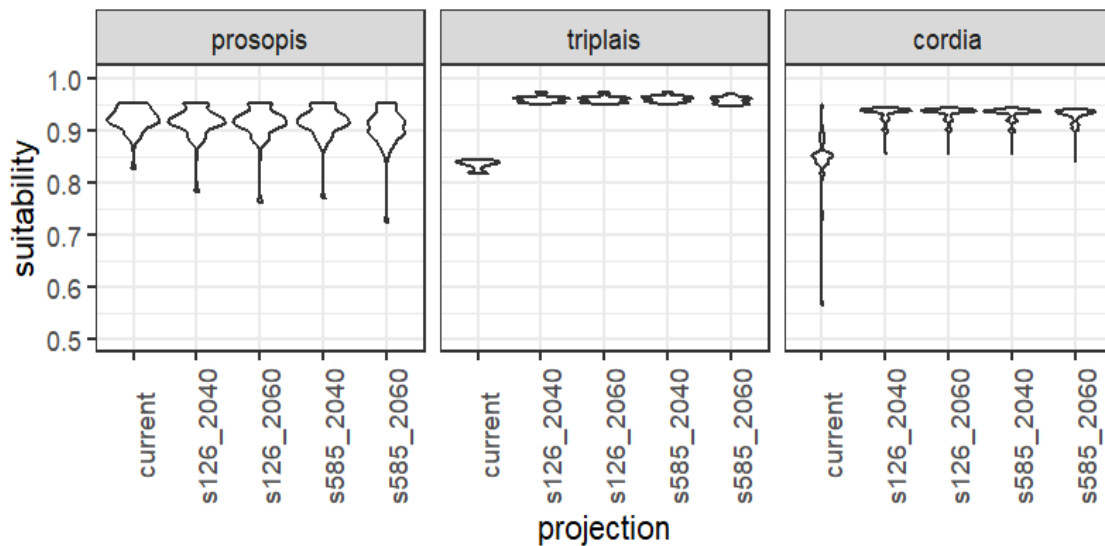


Figure 5. Suitability values in the locations of the plantations

Note. The species analysis are the *Triplaris cumingiana* (Triplaris), *Prosopis juliflora* (prosopis) and *Cordia alliodora* (cordia), based on ensemble species distribution models considering six different algorithms. The values correspond to the projected suitability for current and future conditions considering two periods (2040 and 2060) and two socioeconomic scenarios (126 and 585). 2023.

4. DISCUSSION

Ecosystem restoration is a cost-effective and efficient strategy for mitigating biodiversity loss and climate change (Strassburg et al., 2020). One of the most widely used approaches is the reforestation with native species. In this study, we assessed the species selection and location of plantations in the dry forests of Ecuador using a species distribution model approach to project a range of future spatial distributions of three tree species widely used in the National Reforestation program. Overall, we found that the species selected showed high environmental suitability in the study area and that future projections suggests contrasting results depending on the species.

4.1. Relative importance of environmental factors

Both climate and soil factors were included in the models explaining the current distribution of *Prosopis*, *Cordia* and *Triplaris* globally. However, climatic factors were more relevant than edaphic variables to explain their distribution. This pattern fits well with the hierarchical pattern of environmental factors explaining the global distribution of species.

This is characterized at the global scale by physical factors being more restrictive at large scale, and topographic and biotic interactions more limiting at smaller scales (Pearson and Dawson, 2003). Among climatic factors, temperature seasonality was the most important variable across the three species. This finding fits well with the Tropical Niche Conservatism hypothesis stating temperature seasonality is one of the main factors restricting the distribution of tropical species, and thus preventing latitudinal expansion of taxa of tropical origin (Wiens et al., 2010). Species with tolerances to temperature seasonality evolve and the clade expands to higher latitudes (Stevens 2013). In other words, cold tolerance is a primary constraint on species dispersal from tropical to temperate regions, as tropical species are not adapted to high temperature seasonality or cold environments. *Prosopis* showed a link with a wider number of climatic variables, including also annual precipitation and precipitation of warmer quarter. This pattern was also found in previous studies for species distribution model of tree species in the dry forest of Ecuador (Manchego et al., 2017). In fact, *Prosopis* is among the three species considered in the reforestation program, the most adapted to harsh rainfall conditions, and thus it mirrors well the availability of dry ecosystems in the study area.

4.2. Current and future environmental suitability projection

Triplaris and *Cordia* showed the widest environmental suitability in Ecuador, with only a reduction in potential distribution on the higher elevations. This finding corresponds well with the wide geographical distribution of both species across the tropics. For instance, *Cordia* is widely distributed in continental tropical America from central Mexico to northern Argentina, with a range in latitude of 50° across the tropics (Greaves and McCarter, 1990). In contrast, *Prosopis* potential distribution was restricted to the Western part of Ecuador within the limits of the dry forest ecosystem. This pattern is well aligned with the ecology of the species. In its native range, *Prosopis* is generally found in areas with low water and soil nutrient availability. Thus, *Prosopis* dominates in dry, or seasonally dry areas, and is often found in coastal flats and dunes (Pasiiecznik, 2017).

Future projections of the species did not show major changes in Ecuador. In fact, the plantations of *Cordia* and *Triplais* seem to increase their habitat suitability under all climate scenarios considered here. In contrast, *Prosopis* plantations showed a reduction in habitat suitability, particularly for the worst-case scenario in the period 2040-60. This finding contrast with a previous study showing a potential increase in its distribution for Ecuador towards northern areas (Manchego et al., 2017)

4.3. Applicability to reforestation program

The target species of this study have been widely used in the Ecuadorian National Reforestation Program, since they provide multiple goods and services and are important as forest resources:

- The genus *Prosopis*, is an essential species of the ecosystems in which they appear, both for the plant and animal community, as well as for the subsistence of numerous ancestral and current human groups, in Ecuador it is distributed in habitat, on plains and slopes of the dry forest; Within its uses, the wood is used for carpentry, firewood and charcoal. The most important use is cooking the fruits to obtain algarrobina. Also, as feed for sheep species (Ministry of the Environment Ecuador, 2012).

- *Triplaris*, this species inhabits slopes of dry and premontane forests, in the types of dry seasonal rain forest, Andean dry forest and evergreen lowland forest of the Amazon (Ministerio del Ambiente Ecuador, 2012). It is a species highly required by the furniture industry, due to its noble technological properties, such as its dimensional stability, ease of working, and its attractive veined color.

- *Cordia*, is a widely demanded species in the furniture industries and crafts, as well as in the decorative veneer industry; It is also used in heavy and light construction, boat construction; decks, boats, etc, (Aguirre et al., 2015).

These species have been threatened by a strong retraction due to a historical intensive use. Interestingly, *Triplaris* and *Cordia* showed the widest potential distribution throughout Ecuador and could therefore stand out as favorable species over large areas. In contrast, *Prosopis* is more adapted to dry conditions, where it outperforms other tropical species. Therefore, this species could be selected as a potential species for reforestation in areas with limited water availability. Finally, projections of the future potential distribution of the species did not show important changes in Ecuador, indicating that the selection of species in reforestation programs has probably been adequate under future climate scenarios.

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SUPPLEMENTARY MATERIAL 1

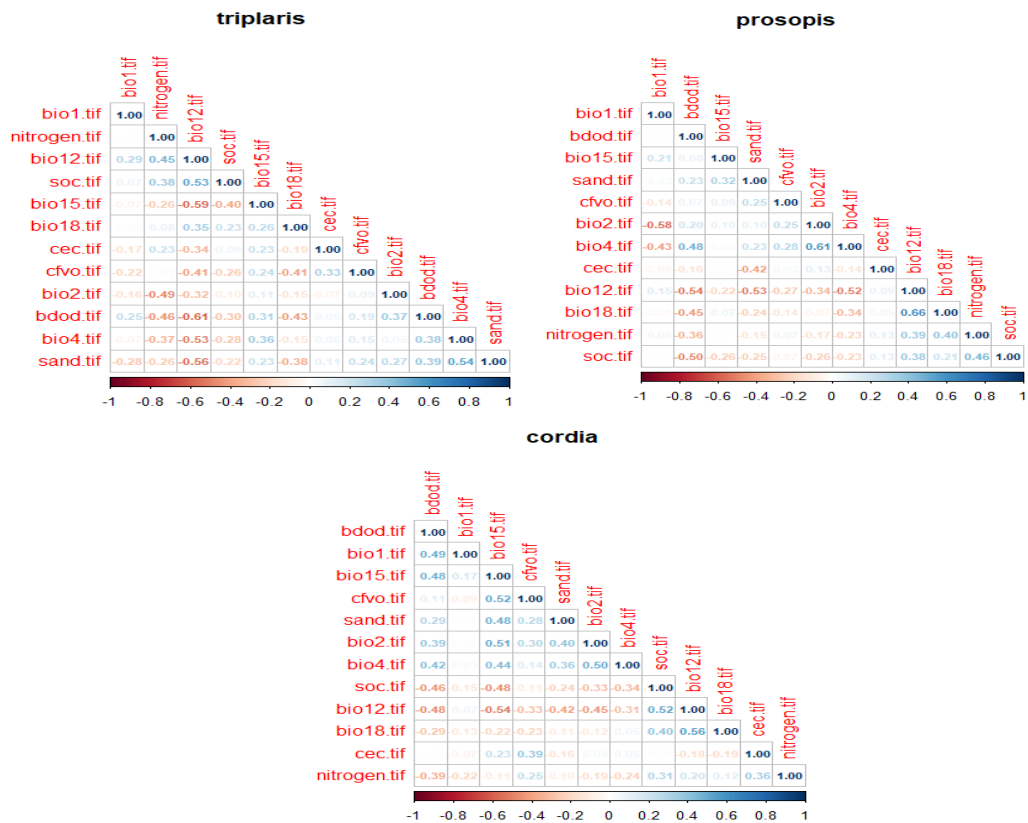


Fig S1. Correlation matrix with Pearson's coefficients across all environmental variables used in the analysis for the three species of the study.

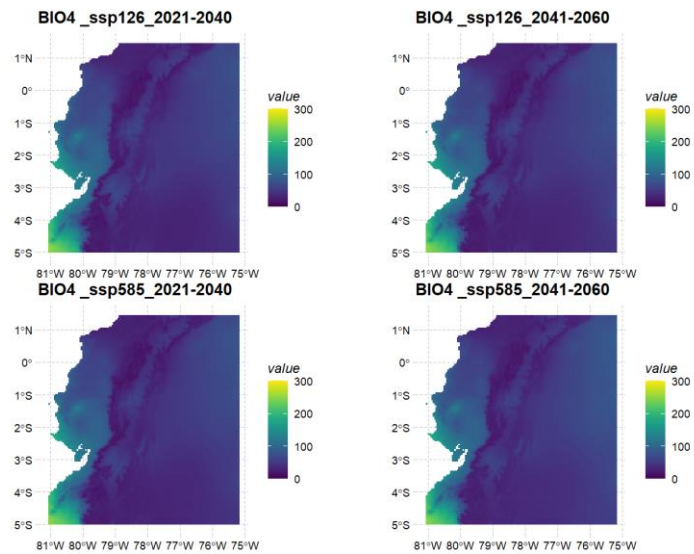


Fig S2. Estimations of temperature seasonality values (BIO4) for two different socioeconomic scenarios (126 and 585) and two temporal periods (2040 and 2060) considering the average of seven different global climate

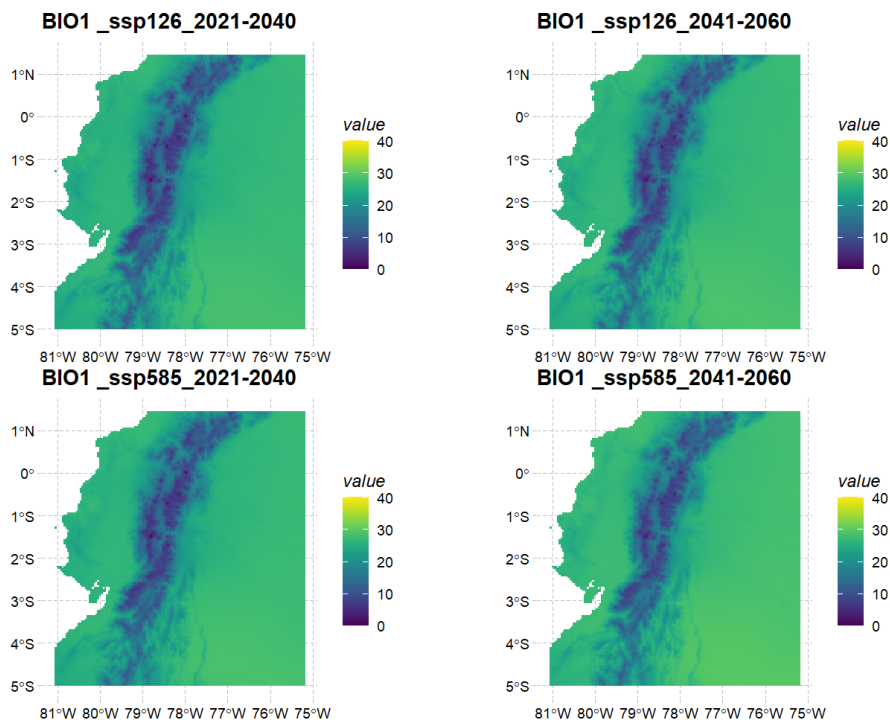


Fig S3. Estimations of mean annual temperature values (BIO1) for two different socioeconomic scenarios (126 and 585) and two temporal periods (2040 and 2060) considering the average of seven different global climate.

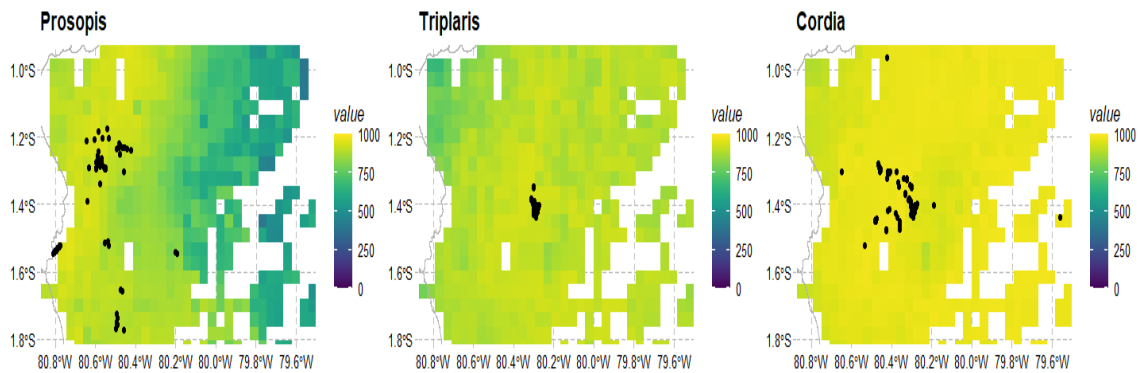


Fig. S4: Current potential distribution of three species in the study area (*Triplaris cumingiana* (tripla), *Prosopis juliflora* (prosop) and *Cordia alliodora* (cordia)) considering the ensemble of six different algorithms.

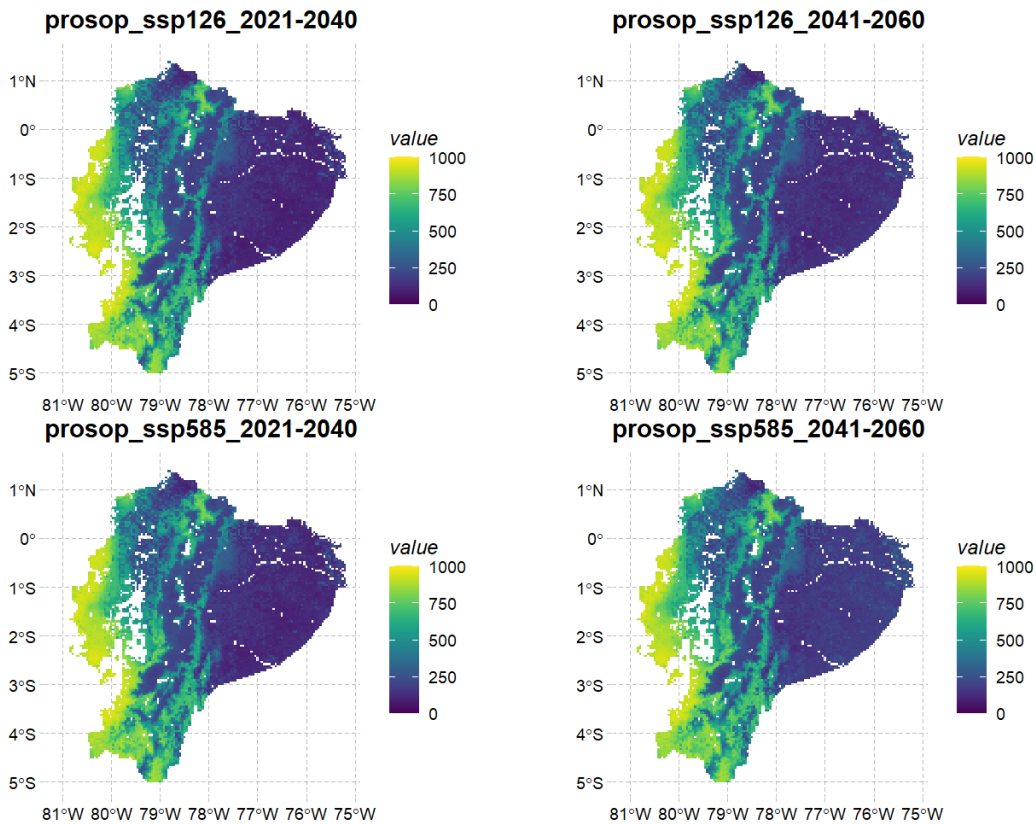


Fig S5. Estimations of suitability values of *Prosopis juliflora* for two different socioeconomic scenarios (126 and 585) and two temporal periods (2040 and 2060) considering the average of seven different global climate.

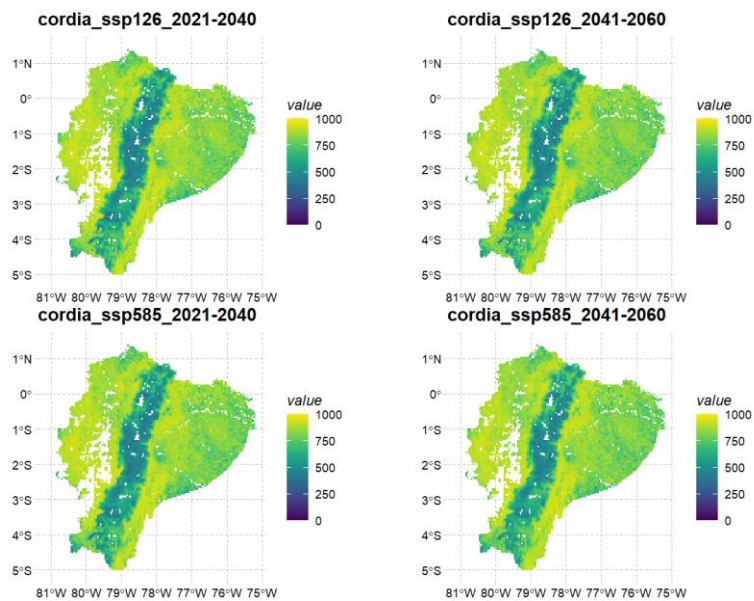


Fig S6. Estimations of suitability values of *Cordia alliodora* for two different socioeconomic scenarios (126 and 585) and two temporal periods (2040 and 2060) considering the average of seven different global climate.

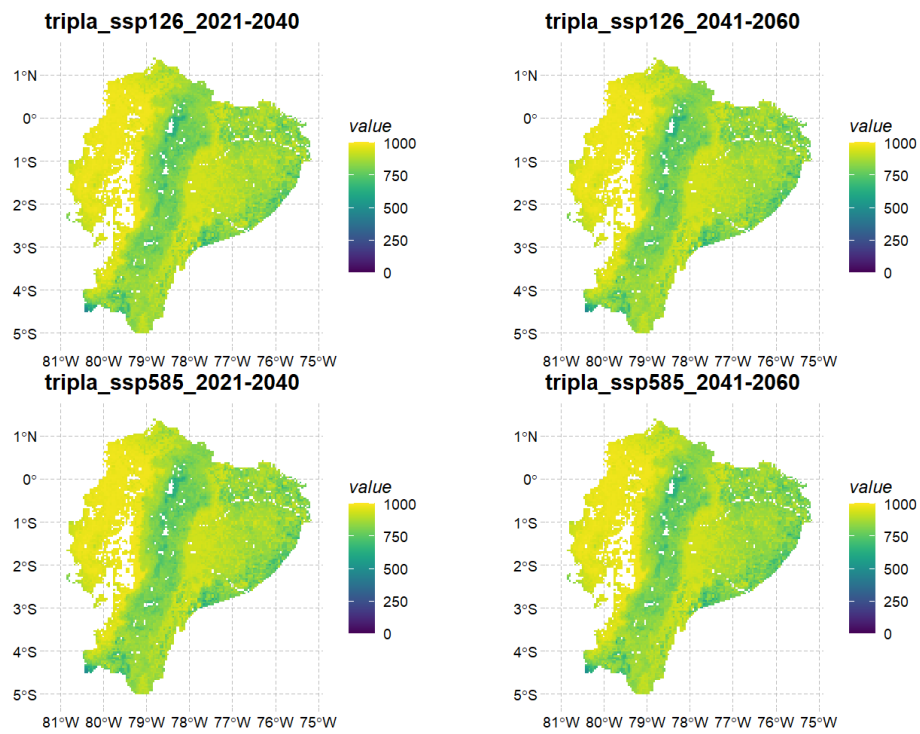


Fig S7. Estimations of suitability values of *Triplaris cumingiana* for two different socioeconomic scenarios (126 and 585) and two temporal periods (2040 and 2060) considering the average of seven different global climate.

Capítulo 3

Plantaciones forestales en Manabí: Evaluación de la fragmentación y la conectividad como apoyo a la conservación de los bosques tropicales secos

Forest plantations in Manabí: assessment of fragmentation and connectivity to support dry tropical forest conservation



"El verdadero sentido de la vida es plantar árboles, bajo cuya sombra no esperas sentarte".

Nelson Henderson



applied sciences

an Open Access Journal by MDPI

Forest Plantations in Manabí (Ecuador): Assessment of Fragmentation and Connectivity to Support Dry Tropical Forests Conservation

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ABSTRACT

In many tropical regions, national forests plantation programs have been promoted. Those plantations frequently contribute to habitat changes. However, the associated effects of forest plantations on habitat fragmentation and landscape connectivity are unclear. From 2008 to 2018, we examined land use changes, plantations, and deforestation of the Manabí province (Ecuador) provided by the Ecuadorian Ministry of the Environment. Four scenarios were created: (i) land uses in 2008, (ii) land uses in 2018, (iii) land uses in 2018 without deforestation, and iv) land uses in 2018 including reforestation. Fragmentation and connectivity metrics were analyzed using ArcGisPro and Graphad 2.6 software, respectively. *Puma yagouarondi* was selected as the reference species. At regional scale, forest plantations had a significant effect on land uses changes and fragmentation during the study period. Forests decreased from 33.7% to 32.4% between 2008 and 2018, although other natural land uses, mostly those involving shrubs, increased by almost double (from 2.4% to 4.6%). Most of the deforestation affected native forests during this period, and most reforested areas in 2018 covered former agricultural land. Fragmentation decreased in the number of patches and increased in the average patch size. When considering reforestation, deforestation was higher than the reforested area (58 km² of difference), increasing the number of patches but with smaller size. Reforestation increased connectivity with a higher number of links and distance, particularly in central and extreme northeast areas of Manabí province. The scenario without deforestation also increased connectivity for *Puma yagouarondi* in the west part of the Manabí province. Our findings suggest that forest plantations contribute to forest conservation by increasing the connectivity between fragmented patches.

Keywords: Afforestation; edge effects; landscape management; dry tropical forests; connectivity

1. INTRODUCTION

Afforestation is a major forest activity in many parts of the world, especially in areas where forests replace degraded lands to promote soil protection, habitat conservation and connectivity (Holl and Karen, 2017). However, afforestation in tropical areas frequently occurs on natural ecosystems such as grassland and secondary forests that are considered poorly productive but might not be the most suitable areas to maximize conservation and biodiversity goals (Bremer and Farley, 2010). Also, large-scale afforestation for carbon sequestration has received a lot of attention (Driscoll et al., 2013; Pawson et al., 2013) bringing into question the possibility of influencing conservation (Horák et al., 2019). Thus, it is of paramount importance to understand the link between afforestation programs and landscape functionality to evaluate the environmental costs and benefits of afforestation policies. One of the most significant effects of afforestation is changes in landscape characteristics. On one hand, new commercial forest plantations could produce the fragmentation of large, continuous native habitats into smaller, isolated patches surrounded by a land use matrix that may be hostile to resident fauna (Castaño-Villa et al., 2019). On the other hand, forest plantations may result in a positive effect when the target is the expansion of native forests (Iezzi et al., 2022). However, according to several authors planted forests appear to be insufficient for promoting conservation of wildlife communities (Brockerhoff et al., 2013), even though those are influenced by forest management and composition (Volpato et al., 2010). Plantations may also have other negative effects because they remove species with high conservation value from the habitats they replace, particularly birds strictly associated with open habitat and grasslands (Brockerhoff et al., 2013).

Although theoretical and empirical evidences suggest that effects of forest plantations may extend beyond forest boundaries (Fischer and Lindenmayer, 2007), little is known about the impact of afforestation on fragmentation. These effects are brought about by habitat fragmentation, in which complex land uses matrixes (agriculture, secondary forests, grasslands, etc.) are broken up into smaller patches. The capacity of animal and vegetal species to use the matrix surrounding forest plantations partly determines the degree to which plantations contribute to connect isolated forest areas (Gardiner et al., 2018). The idea that fragmented systems are comprised of "island-like" remnants of suitable habitat surrounded by land uses with no ecological value can oversimplify the complexity of fragmented landscapes and underestimate ecological values of anthropic landscapes (Ries et al., 2004). Those landscapes can still provide sufficient connectivity through ecological corridors to sustain or at least allow the movement of wild animal and plant propagules even if those landscapes lack the

characteristics required for permanent habitat suitability (Ewers and Didham, 2006). Forest plantations can significantly increase the amount of suitable habitat at landscape scale through changes in species richness, composition, and abundances (Rivas et al., 2021). For instance, some species may experience an increase in habitat availability due to an increase of forest edges. These species tend to benefit from more fragmented landscapes (Plan Nacional de Desarrollo 2017-2021 Toda Una Vida | SITEAL, s. f.), suggesting that forest plantations on agricultural dominated lands may contain more species simple agricultural habitats. Also, penetration of edge effects into adjacent habitats created by forest plantations may greatly influence changes in landscape features. Therefore, understanding changes in landscape configuration and composition due to forest plantations is extremely relevant to characterize their potential effects on fragmentation and connectivity.

Tropical forests in Ecuador have been extensively deforested, primarily for agricultural purposes, and about 24% (2020-2022) of these forests have vanish (Harper et al., 2005). To reverse this process, Ecuador has promoted an ambitious National Forest Plantation Program (Prefectura de Imbabura, 2014) A long-term trend of social rural changes and abandonment of poorly productive soils have led to an increase in afforestation rates on marginal agricultural land in Ecuadorian tropical dry forests over the past decade. Implementation of public regulations provided financial support for afforestation and was partly justified by the goal of restoring ancient forest habitats and their associated biodiversity (Consejo Provincial de Manabí, 2021; Prentice, 1990). Our main goal was to characterize how new forest plantations from 2008 to 2018 have changed habitat fragmentation and connectivity in dry areas of Ecuador. Specifically, we aimed to i) assess land use changes and their effect on fragmentation and connectivity across planted landscapes in comparison to native forests remains, ii) identify consequences of these changes for certain vertebrate species that are quality indicators of Ecuadorian tropical dry forests, and iii) determine whether particular areas of the landscape are important in future plantations in this fragmented system. Based on that, we analyzed the implications of afforestation for conservation in dry tropical areas of Ecuador.

2. MATERIALS AND METHODS

2.1. Study sites

Manabí is located in the center of the coastal region of Ecuador and in the most western part of the South American continent, on the margins of the Pacific Ocean. It maintains an extension of 19,516.6 km², 7.36% of the national surface, positioning it as the fourth province with the largest continental area and the first in agricultural production. The study area covers six cantons (Jipijapa, Paján, Santa Ana, 24 de Mayo, Olmedo and Puerto López) (Gentry, 1986), all located in the southern zone of the province of Manabí (0°45'00"S-80°05'00"W, Fig. 1), and in the biogeographical region of Ecuador Coast. Five types of ecosystems are found in this area: low deciduous forest, deciduous shrub and grassland, deciduous forest, semi-deciduous forest, and seasonal evergreen forest (Ministerio del Ambiente, 2014; Mosandl et al., 2008; Peralvo and Delgado, 2010). Deciduous forests presenting a higher degree of threat, greater fragility and less connectivity, in addition to less protection and research than seasonal evergreen forests (Rivas et al., 2020).

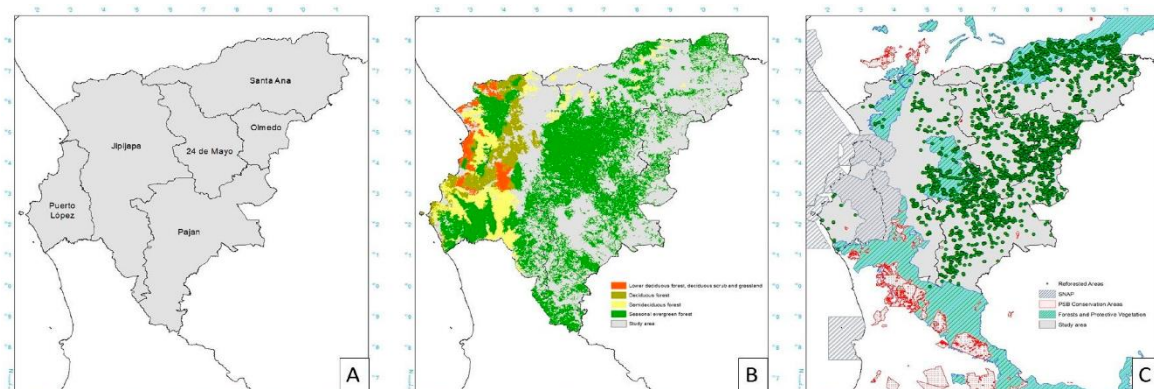


Figura 1. (A) Área de estudio delimitada políticamente en cantones. (B) Ecosistemas en el área de estudio. (C) figuras de protección presentes en el área.

Manabí Region is characterized by high levels of biodiversity (McGarigal, 1995), although large forest areas have been modified from extensive and unsustainable agricultural practices leading to fragmented landscapes with forest patches in the range of 5 and 100 ha (Minor and Urban, 2007). Manabí presents three types of nature protection areas: National Systems of Protected Areas (SNAP), Forests and Protective Vegetation and Programa Socio Bosque (PSB) Conservation Areas. SNAP are in the highest category of protection under national environmental legislation covering 51 nature reserves covering 20% of Ecuador. They are areas of land and/or sea especially

dedicated to the protection and maintenance of biological diversity, also as natural resources and associated cultural. PSB Conservation Areas provide economic incentives to peasants and indigenous communities that voluntarily commit to the conservation and protection of their native forests, moorlands or other native vegetation. Protective forests are natural or planted forests, shrub or herbaceous formations in public or private domain located in areas of rugged topography, in critical watersheds, which are not suitable for agriculture or livestock farming. In Ecuador it has been shown that SNAP prevent deforestation, but not all protection figures are effective (Van Der Hoek, 2017). In addition, in Ecuador there are new approaches since the year 2000, with the incorporation of basic criteria for Sustainable Forest Management and the publication of secondary forest regulations in forest legislation (Ministerial Agreement 125 of the Ministry of Environment and Water of Ecuador), sustainable forest management is a binding provision in Ecuadorian forestry policy. However, after 20 years, it has not yet been possible for forest owners to manage natural forests with a long-term vision, ensuring that they maintain their sustainability (Trelles Jiménez, 2020).

2.2. GIS sources

We downloaded GIS layers to delimit the provinces, land uses, and deforested-forested areas between 2008 and 2018. Administrative division was obtained from the Military Geographic Institute of Ecuador (available at <https://www.geoportaligm.gob.ec/portal/index.php/cartografia-de-libre-acceso-escala-50k/> accessed on 23 February 2023). Land use maps for the years 2008 and 2018 and deforestation layers (2008-2014, 2014-2016, and 2016-2018) were obtained by the Ecuadorian Ministry of the Environment (available at <http://ide.ambiente.gob.ec/mapainteractivo> accessed on 23 February 2023) based on Landsat and ASTER satellite images at a pixel size of 30 m (European Commission. Joint Research Centre. Institute for Environment and Sustainability, 2013; Foltête et al., 2012; Ministerio del Ambiente, 2014) (Table 1). Based on validation fieldwork the Kappa index of these maps was approximately 0.7 (Ministerio del Ambiente, 2014). A single deforestation layer was calculated as a merge of the three periods indicated above. To obtain the geographical location of the reforested areas, we obtained the coordinates and area of all reforested plots from the Department of Environmental Management of the Provincial Government of Manabí, for the period 2008 - 2018. For each set of coordinates, we created individual forest plantations polygons. As the shape of the plantation was not available, we created squared polygons centered at each set of coordinates maintaining

the size of the area reforested reported. The geographic coordinate of the centroid of each forest plantation was used for fragmentation and connectivity analyses.

2.3. Land cover change and fragmentation

To estimate land use changes between 2008 and 2018, we created an intersection matrix taking 2008 (LUSES2008) as the initial year. First, we intersected deforested and reforested layers to identify three different cases of land use change between 2008 and 2018 (only reforested, only deforested and deforested+reforested). Then, this layer was intersected with the LUSES2008 layer and LUSES2018 to identify land use changes. In this analysis, we considered four different groups of land use classes derived from the initial classification: native forests, agriculture land, anthropic zones, water, and other natural terrain (Table 1). To estimate fragmentation metrics, we elaborated four scenarios of land use using the full list of classes (see Table 1): (i) LUSES2008, (ii) LUSES2018, (iii) LUSES2018 + deforestation (the areas deforested between 2008–2018 are added as native forest in LUSES2018) and (iv) LUSES2018 + forested (the areas reforested between 2008–2018 are added as native forest in LUSES2018). Then, three fragmentation metrics were calculated for the native forest class in each scenario: number of patches, average patch size and edge density (de la Sancha et al., 2021).

Table 1. Classification of Land uses classes of Ecuador from Ecuadorian Ministry of the Environment (available at <http://ide.ambiente.gob.ec/mapainteractivo>, accessed on 23 February 2023) based on Landsat and ASTER for the study areas (MAE y MAGAP, 2015) and cost values (resistance values to move through them)

Name	Group	Definition	Cost
Native forest	Native forest	Arboreal ecosystem, primary or secondary, regenerated by natural succession; it is characterized by the presence of trees of different native no dry forest species, varied ages and sizes, with one or more strata.	1
Forest Plantation	Other natural terrain	Anthropically established tree mass with one or more forest species	1
Shrub vegetation	Other natural terrain	Areas with a substantial component of non-tree native woody species. Includes degraded areas in transition to dense canopy coverage and paramo.	2
Herbaceous Vegetation	Other natural terrain	Areas made up of native herbaceous species with spontaneous growth, which do not receive special care, used for sporadic grazing, wildlife or protection purposes.	2
Natural water	Water	Surface and associated volume of static or moving water.	5
Artificial water	Water	Surface and associated volume of static or moving water associated with anthropic activities and the management of water resources.	5
Populated Area	anthropic zones	Areas mainly occupied by homes and buildings intended for communities or public services	10
Infrastructure	anthropic zones	Areas for transport, communication, agro-industrial and social.	10
Area without vegetation cover	Other natural terrain	Areas generally devoid of vegetation, which due to their edaphic, climatic, topographic or anthropic limitations, are not used for agricultural or forestry use, however they may have other uses	2
Agricultural Land	Agricultural Land	Area under agricultural cultivation and planted pastures, or within a rotation between them, includes areas of annual crops, semi-permanent crops, permanent crops, grasslands and agricultural mosaic	5

2.4. Connectivity analysis

We used graph theory to look at structural connectivity. Graph theory is a good way to find conservation targets because it does not need demographic data like most other conservation priority methods (Minor and Urban, 2007). According to Calabrese and Fagan (Calabrese and Fagan, 2004) this approach provides a comprehensive, robust analysis of connectivity with minimal data requirements. Graphad 2.6 software (Scriven et al., 2019) was used to evaluate functional connectivity.

Functional connectivity was calculated for *Puma yagouaroundi* (jaguarondi) as reference species (medium-sized mammal), for the four scenarios indicated in section 2.3 (Giordano, 2016). First, these scenarios were converted to raster layers (30 x 30 m) and each land cover was assigned a cost (Table 1). This cost is an estimated resistance value for the reference species to move through each land-cover type. Native forest areas were considered "habitat" (cost value of 0). Subsequently, links between patches were created accumulating the cost values between patches. Links between patches only occur if the accumulated cost is less than 166 (approximately 5 km of distance with a cost value of 1). This approach allowed to assess the significance of individual planted patches (i.e. nodes in the network) within each regional network (via node-level metrics that can identify which patches facilitate landscape connectivity (Navarro Cerrillo et al., 2019).

In this method, a component is a group of connected nodes. Species can move (link) between patches (nodes) across the same component, but not across different components (Rivas-Torres et al., 2018). We calculated global connectivity metrics (Flux, Equivalent Connectivity, Probability of Connectivity and Number of Components) and metric per patch (Current Flow) (Table 2). Global connectivity metrics show different features, being Probability of connectivity (PC) the most useful (value between 0 and 1) to compare connectivity among ecosystems. Current Flow (CF) is based on circuit theory and analyze the links between patches at landscape scale. These metrics have already shown their usefulness in analyzing connectivity in fragmented landscapes (Jaramillo et al., 2023; Navarro-Cerrillo et al., 2022). Number, distance in cost and distance of the links for the four scenarios were also calculated. Finally, corridors were calculated as the accumulated number of links between patches given the maximum cost distance of 166 (Scriven et al., 2019). Corridors show the area that can be traversed between two patches habitat ie. the area representing the set of possible paths connecting two patches (Scriven et al., 2019). and were used to establish potential areas representing a set of possible "new forested paths" for connecting natural forest areas. The corridor was divided into six

categories: no corridor (0), very low (1-13), low (14-55), medium (56-138), high (139-291) and very high (292-528).

Table 2. Description of connectivity metrics analyzed according to (Foltête et al., 2021).

Metric	Level	Formula	Meaning	References
Flux (F)	Global level and Components level	$S\#F = \sum_{i=1}^n \sum_{j=1, j \neq i}^n a_j^\beta e^{-ad_{ij}}$	Sum of potential dispersion from all patches	(Drummond et al., 2010; Foltête, Clauzel, Vuidel, et al., 2012; Saura & Torné, 2009)
Equivalent Probability (EC)	Global level	$EC = \sqrt{\sum_{i=1}^n \sum_{j=1}^n a_i a_j e^{-ad_{ij}}}$	Square root of the sum of products of capacity of all pairs of patches weighted by their interaction probability	(Saura et al., 2011)
Probability of connectivity (PC)	Global level	$PC = \frac{1}{A^2} \sum_{i=1}^n \sum_{j=1}^n a_i a_j e^{-ad_{ij}}$	Sum of products of capacity of all pairs of patches weighted by their interaction probability, divided by the square of the area of the study zone. This ratio is the equivalent to the probability that two points randomly placed in the study area are connected.	(Saura & Pascual-Hortal, 2007)
Number of Components (NC)	Global level	NC = nc	Number of components of the graph.	(LANDSCAPE CONNECTIVITY: A GRAPH-THEORETIC PERSPECTIVE - Urban - 2001 - Ecology - Wiley Online Library, s. f.; Urban & Keitt, 2001)
Current Flow (CF)	Local Level	$CF_i = \sum_j^n c_i^j$	Sum of currents passing through the patch i. C_i^j represents the current through the patch i when currents are sent from all patches (except j) to the patch j. The patch j is connected to the ground (Girardet et al., 2013).	

Where: N: number of patches, nc: number of components, nk: number of patches in component k, Ni: all patches close to patch i, ai : capacity of patch i (generally the surface area), ack: capacity of component k

(sum of the capacity of the patches composing k), A : area of the study zone, d_{ij} : distance between patches i and j (generally the least-cost distance between them), $e^{-\alpha d_{ij}}$: probability of movement between the patches i and j , α = brake on movement distance, β = exponent to weight with more or less capacity.

3. RESULTS

3.1. Land cover change and fragmentation.

In 2018, the dominant land use in the study area (4791.43 km²) was agriculture (61.91%; Fig. 2). Forest areas decreased from 33.7% to 32.45% between 2008 and 2018 (Figure 2), although other natural land uses, mostly shrubs, increased almost double (from 2.4% to 4.68%). Most of the deforestation affected to native forests during this period, and most of reforested and afforested areas in 2018 covered former agricultural land (Fig. 2).

Fragmentation data showed that 61.48 km² of native forests were lost between 2008 and 2018, decreasing the number of patches and increasing the average size (Table 3). The 2018+forested scenario showed a large increase in the number of patches, but decreasing their average size, and also increased the number of patches compared to 2018, but not compared to 2008, with an average area close to the scenario of 2018 (Table 4). The comparison between the scenarios 2018+forested and 2018+deforestation showed that the area lost due to deforestation is greater than the afforested area (58 km² of difference; Table 4).

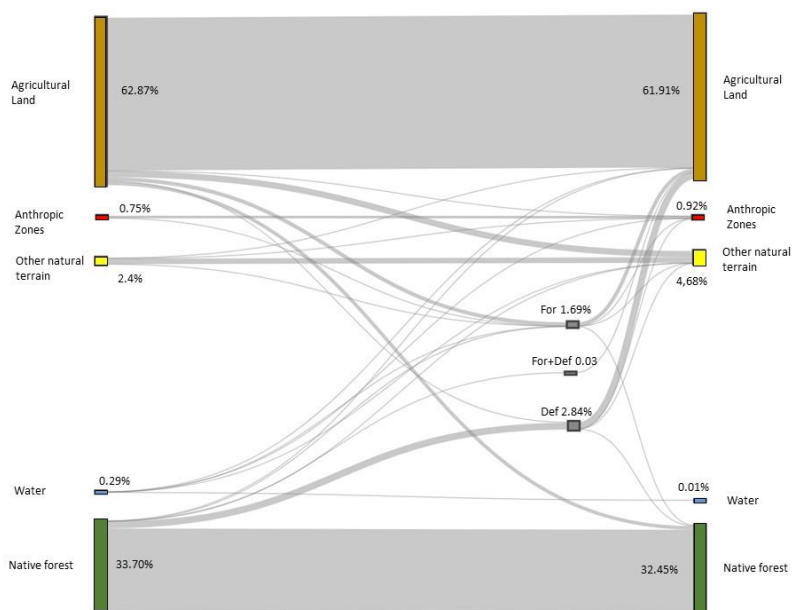


Figure 2. Transition in land uses between 2008 and 2018 in study area (in %).

Fragmentation data showed that 61.48 km² of native forests were lost between 2008 and 2018, decreasing the number of patches and increasing the average size (Table 3). The 2018+forested scenario showed a large increase in the number of patches, but a decrease in their average size, and also increased the number of patches compared to 2018, but not compared to 2008, with an average area close to the scenario of 2018 (Table 3). The comparison between the scenarios 2018+forested and 2018+deforestation showed that the area lost due to deforestation is greater than the afforested area (58 km² of difference; Table 3).

Table 3. Fragmentation metrics for native forest (number of patches, patch area and total edge) in the Manabí province (Ecuador) for Land uses scenarios: 2008 (LUSES2008), 2018 (LUSES2018), 2018 avoiding deforestation (LUSES2018 + def), and 2018 considering reforestation (LUSES2018 + for).

Scenario	Overall area (km ²)	Number of patches	Patch area (km ²)			ED = Patch perimeter / Patch area		
			Average	Median	S.D	Average	Median	S.D
LUSES2008	1614.54	1600	1.01	0.01	23.80	1809.59	77.78	56280.65
LUSES2018	1553.06	1434	1.08	0.05	24.21	215.85	28.21	1895.71
LUSES2018+for	1623.46	3340	0.49	0.02	16.23	109.91	31.17	1245.31
LUSES2018+def	1681.79	1581	1.06	0.02	24.85	1651.67	44.44	56493.51

3.2. Connectivity analysis.

The scenarios with better connectivity were those where forest areas increased (LUSES2018+deforestation and LUSES2018+forested). In this case, reforestation increased connectivity, even though LUSES2018+forested had less area than LUSES2018+deforested, LUSES2018+forested presented better flux and CF (Table 4, Fig. 3).

Table 4. Connectivity metrics across native forest patches (Flux, F; Probability of Connectivity, PC; Number of Components, NC; and Current Flow CF) in the Manabí province (Ecuador) for Land uses scenarios: 2008 (LUSES2008), 2018 (LUSES2018), 2018 avoiding deforestation (LUSES2018 + def), and 2018 with reforestation (LUSES2018 + for).

Metric	Scenario			
	2008	2018	2018 + def	2018 + for
F	4.14 x 10 ¹¹	5.01 x 10 ¹¹	6.08 x 10 ¹¹	1.23 x 10 ¹¹
EC	1.14 x 10 ⁹	1.14 x 10 ⁹	1.25 x 10 ⁹	1.19 x 10 ⁹
PC	0.01383299	0.01384695	0.01669168	0.015178734
NC	57	63	55	55
CF (Average)	3042.34	6346.05	5791.91	64,658.92
CF (patch with higher CF)	206,443.39	281,173	345,865.63	3,353,36140

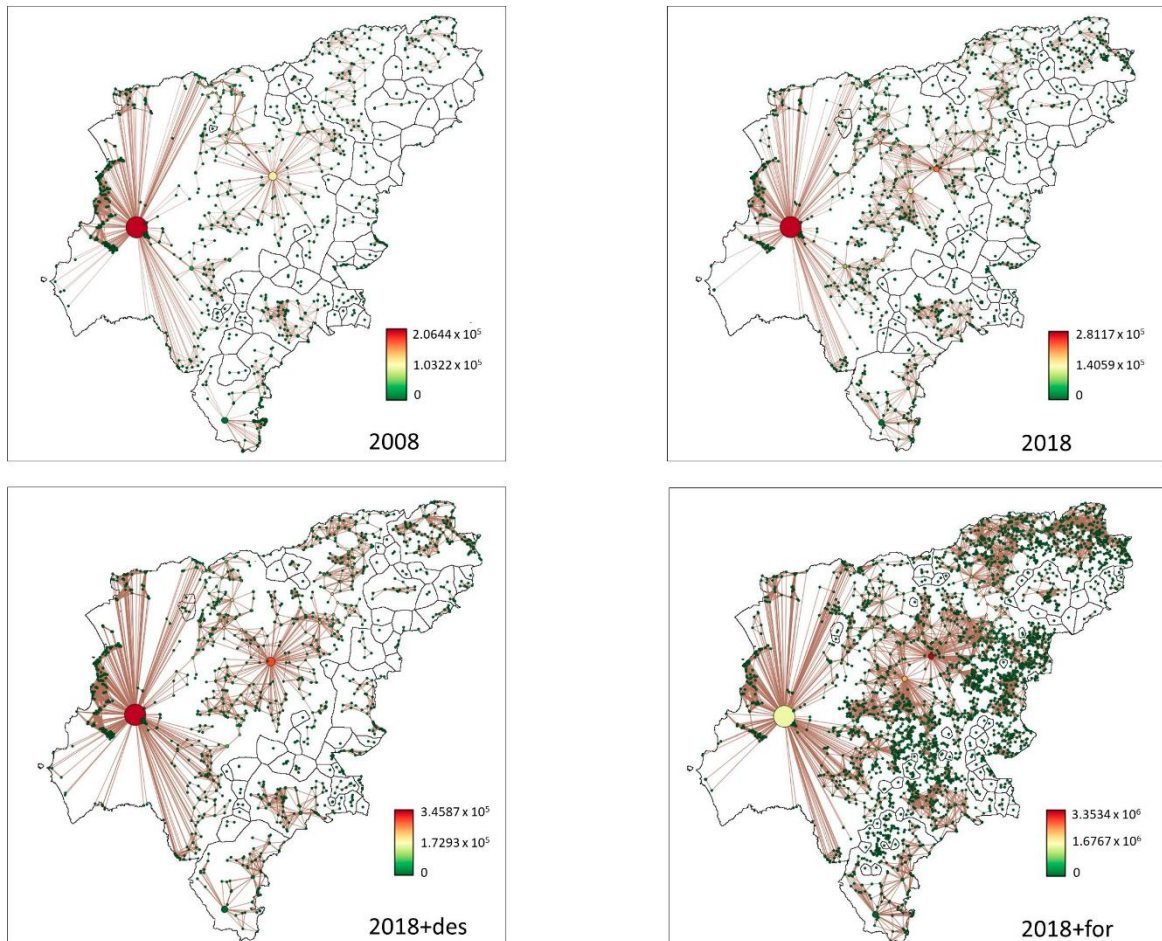


Figure 3. Current flow metric in the Manabí province (Ecuador) for land use scenarios: 2008 (LUSES2008), 2018 (LUSES2018), 2018 avoiding deforestation (LUSES2018 + def), and 2018 considering deforestation and reforestation (LUSES2018 + for). Components (areas outlined in black), connections between the patches (the size of the line indicates the connectivity; greater thickness indicates more connectivity) and connectivity of the patch (color of the circle) are shown. The size of the circle indicates the relative size of each patch.

Links analysis showed that scenarios with increasing forest areas (LUSES2018 + deforested and LUSES2018 + forested) had a higher number of links. LUSES2018 + deforested scenario had a number of links four times greater than that of LUSES2008, (Table 5 and Fig. 4).

Table 5. Number of links, distance in cost and meters of the links generated in the 4 scenarios.

	Number of links	Distance in cost			Distance in meters		
		Average	Median	S.D	Average	Median	S.D
2008	1428	84.10	86.37	49.27	1482.60	1235.95	1152.19
2018	5301	86,27	90.08	50.02	1381.92	1146.40	1096.18
2018+for	18430	96.89	103.34	46.74	1247.94	1026.40	918.51
2018+des	6001	84.83	87.91	49.70	1520.34	1301.54	1170.28

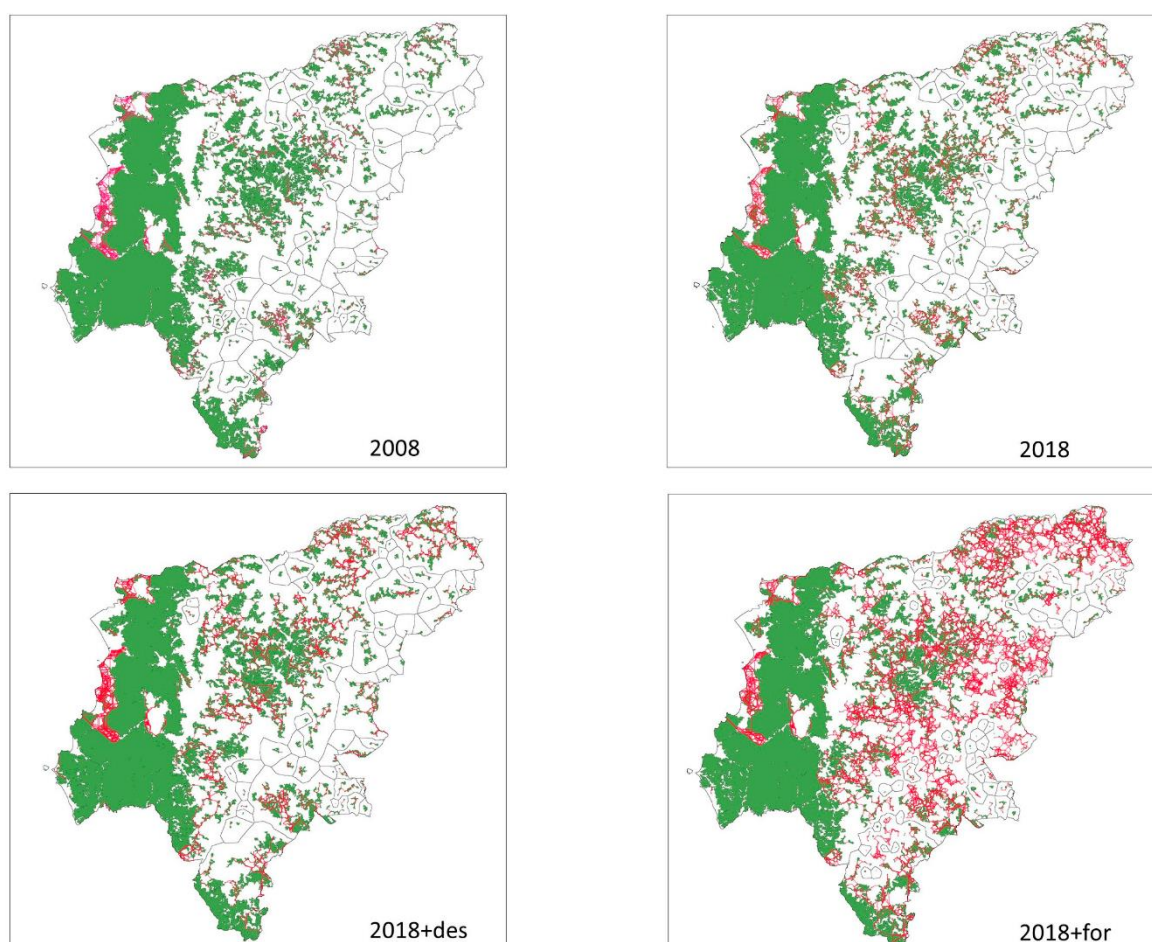


Figure 4. Forest patches (green), links between the patches (red) and components (areas delimited by black lines) in the Manabí province (Ecuador) for Land uses scenarios: 2008 (LUSES2008), 2018 (LUSES2018), 2018 avoiding deforestation (LUSES2018+def), and 2018 avoiding deforestation and reforestation (LUSES2018+for).

When considering only the LUSES2018+deforestation scenario, connectivity increased for the reference vertebrate species in the west part of the Manabí province (Fig. 5). On the other hand, for the reforestation scenario (LUSES2018+forested) the number of links also increased on central and extreme northeast areas (areas where most of the reforestation was done) (Fig. 5).

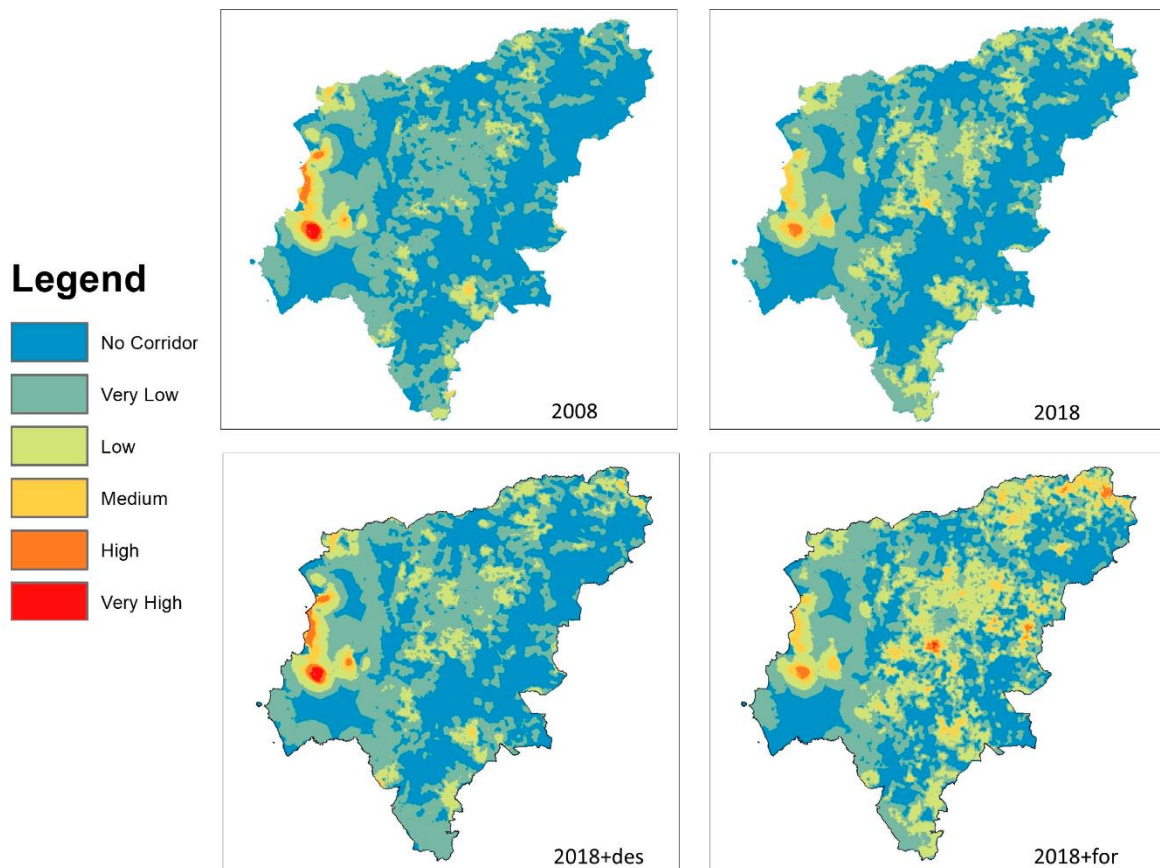


Figure 5. Corridor in the Manabí province (Ecuador) for land use scenarios: 2008 (LUSES2008), 2018 (LUSES2018), 2018 avoiding deforestation (LUSES2018 + def), and 2018 considering reforestation (LUSES2018 + for). Corridors show the area representing the set of possible paths connecting two patches. Corridors were divided into six categories: no corridor (0), very low (1–13), low (14–55), medium (56–138), high (139–291) and very high (>292).

4. DISCUSSION

National reforestation programs are a frequent policy in rural areas of the Tropic to reduce poverty and to increase biodiversity (Holl, 2017). In recent decades, balance between economic growth and ecological preservation has become a pressing issue in Ecuador (Proyecto, s. f.). Thus, forest plantations have been promoted as an essential part of the rural development policy and it is likely that there will be ongoing pressure to establish additional plantations. Our findings suggest that forest plantations increase fragmentation but may contribute to landscape connectivity between habitat patches in dry tropical forests. Forest plantations provide new links between native fragments in both agricultural and forestry landscapes at the cost of increasing fragmentation in terms of edge availability and number of patches. The increase in edge forest habitat might be relevant for generalist species but might limit the suitability of forest patches for species strictly associated with Ecuadorian dry forests.

4.1. Land uses changes and fragmentation

It is generally accepted that land uses changes affect biodiversity levels modifying the dynamics of animal and vegetal populations and their long-term viability (Proyecto, s. f.). Fragmentation relies on the structural complexity of the land uses matrix, modifying the dispersion capability for species in the landscapes. According to our results, reforestation activities resulted in a more compact network with more fragmentation (i.e., increasing number of patches and average patch size decreases). Those effects were more concentrated along areas with native forests remnants. Areas with dominant agricultural uses maintained high values of fragmentation metrics (Pliscoff et al., 2020). Our results are consistent with previous findings, showing that forest plantation expansion may increase native forest habitat but also increased fragmentation (Liu et al., 2019). This contrasting pattern may lead to perceive that the current shift from marginal tropical agricultural lands to plantations will have a negative effect on flora, fauna and some ecosystem services (Edwards et al., 2019). However, the presence of remnants patches of forests, as part of an interdependent forest net, can act as safeguarded areas contributing to landscape arrangement (Martensen et al., 2012). Forest plantations may increase the dispersion availability in fragmented landscapes, with plantations serving as steppingstones. On this case, generalist species can easily move across a landscape because they don't need specific habitat conditions, prefer open spaces or more edges, or have a larger home range or higher dispersion capability than specialist species (Keeley et al., 2021).

Our results also show that forest area in Ecuador is decreasing, and reforestation efforts are not enough to reduce the high rates of deforestation suffered in the country. Ecuador is one of the South American countries with the highest deforestation rate. The coast of Ecuador presents highly fragmented and very little protected ecosystems (Lessmann et al., 2014; Rivas et al., 2020). It is essential to stop deforestation, since if this trend continues, a highly fragmented ecosystem will be formed, with very small patches, harming species that have a high area requirement or forest specialists.

4.2. Connectivity

To provide insights into the interaction of forest plantations within heterogeneous landscapes, numerous studies have examined changes in landscape pattern and connectivity (Tarabon et al., 2021). Landscape connectivity of dominant land uses changed significantly over time in Manabí province (i.e., class types and surface of land uses) as result of forest plantations despite relatively constant dominance of agricultural cover. When we compared connectivity in scenarios considering only deforestation and reforestation, we found that forest plantations contribute to link native forest fragments, which have a middle to high conservation value. Thus, as we initially stated in our hypothesis, forest plantations have contributed to improve connectivity, as well as the preservation of native forest remains (Figure 6).

Threatened species receive priority in conservation planning because, among other factors, their populations are declining due to habitat fragmentation (Martensen et al., 2012). Therefore, maintaining or restoring connectivity between fragmented habitats has been suggested as the key to reduce the negative trends for several endangered species populations. Connected habitats more effectively preserve species and ecological functions. According to our results, we found an increase of connectivity due to the new reforested areas. Despite being small, reforestation can act as stepping stones to connect patches with larger surfaces (Herrera et al., 2017; Siqueira et al., 2021). This information is important because many key species have connectivity requirements. For instance, the jaguarundi (*Puma yagouaroundi*) occupies less human-influenced landscapes and is very sensitive to habitat loss and disturbed areas. As a result, they face a greater risk of extinction (Keeley et al., 2021). Our research revealed that changes in connectivity due to reforestation activities may generate critical landscape connections for jaguarundi. In this instance, the species would benefit from the use of reforestation strategies that preserve or improve landscape connectivity in the study area. Many species have long distance movement in the landscape, but others are less mobile and need “forest islands” to move around and spread out across the land uses matrix (Keeley et al., 2021). Thus, habitat

connections between strictly Protected Areas and the mosaics of forest plantations could contribute to species conservation.

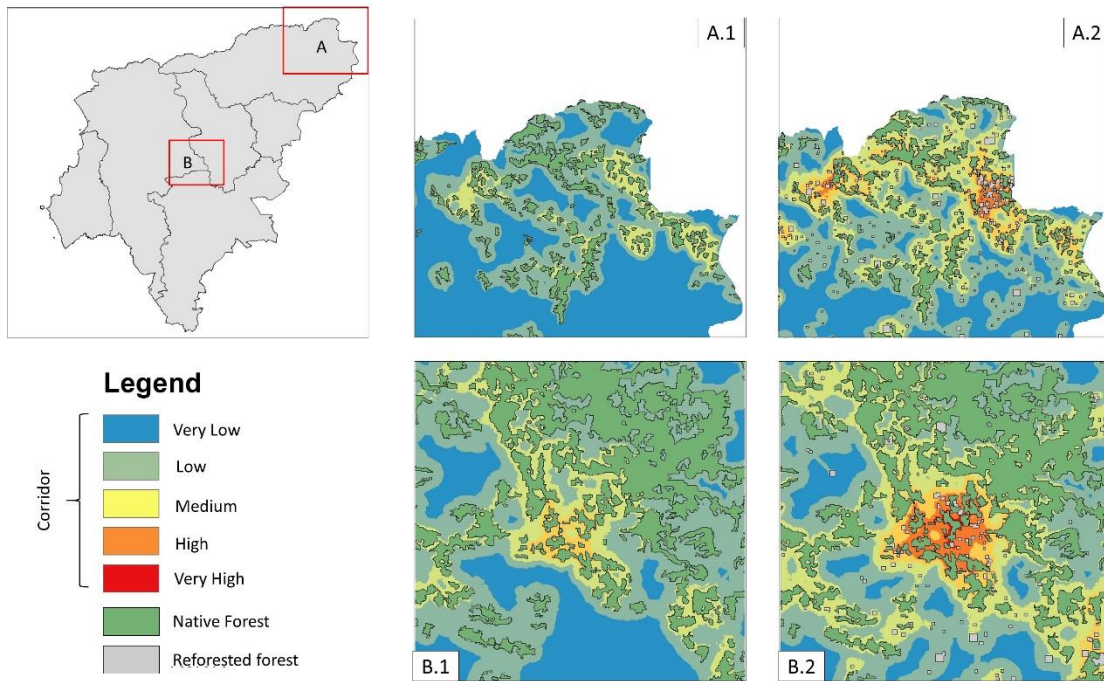


Figure 6. Corridor in the Manabí province (Ecuador) related to native and reforested forests in two locations (North—A and Central—B) and two scenarios (A1,B1) Land use scenarios 2018 (LUSES2018), (A2,B2) Land use scenarios 2018++forested (LUSES2018 + forested). The reforested patches in scenario LUSES2018 + forested are in grey color. The corridor was divided into six categories: no corridor (0), very low (1–13), low (14–55), medium (56–138), high (139–291) and very high (>292).

4.3. Prioritization of forest plantations to improve connectivity.

Forest plantations may contribute to prioritize connectivity and safeguard local threatened species (Tarabon et al., 2021). We presented a network of corridors under the current afforestation program in Ecuador and identified potential corridors that combine various current land uses (Fig.5). Because they have the potential to improve the impact of forest plantations in terms of biodiversity, these findings are relevant to the National Forest Plantation Program. First, native forest fragments have high conservation value, and plantations can improve their connectivity by incorporating spatial structural complexity for specialist species with dispersal ability across the landscape (Keeley et al., 2021). Second, even though technical viability of this multi-species plantation framework

needs to be further evaluated, it provides preliminary evidence of contributing to improve corridor networks ensuring the persistence of species with distinct habitat preferences, sensitivity to native forest replacement, and movement capacity. To avoid clearing of native forests within the potential corridors that could be used in the connectivity network, forest plantation and forest management must include biological corridors as a critical task in their planning (Lessmann et al., 2014). As a result, preservation of landscape elements that make a more significant contribution to landscape connectivity should be a top priority for the sustainable planning of forestry landscapes in Ecuador. By specifying the effects of plantations on the landscape-scale movement of multiple species, the temporal dynamic of natural and planted forestry landscapes must be considered, and focal species should be identified. Also, the socio-ecological framework of forestry of rural communities is not well understood. Therefore, by restoring habitat, forestry could contribute to the improvement of threatened species' population viability connecting the landscape to avoid detrimental effects on animal and plant populations. Promoting sustainable forest plantations may contribute to establishing a link between forest sustainability and conservation biology, as well as the care and protection of endangered and endemic species.

5. CONCLUSIONS

Deforestation has been the primary cause of fragmentation in Ecuador during the last decades. The remnant forest areas are particularly susceptible to additional habitat loss. Our results indicate that reforestation activities since 2008 in the Manabí province has increased fragmentation. However, they have also increased connectivity by linking remanent forest patches. Although there is no in-depth knowledge of species requirements on habitat fragmentation and connectivity, these changes probably contribute positively for species conservation. To address this issue, significant, long-term projects tracking changes in biodiversity and forest cover over time and space are required. We suggest that the new forest plantations patches can be used for native fauna as steppingstones to colonize other native forest areas at the cost of adding higher fragmentation in terms of edge availability and number of patches. It is fundamental to increment forest cover in Ecuador, and to focus on the reduction of drivers promoting deforestation.

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Capítulo 4

Land uses impacts of extensive reforestation programs in Ecuador: lessons for the future.

Impactos en los usos de la tierra de los programas extensivos de reforestación en Ecuador: lecciones para el futuro



“Una nación que destruye su suelo se destruye a sí misma. Los bosques son los pulmones de la tierra, purifican el aire y dan fuerza pura a nuestra gente”

Franklin D. Roosevelt

ABSTRACT

In South America, large-scale restoration projects have been led by the state, starting in the 1980s, when properly designed concepts and methodologies were lacking. Deforestation occurred in Ecuador because of extensive changes in land use brought about by a variety of economic and political developments. This study focuses on the identification of reforestation programs using GIS software, integrating species distribution models including an analytical framework, for decision making. To define priority areas for reforestation. In any case, reforestation programs have not yet been fully analyzed. This study evaluates the new verifiable reforestation process by portraying it through some highlights that help to understand the social, political and financial environment in which the counterfeit timber recovery strategy was created in Ecuador after a while. The study provides because of the great efforts to increase forest cover in recent years, 248,064 hectares of the country's total area have recently been artificially regenerated. Through critical comparisons between cases, we found that the ability of Ecuador's reforestation programs to restore their forests was frequently influenced by external variables such as biophysical conditions, community characteristics, and regulations at the local, regional, and state levels. The illustrations obtained from this study can help to plan far-reaching reforestation strategies and what they could mean for other parts of the South American countries. They can also shed light on the debate on possible strategies to stop deforestation and forest degradation.

Keywords: Afforestation, land-use policy, rural development, tropical countries, deforestation; reforestation; community participation; forestry fund; payment mechanism.

1. INTRODUCTION

Reforestation is a critical component to reduce deforestation all over the planet. From 2000 to 2020, the Food and Agriculture Organization reported that an average of 5.3 3×10^6 ha were reforested annually. The advantage of explicit reforestation projects to restore degraded forest lands, most of which were in mountainous regions, has as primary objective the preservation of ecosystem services like soil stabilization and upkeep hydrologic cycle to maximize the overall benefits of forest land restoration. Consequently, in many countries, it is essential where these ecosystem services are produced to locate the areas that maximize restoration benefits. However, the lack of prioritization of suitable sites for tree plantations has produced main flaws, as managers in charge of reforestation activities frequently lack the necessary expert knowledge (Choi et al., 2019). As a result, managers frequently attempt to achieve their programmatic objectives without carefully considering whether the areas chosen for reforestation are the most appropriate or even a priority.

Ecuador has a land area of 256,370 km² and an estimated 17,096,789 people, and it shares boundaries with Colombia to the north, Peru to the south and east, and the Pacific Ocean to the west. In addition to the land area, Ecuador's territory includes a maritime area of 1'092,140 km³, or 4.3 times the continental territory, including Costa Rica's Cocos Island on the Galapagos Islands' maritime border (Cañadas Cruz, 1983; Jørgensen et al., 2011; Leimbeck et al., 2004; Sierra, 1999; Wolf, 1892). Ecuador has been identified as a center of biodiversity, with majority located within the Tropical Andes biodiversity hotspot, which is regarded as the richest hotspot on the planet (Rieckmann et al., 2011). Ecuador has a unique flora that exhibits a high degree of endemism. Ecuador has one of the highest rates of deforestation reported to date (Tapia-Armijos et al., 2015). However, Ecuador is one of the countries with the highest rate of deforestation in Latin America. The annual rate of change of forest cover in continental Ecuador has been varying over time going from -0.71% for the period 1990 - 2000 and -0.66% for the period 2000 - 2008. This corresponds to an average annual deforestation of 89,944 ha/year and 77,647 ha/year, for each period, respectively, at values as -0.37% for the period 2008-2014 (47,497 ha/year). (2000-2008 108.666 ha, 2008-2014 97.918 ha, 2014-2016 94.353 ha) (In particular, Esmeraldas, Manabí, Morona Santiago, Sucumbíos y Zamora Chinchipe provinces 2008-2014 (Kleemann et al., 2022; Noh et al., 2022).

Deforestation and fragmentation have been shown to have a significant impact on species diversity and richness in the country. According to various authors, the impact of this process on the drastic reduction in national forest area ranges from four to seven

million hectares, or 16 to 28 percent of Ecuador's total forest area (Segovia and Berbey-Álvarez, 2021). Ministry of Environment faces two essential problems: i) the high rate of deforestation remains in the 2000-2008 period of 77,647 ha year⁻¹ despite the improvements compared to the previous decade; and ii) impacts on hydrographic basins that have lost vegetation cover and have suffered soil degradation are reflected in the reduction of water resources in quality and quantity; as well as the increase in the emission of carbon into the atmosphere, the loss of biodiversity, the alteration of the landscape and the increase in vulnerability to climate change (Ministry of the Environment, 2014).

The combination of spatial analysis with multicriteria modeling using Geographical Information Systems (GIS) enables decision-making in reforestation programs under circumstances of high uncertainty and a lack of empirical data (Orsi and Geneletti, 2010a). Multicriteria modeling assists the decision-maker in evaluating value assessments from single or multiple experts to systematically analyze complex problems and identify the decision alternatives, as well as the attributes and their importance (weight) used to evaluate the reforestation performance alternatives. To maximize success and the overall benefit of a reforestation program, these GIS methods combine the attributes and their weights to score the options, making it simpler to select the best one. They can also be connected to tools from operations research (Jaimes et al., 2012).

This study aims to fill in the gaps in our understanding of the following aspects of extensive reforestation process that has taken place in Ecuador: i) extension for reforestation in Ecuador since the end of the 20th century; ii) legal and administrative bodies tasked with carrying out this task; iii) investment in national projects for afforestation and reforestation; iv) tree species used; v) technology and technical infrastructures used; and vi) the structure of forest ownership as a result of extensive afforestation and reforestation. This study's findings have practical implications and add to the body of research on comparing restoration cases from South America nations, which have received little attention.

2. MATERIAL AND METHODS

2.1. Study area

Manabí is located in the center of the coastal region of Ecuador and in the most western part of the South American continent, on the margins of the Pacific Ocean. It has an extension of 19,516.6 km², 7.36% of the national surface, positioning it as the fourth province with the largest continental area and the first in agricultural production. Manabí is distributed in three zones (Gentry, 1986) (north, center and south), and the study covered

six cantons (Jipijapa, Pajan, Santa Ana, 24 de Mayo, Olmedo and Puerto López), all of them located in the southern zone of Manabí ($0^{\circ}45'00''\text{S}$ - $80^{\circ}05'00''\text{W}$, Fig. 1). In the biogeographical region of Ecuador Coast, five types of ecosystems are found in this area: low deciduous forest, deciduous scrub and grassland, deciduous forest, semi-deciduous forest, and seasonal evergreen forest (Ministerio del Ambiente, 2014; Mosandl et al., 2008; Peralvo and Delgado, 2010). Deciduous forests presenting a higher degree of threat, greater fragility, and less connectivity, in addition to less protection and re-search than green forests (Rivas et al., 2020). Manabí Region is characterized by high levels of biodiversity (McGarigal, 1995), although large forest areas are modified from extensive and unsustainable agricultural practices leading to fragmented landscapes with large areas of uncontrolled deforestation and land use change (Minor and Urban, 2007).

Manabi presents three types of protection areas: National Systems of Protected Areas (SNAP), Protection Forests and Programa Socio Bosque (PSB). SNAP covers 51 nature reserves that extend in approximately 20% of the surface of Ecuador oriented to guaranty connectivity of the most important ecosystems. PSB Areas are zones that maintain native vegetation formations that meet the objectives indicated in the agreement established by the socio bosque program. Protective forests include those vegetation covers, natural or cultivated, in public or private domain, which are located in priority watersheds. In Ecuador it has been shown that SNAP prevent deforestation, but not all protection figures are effective (Rivas et al., 2021).

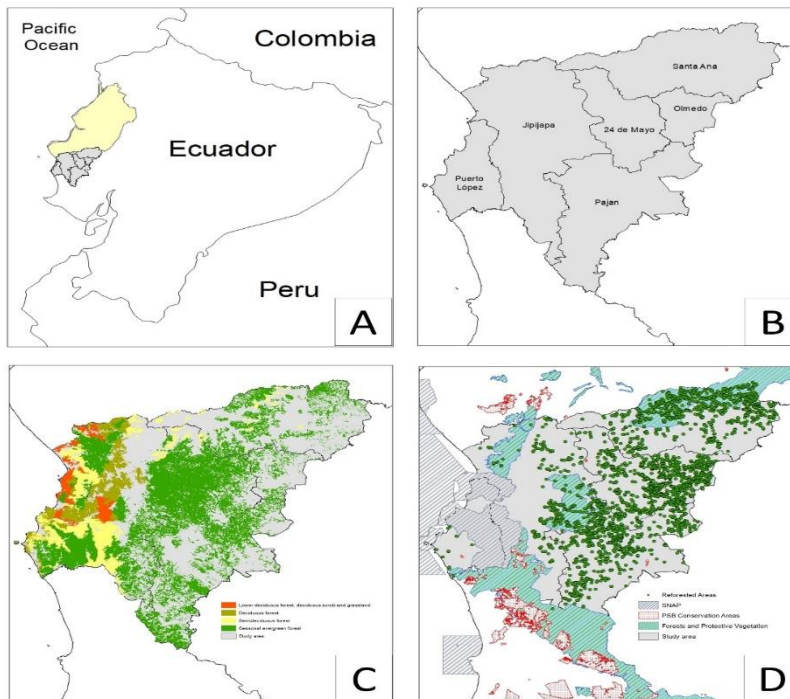


Figure 1. Location and delimitation of the study area

Note. A) Mainland Ecuador with Manabí province in yellow and study area in grey. B) Study area politically delimited in cantons. C) Ecosystems in the study area. D) Protection figures present in the area including the reforested areas (green dots).

2.2. Selection of reforestation programs

Two reforestation programs were chosen to compare: 1) Programa Nacional de Restauración Forestal con Fines de Conservación Ambiental, Protección de Cuencas y Beneficios Alternos (2017); and 2) Proyecto Socio Bosque (2019). These initiatives, along with incentive-based programs intended to decrease native forest loss while increasing forest cover, were crucial to the restoration of the forest. The two programs had the same complementary goals of reducing poverty and promoting rural development, involved government-led restoration programs, and were characterized by strong state authority during their implementation. We used two distinct sources of empirical data used: i) legal documents like laws, agency policy reports; and ii) publications in scientific journals and international organizations. Although reforestation policy of Ecuador did not exactly meet the definition of a payment mechanism, this study considered it to be one after reviewing the main forest restoration strategies that were implemented with various incentive programs (including cash and in-kind payments).

2.3. GIS sources

We downloaded GIS layers to delimit the provinces, land uses, and deforested-forested areas between 2008 and 2018. Administrative division was obtained from of the Military Geographic Institute of Ecuador (available at <https://www.geoportaligm.gob.ec/portal/index.php/cartografia-de-libre-acceso-escala-50k/>) and six cantons (Jipijapa, Pajan, Santa Ana, 24 de Mayo, Olmedo and Puerto López). Land uses 2018 were obtained by the Ecuadorian Ministry of the Environment (available at <http://ide.ambiente.gob.ec/mapainteractivo>) based on Landsat and ASTER satellite images at a pixel size of 30 m (European Commission. Joint Research Centre. Institute for Environment and Sustainability., 2013; Foltête et al., 2012; Ministerio del Ambiente, 2014) (Table 1). Kappa index of this maps was approximately 0.7 (Rivas et al., 2020). To obtain the geographical location of the reforested areas, we obtained the coordinates and surface of all reforested plots from the Department of Environmental Management of the Provincial Government of Manabí, for the period 2008 - 2018. The actual limits of reforested plots are not available, thus, for each set of coordinates, we created an individual forest plantations polygon with square shape and the size of the area reforested.

Once the study area was delimited, a hexagonal grid of 50 ha per hexagon was drawn up. Subsequently, the land use layers of the year 2018 were used to select the land uses that were considered to be suitable for reforestation and intercepted with the hexagons. The land uses considered for reforestation are: Agricultural, scrub, grassland, and areas without vegetation cover (Fig 2).

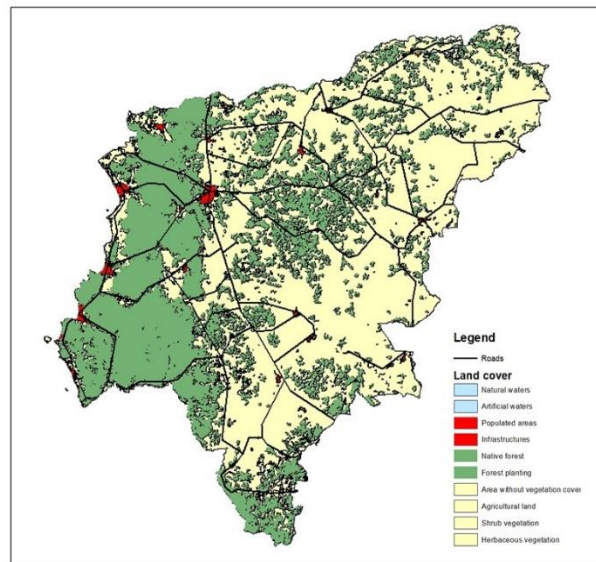


Figure 6. Lands cover and roads in the study area

Note. Adapted and developed in 2023.

The hexagons grid was created with the potential reforestation zones, this layer was intercepted with the following layers: natural areas, priority areas for restoration, connectivity, population density, rare species, roads, populated areas, and infrastructure. Subsequently, each hexagon was given a value according to the intercepted layer, in the case of roads and populated areas and infrastructure, a buffer was made at 250 m and 500 m and the values were negative, as these areas are considered the worst zones for reforestation (Table 1).

The connectivity layer was created using the Graphab 2.6 program. This program is designed to calculate Ecological connectivity using Graph theory. It uses the native forest areas of the 2018 land use layer as possible habitat, and we calculated the connectivity of adding forest patches in the possible reforestation areas. We calculated 298153 possible forest patches (one every 100 meters). The metric used was Connectivity metrics (Flux, F; Probability of Connectivity, PC; Number of Components, NC; and Current Flow CF) in the Manabí province (Ecuador) for Land uses scenarios: 2008 (LUSES2008), 2018 (LUSES2018), 2018 avoiding deforestation (LUSES2018+def), and 2018 avoiding deforestation and reforestation (LUSES2018+ref) EC. These were then intercepted with the hexagon matrix and each hexagon was given the highest connectivity value. Areas with attributes considered beneficial for reforestation received positive values, those considered detrimental received negative values. The layers comprised values between 1 and 5 and all had the same weight. This was done because all the

factors analyses were considered to be of equal importance; Ecological (connectivity and rare occurrence), social (population density), political (protected areas and priority areas for reforestation) and development (roads and populated areas and infrastructure) values were considered (Table 1). Finally, all hexagon values were summed, and a reforestation suitability layer was created.

2.4. Analytical Framework

The analytical framework included the contextual factors (physical conditions, and socioeconomic rules-in-use), as well as the actors and action included in the reforestation programs (Table 1), (Le et al., 2012). This study focused on previous research and Chapters (Chapter 2 and 3) relevant variables. Deforestation, fragmentation, and connectivity patterns were used to define regulatory frameworks. According to its general characteristics, as well as its payment and design characteristics, the following seven variables were examined (Baynes et al., 2015; Le et al., 2014): i) protected areas, ii) restoration priority areas, iii) population density (2008), iv) presence on vulnerable species, v) proximity Urban areas-infrastructure, vi) roads; and vii) connectivity (Table 1).

Table 1. Suitability, value, classification and source data used.

Layer	Protected Areas	
Type	Value	Source: http://ide.ambiente.gob.ec/mapainteractivo/
National Park	5	
Protected Forest	3	<i>Elaborated by: Ministerio del ambiente de Ecuador</i>
Areas under other conservation figures	1	
Non-protected	0	
Restauracion Priority Areas		
Very high	5	<i>Source:http://ide.ambiente.gob.ec/mapainteractivo/</i>
High	4	
Median	3	<i>Elaborated by: Ministerio del ambiente de Ecuador</i>
Low	2	
Non-clasified	0	
Population density (2008)		
Very high	1	<i>Source: https://www.geoportalmg.gob.ec/</i>
High	2	
Median	3	<i>Elaborated by: Instituto geográfico Militar de Ecuador</i>
Low	4	
Non-clasified	5	
Presence on vulnerable species		
Presence	5	<i>Source: (Dinerstein, E; et al., 2020)</i>

Non-presence	0		
Proximity Urban areas-infrastructures			
Buffer 250 m	-5	<i>Source: http://ide.ambiente.gob.ec/mapainteractivo/</i>	
Buffer 500 m	-2.5	<i>Elaborated by: Ministerio del ambiente de Ecuador</i>	
Roads			
Buffer 250 m	-5	<i>Source: https://www.geoportaligm.gob.ec/</i>	
Buffer 500 m	-2.5	<i>Elaborated by: Instituto geográfico Militar de Ecuador</i>	
Connectivity			
	<i>Classification</i>		<i>EC</i>
Very low	0-20%	1	0,01595613428- 0.01600243573
Low	20-40%	2	0.01600243573-0.01604873718
Medium	40-60%	3	0.01604873718-0.01609503862
High	60-80%	4	0.01609503862-0.01614134007
Very high	80-100%	5	0.01614134007- 0.01618764151

Note. Layers used to create the suitability layer, the value, the classification, the source and the elaboration of the layers used are noted. Adapted, 2023.

2.5. Priority areas for reforestation

To define the priority areas for reforestation (Cruz-Bello and Sotelo-Ruiz, 2013), we integrated a GIS analysis of reforestation-related layers (e.g., land use/land cover, position in the watershed, soil type, species habitat potential, previous forest plantations, fragmentation and connectivity, and poverty). For identifying high-priority reforestation areas, the layers were ranked on an ordinal scale based on their relative importance for reforestation. Following the advice of (Domingues et al., 2020), redundant, unnecessary, or nonoperational attributes were removed (Orsi and Geneletti, 2010) To determine the weight of each of these variables, the maximum weight (Table 1) was assigned to each attribute in accordance with the positive impact on reforestation, whereas the minimum value was assigned to the attribute with the least positive impact on reforestation.

Two analyses were made, i) with all the attributes in table 1, ii) with all the attributes in table 1 minus the areas classified as priority areas for reforestation by the ministry. This allowed us to do our own analysis and compare and contrast it with the areas already reforested, and to compare our classification of priority areas with the ministry's areas. Attribute rating was integrated in a geographic information system using a direct rating approach (Valiris et al., 2005) (into a standardized scale in terms of priority for reforestation and aggregated through a geometric mean (Lai et al., 2002) and normalized (Shepetukha and Olson, 2001). For each attribute, a vector o point map layer was generated using real data (Table 1). We used a spatial resolution on which each pixel

of 50 ha represented a unit of analysis. All the spatial analyses were performed with ArcGisPro 10.0.

The priority for reforestation in each pixel was calculated by a weighted linear combination (Malczewski, 1999).

$$y = \sum_{i=1}^n x_i b_i,$$

where y is the priority for reforestation, xi is the standardized value of attribute i for each pixel, and bi is the weight of attribute i. The continuous scores of priorities for reforestation resulting from the multiattribute technique were transformed to five ordinal categories: very low, low, moderate, high, and very high. Five categories were deemed appropriate for conveying meaningful geospatial information (Cowan, 2001).

3. RESULTS

3.1. Reforested area

Between 1985 and 2014, there is a record of a total of 248,064 hectares reforested in the country, of which 43% correspond to the execution of the Ministry of Agriculture in its three projects Forest Plan; BID 808 and Proforestal Project; the United Nations Organization for the Agriculture and Food (FAO) contributed with 11%; the Forestry Face Program of the Ecuador S.A.” (PROFAFOR) with 9%; the Ministry of the Environment with 34% and the Secretariat of the Water with 3%. In 2011, the Ministry of the Environment began reforestation activities for the protection and conservation of degraded areas without vegetation cover, establishing 10,055 ha nationwide in that year, 12,065 ha during 2012. Considering that the current Restoration offer is non-existent, the Ministry of the Environment through the National Reforestation Program since 2019 has set an accumulated goal of restoration in 3 years of at least 30,000 hectares:

3.2. Land availability for the purpose of reforestation

To make viable the execution of forest restoration for the purposes of conservation, USD. 80,822,000.00 were transferred directly to MAE for the National Reforestation Program (NRP) for an amount of with a goal of 500,000 hectares. On this context, NRP subscribed 332 agreements in the years 2014 and 2015, of which 303 were subscribed with the Provincial and Municipal authorities (GAD) and 29 were private individual agreements (natural persons). Of the agreements signed directly between MAE with Natural Persons and GAD, there was an execution from the year 2014 to 2018 of USD. 49,888,571.98 of a prioritized amount of USD.67.219.956, 06; representing 74.22%.

It should be noted that the lack of budgetary resources affected the disbursements to the GADs, according to the form of payment stipulated in the agreements, with a term of 3 years, which affected compliance with the proposed goal of the hectares.

Additionally, since 2018, the NRP had the contribution of GCF Cooperation Funds administered by the United Nations Development Program (UNDP) through the "Comprehensive Amazon Forest Conservation and Production Program Sustainable" who oversaw making payments to the Municipalities of the Southwest of the Province of Loja "Dry Forest". This program was oriented to the management of the ecosystem restoration as a mechanism of adaptation, mitigation, and local resilience against global climatic changes in the Bosque Seco biosphere reserve with an amount of USD 51,103.39.

3.3. Geographic location and territorial impact

Given the high cost of implementing restoration projects, NRP targeted the incentives in areas with higher probability of reforestation success and significant impacts on degraded ecosystems. In this sense, NRP defined priority locations to carry out restoration projects, (Fig. 3) in rural population that lives in deforested areas that should be restored. The NRP benefited 946,664 people in 2018 and 1,106,746 people in 2021. The unsatisfied demand (Table 2) was 557,576.98 ha (2018); because it the requested budget was able to cover 30,000 hectares under actions of restoration (Table 2).

3.4. Species used in reforestation

The reforestation programs in Equatorial dry forest have focused mainly in three native tree species: *Triplaris cumingiana* Fisch & C.A. Mey. ex. C.A. Mey., *Prosopis juliflora* (Sw.) DC and *Cordia alliodora* (Ruiz & Pav.) Oken.

Table 2. Species used in reforestation

Especie	Cantones						Total
	24 De Mayo	Jipijapa	Olmedo	Pajan	Puerto Lopez	Santa Ana	
Aguacate		150,64					150,64
Algarrobo		3170,03		651,89	342,78		4164,7
Amarillo						103,44	103,44
Balsa	26244,12	11158,41	29740,06	46235,64		61283,42	174661,65
Cacao	310,32	802,78	3057,78	424,81		2892,59	7488,28
Caimito		51,72					51,72
Caoba		523,53		1838,08	81,22	671,95	3114,78
Cedrela	299,87	6498,1	304,59	2562,3	1147,04	207,87	11019,77
Cedro		83,15					83,15
Chisparo		51,72		51,72			103,44
Eucalipto		51,72					51,72
Fernan Sanchez	1344,72						1344,72
Guaba		57,48				157,05	214,53
Guachapeli	51,72	2789,72	1447,19	1356,39		2994,79	8639,81
Guanabana			191,78			442,96	634,74
Guayacan		224,6	51,72	255,25	249,54		781,11
Laurel	1499,88	51,72	51,72				1603,32
Leucaena			87,73				87,73
Limón						540,95	540,95
Mandarina		51,72					51,72
Mango				51,72			51,72
Melina						161,4	161,4
Moringa				51,72			51,72
Naranja		1499,88	103,44	471,24		483,79	2558,35
Pachaco		137,98		363,5		5854,41	6355,89
Pechiche			51,72		83,9		135,62
Roble	1189,56		142,41	89,68			1421,65
Saman				845,12		146,33	991,45
Tamarindo	155,16	248,74		63,17			467,07
Teca	2725,73	187,98	3753,62	2999,47		3058,91	12725,71
Toronja						128,52	128,52

Note. Area in hectares of timber and fruit tree species reforested and afforested according to the distribution in cantons of the province of Manabi.

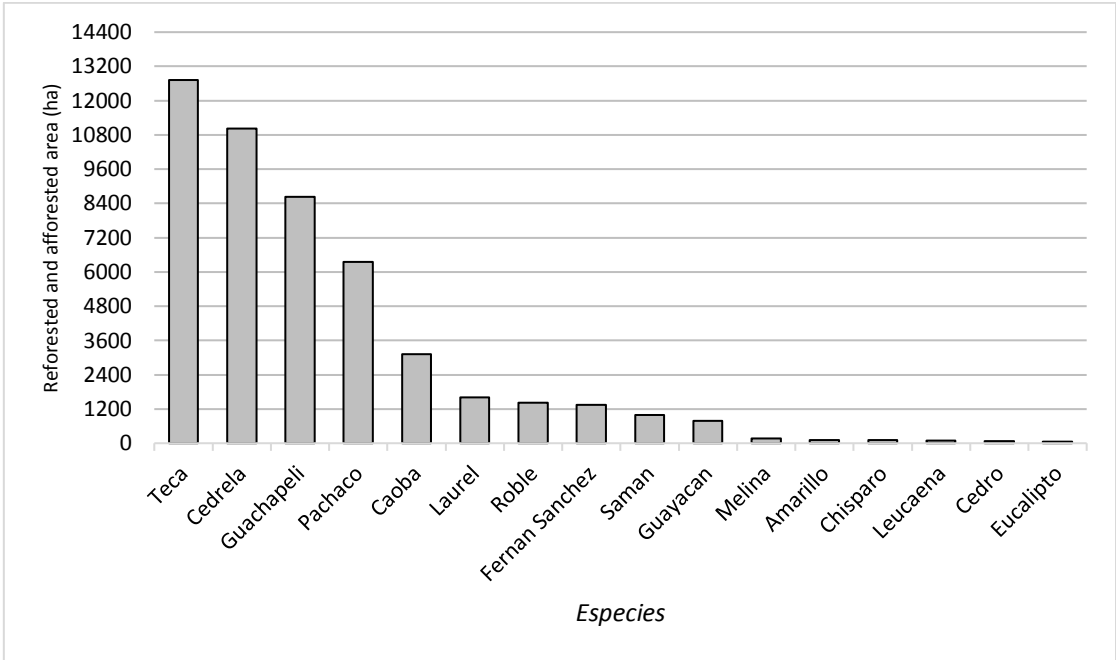


Figure 7. reforested and afforested tree species

Note. Accumulated reforested and afforested area in Manabí province.

3.5. Priority areas for reforestation

Seven attributes were identified for determining high-priority areas for reforestation: i) protected areas, ii) restoration priority areas, iii) population density (2008), iv) presence on vulnerable species, v) proximity Urban areas-infrastructures, vi) roads; and vii) connectivity (Table 1, Fig. S2-S5 Supplementary Material).

According to the multiattribute model, reforestation suitability layer shows that more reforestation effort was established in unsuitable areas (very low and low, 38.56%) or medium suitability (38.68%), in contrast with suitable areas (high and very high, 22.76%) (Figure 4, Table 3). This result supports the use of the optimization model to select the areas that maximize the benefit of reforestation.

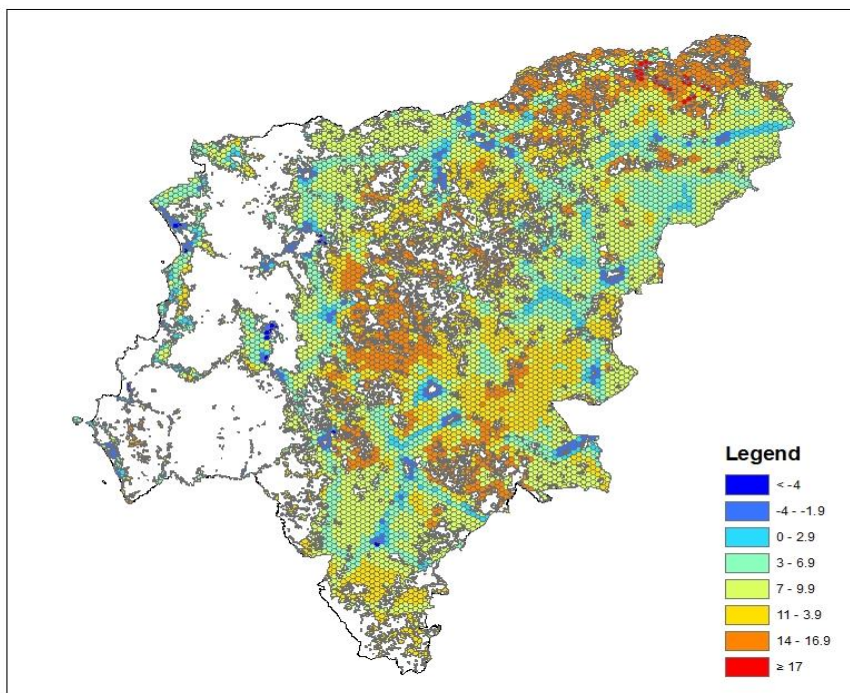


Figure 8. Priority areas for reforestation

Note. Reforestation priority areas identified through spatial multiattribute analysis in Manabí Region (Ecuador).

Table 3. Priority areas for reforestation in Manabí Region (Ecuador)

	Very Low	Low	Medium	High	Very high
Range	<0	0-4.9	5-10.9	11-15	<15
Hectares	863.78	1763.57	2635.18	1281.43	269.64
%	12.68	25.88	38.68	18.81	3.96

Note. Adapted the Ministry of Environmental, Ecuador. 2020.

The suitability map generated without considering the restoration areas show that the average value of the hexagons decreased, causing a generalized decrease in reforestation potential values (Fig. 5, Table 4). Negative values are more present, with roads and populated areas being more important.

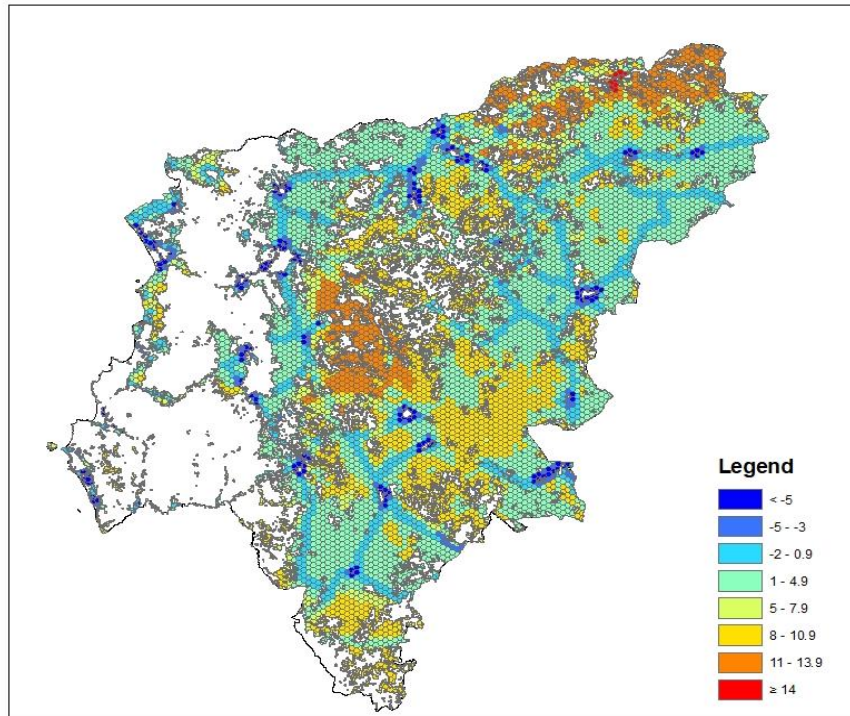


Figure 9. decrease in reforestation potential values

Note. Reforestation priority areas identified through spatial multiattribute analysis in Manabí Region (Ecuador) without considering governmental priority the restoration areas.

Table 2. Reforestation priority areas identified through spatial multiattribute

Value	<-2	-2 - 3	3.1 - 8.9	9 - 12.9	<13	
Range	Very low	Low	Medium	High	Very high	Overall
Low	0.50	12.79	6.88	1.01	0.00	21.18
Medium	1.43	12.51	10.61	2.33	0.01	26.89
High	1.29	19.08	20.94	7.74	0.02	49.07
Very high	0.12	0.99	1.37	0.22	0.00	2.71
Overall	3.34	45.36	39.81	11.31	0.03	100

Note. Reforestation priority areas identified through spatial multiattribute analysis in Manabí Region (Ecuador) without considering governmental priority the restoration areas. Adapted 2022.

4. DISCUSSION

On this chapter we review the implementation of the National Reforestation Plan of Ecuador and systematically identifying priority areas for upcoming reforestation efforts through the use of a decision support system that combines multiattribute decision-making, spatial analysis, and optimization. These approaches have been described and examined in other countries by using analytical (Ordóñez Galán et al., 2009), or GIS-based approaches (Kim et al., 2012). Even though those studies are connected to this research, the integration of species distribution model and fragmentation-connectivity data is novel in determining which sites should get priority for tree restocking. In essence, our method demonstrated the steps necessary to select the areas in a systematic manner by including the analysis of areas that have already been planted in previous actions, the analysis can be extended for a long-term program. Notwithstanding, this drawn-out program at a provincial scale represents a test for National Reforestation Programs.

4.1. Success of National Reforestation Plan of Ecuador

Lewis (2005) defines ecological restoration as the process of assisting a degraded, damaged, or destroyed ecosystem's recovery. The goal of this process is to replicate the structure, functionality, diversity, and dynamics of the specified ecosystem by using reference ecosystems as models. The three main goals of National Reforestation Programs are: 1) to develop new sustainable ecosystems with both human and ecological value, 2) the cost-effective realization, and 3) to evaluate the extent to which restoration goals are met. These programs are designed to create and restore sustainable ecosystems that are valuable to both humans and nature. These objectives were only partially met by Ecuador's NRP, and little progress was made in restoring forest ecosystems during the study period.

Ecuador has carried out several NRP between 1986 to 2020. The primary objectives of this project were to increase forest area, forest stock, and forest carbon sink ability, as well as to further improve the lives of people who live in forest areas. Certainly, the lessons learned from the first phase of the project should be taken into consideration to avoid repeating them. The NRP of Ecuador has made significant progress in some regions covering between 1985 and 2014 a total area of 248,064 hectares reforested in the country, of which 43% correspond to the execution of the Ministry of Agriculture in its three projects with an invested nearly 80 million US dollars by the end of 2014. Large marginal agricultural areas were used for the purpose of forest regeneration, contributing to forests harvest reductions, resource protection, and the entire area covered by the NRP

has seen a significant improvement in ecological conditions, with obvious mitigation of soil erosion (Bare & Ashton, 2016). Forest employees have been transferred to afforestation and other activities related to forest management. According to Stokes et al. (2019), NRP reduce timber harvests from natural (or mixed) forests and increase forest cover.

At the national level, inappropriate species selection is common. Although native species have been used first, and even though the central and local government have tried to promote the use of these species, some wood species, for example, especies nativas *Triplaris cumingiana*, *Prosopis juliflora* y *Cordia alliodora*, may not be the best option for conserving soil on steep terrain, and erosion rates may increase because understory vegetation is frequently damaged or unable to grow in shade (Genet et al., 2008).

The NRP still faces a number of difficult obstacles despite these accomplishments. These difficulties remember weighty dependence for state finance, the absence of between organization participation, the inadequate thought of nearby interests, the disregard of proper practices, and the inflexibility and irregularity of specific arrangement measures (Sanchez, 2015). Some national and international assessment are concerned that the NRP of Ecuador appears to be working, but it is important to be careful when interpreting the progress described above in locations where exotic timber or not suitable species have been planted in place of natural forest (Lazos-Chavero et al., 2016; von Kleist et al., 2021). The NRP-Ecuador encourages afforestation at any cost, encouraging the transition from abandoned or marginal natural vegetation to man-made forests as a rapid landscape restoration (Romo Lozano, 2021; Vadell et al., 2016).

4.2. Analysis to Identify Reforestation Priority Areas

In previous studies, a heuristic strategy based on GIS have been used for spatial multiattribute analysis and optimization to identify reforestation priority areas. The benefit of utilizing such methodologies is that although they don't give an ideal arrangement, they can address different spatial scenarios giving options to achieve reforestation goals. For instance, (Espelta et al., 2003) utilized these methods to evaluate the advantages of different strategies for reforestation, considering the performance of the plantation, financial cost, and effects on the environment.

To determine spatial-explicit priority areas for reforestation, the decision support system used in this study took environmental and social factors into account. This support system also aided in understanding why some regions were better suited for reforestation than others and the essential ecosystem services that newly planted forests provide.

There are two sets of the variables used in this study: 1) characteristics that estimate the environmental potential of a site for reforestation (e.g., presence on vulnerable species, and connectivity, and 2) socioeconomic characteristics that favor the success of reforestation (e.g., protected areas, restoration priority areas, population density, proximity Urban areas-infrastructure, and roads. The first set accounted essential environmental factors to identify priority areas for reforestation. There is a lack of studies using connectivity and species vulnerability for planning reforestation success (Günter et al., 2009), though the significance of this role may vary by tree species. Connectivity, as a crucial criterion when choosing priority reforestation areas. Socioeconomic features have been mentioned as factors that determine a propensity for forest degradation and its cumulative effects (Adams et al., 2016). Thus, if the aim is to achieve tree planting success, their inclusion in the multiattribute analysis as some of the most crucial attributes was obvious. Gkaraveli et al. (2004a) used the ecological criterion "retain existing woods" to identify priority areas for native woodland expansion and restoration, concur that forests are the most significant category of land use attribute. It also relates to what Geneletti (2004) refers to as 'Effortlessness,' the idea that woodland lands have a higher standard of protection than other types of land. Additionally, Nagendra (2007) mentioned that population density in relation to land tenure was a key element in forest management activities, including reforestation. The willingness of landowners to allow tree planting on their property is one of the main obstacles to reforestation, according to socioeconomic criteria used in the analysis (Gkaraveli et al., 2004).

Based on their priority and the available budget, decision-makers can use the method described here to determine which areas should be reforested annually. We discovered that the area with the highest priority for reforestation was not located in the most suitable (only 22.76%). This suggests that reforestation have been established out of the suitable woodland areas. Since in Ecuador most of the land is not under public control, deciding which regions will be replanted ultimately requires complex discussion with the landowners. However, by using this methodical approach, the decision-makers could start the negotiation before the start of each new reforestation season. Additionally, as suggested by Southworth and Nagendra (2010), this study produced data on the elements that can help promote a reforestation program with the best outcomes, the factors that might make some areas more successful for reforestation than others, and the benefits that might result from reforestation of the chosen areas.

4.3. CONCLUSIONS

A variety of factors, including human-caused disturbances, logging, and climate change, among other, have shaped Ecuador's forest dynamics. Between 1975 and 2020, Ecuador had one of the highest deforestation rates of the world, contributing to forest ecosystem's fragmentation and degradation. The traditional timber harvesting orientation of the forest management strategy has shifted to promoting forest conservation after the NRP was implemented in 1986. Globally, NRP has been positive for forest ecosystem restoration, and the pattern of forest landscape suggested that the forest ecosystem's composition and structure had been significantly restores. However, NRP of Ecuador involves many things, not just technical issues but also social, economic, and even political ones. It is challenging to achieve optimal or perfect status for all these factors. Reforestation priority areas and plantation failures can be improved through technical correction, compromise, and the pursuit of a win-win arrangement among the stakeholders. However, additional parameters related to restoration of forest ecosystem must be addressed, but they are crucial and should be discussed in subsequent work.

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SUPPLEMENTARY MATERIAL 2

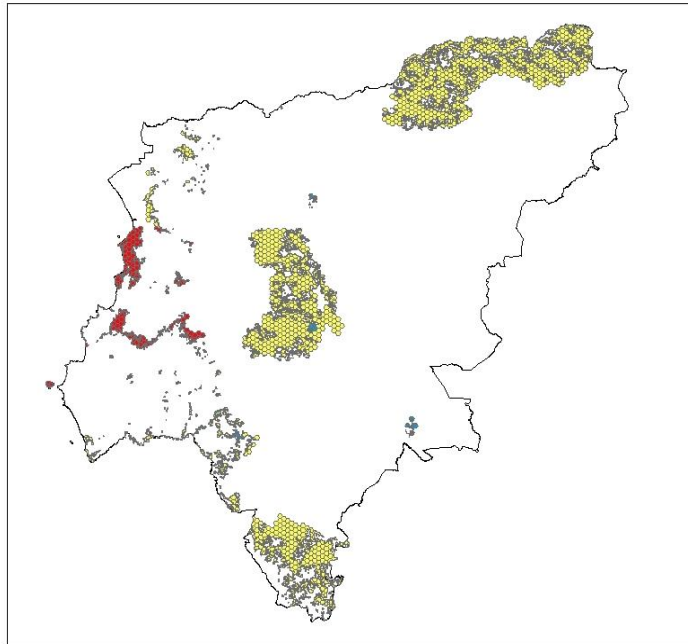


Figure S2.- Hexagons intersected with natural areas, in red national parks, in yellow protective forest and in blue areas under other conservation figures.

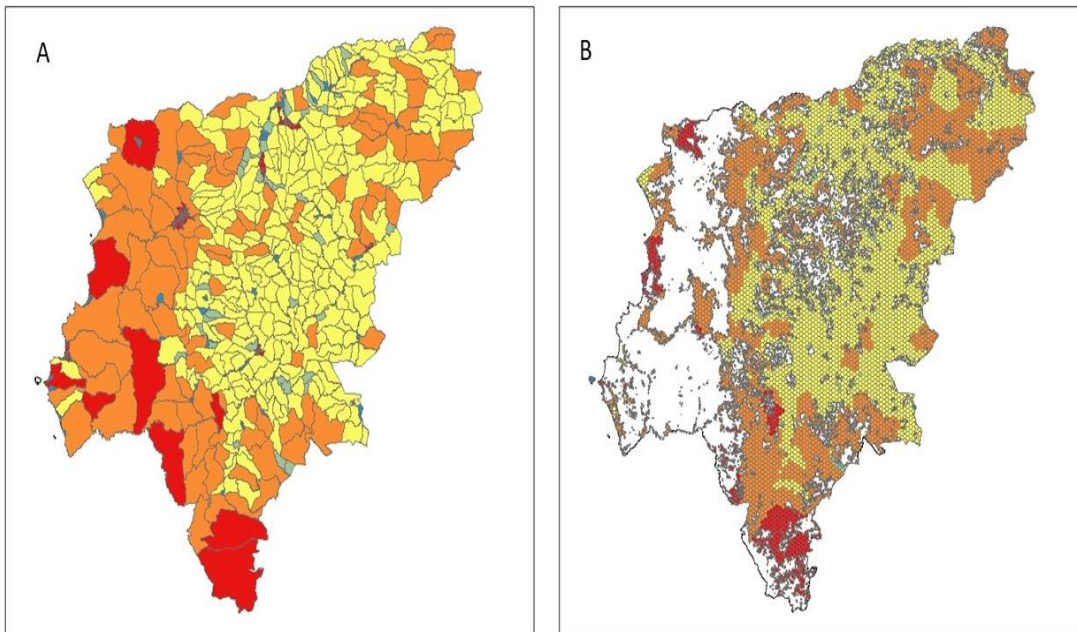


Figure S3.- A) Population density B) and hexagons classification of study area (right). Warmer colors indicate high reforestation interest values and low population densities

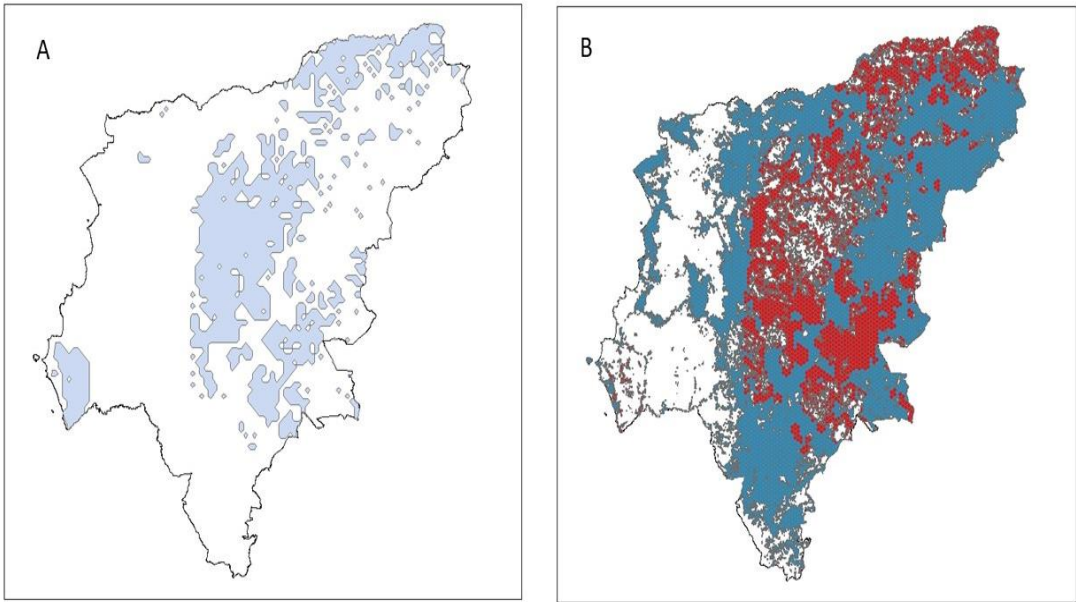


Figure S4.- A) Vulnerable species presence B) hexagons classification of study area . Warmer colors indicate higher values. Dinerstein et al. 2020. A “Global Safety Net” to reverse biodiversity loss and stabilize Earth’s climate. ScienceAdvance. DOI: 10.1126/sciadv.abb2824.

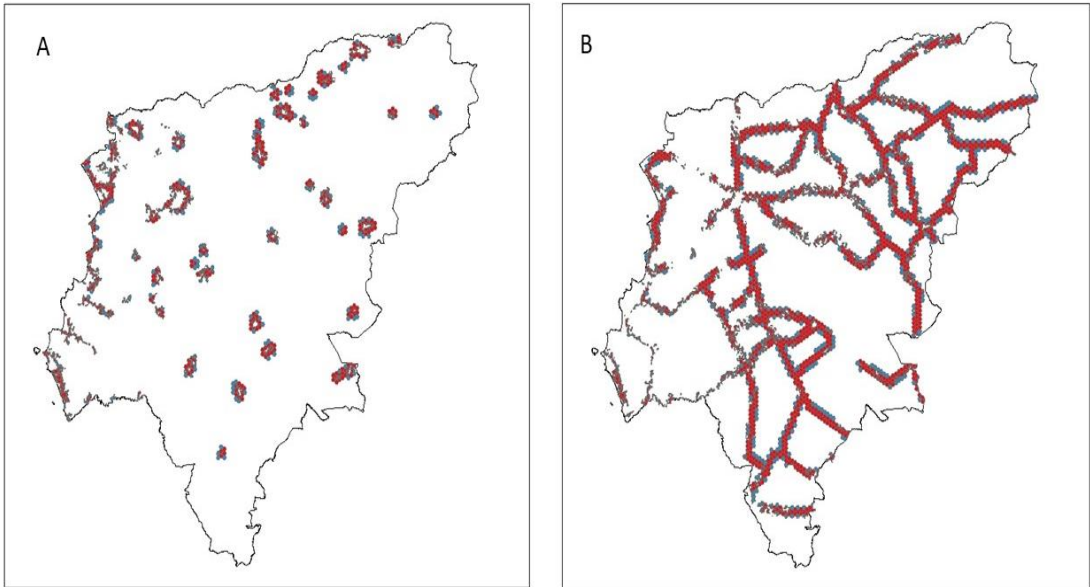


Figure S5.- A) hexagons intercepted with the buffer of infrastructures areas and populated areas B) hexagons intercepted with the buffer of roads (. Red colour indicates the 250 m buffer (5) and blue colour indicates the 500 m buffer (-2.5).

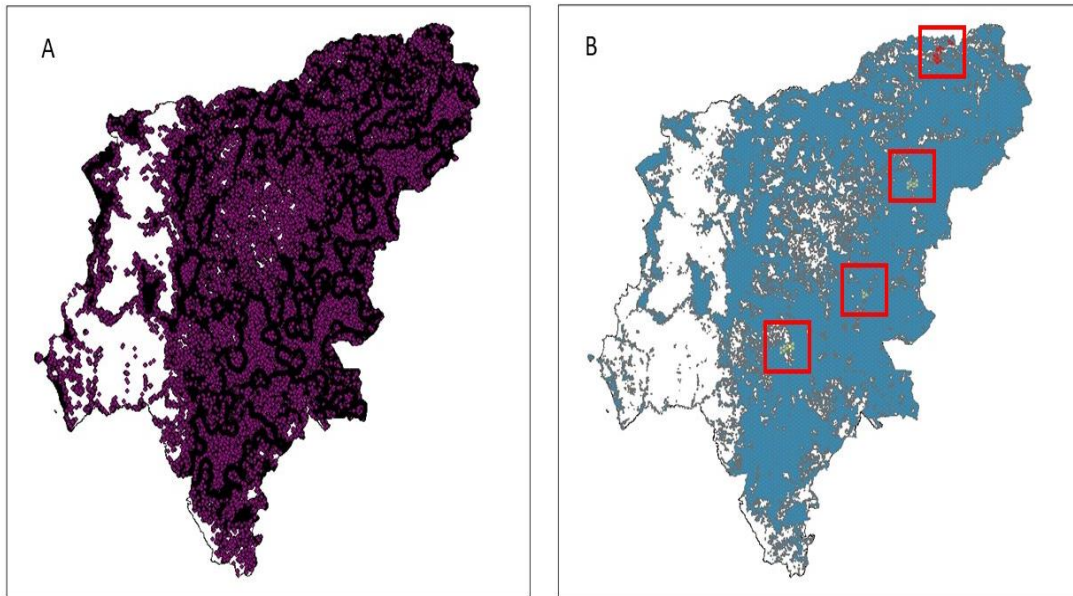


Figure S6.- A) Reforestation points analysed to measure connectivity. B) Hexagons with where to reforest increase connectivity, in the red square the most important areas are highlighted. Warm colours indicate more connectivity.

Capítulo 5

Discusión general

Estudio de potencialidad de las áreas reforestadas en la provincia de Manabí Ecuador



*“No existe mejor momento para cuidar nuestro planeta que
Hoy, ya que el mañana es posible que nunca llegue”*

Alex Quimis Gómez

1. Estudio de potencialidad de las áreas reforestadas en la provincia de Manabí Ecuador

Los programas de reforestación en el bosque seco ecuatoriano se han enfocado principalmente en tres especies de árboles nativos: *Triplaris cumingiana* Fisch & C.A. Mey. ex. CALIFORNIA. Mey., *Prosopis juliflora* (Sw.) DC y *Cordia alliodora* (Ruiz & Pav.) Oken. Estas especies brindan múltiples bienes y servicios (Campos & Velez, 2015) pero han sido amenazadas por una fuerte retracción debido a un uso intensivo histórico. Además, no existe una imagen clara del efecto del cambio climático en la sostenibilidad futura de estas plantaciones forestales. De hecho, aunque existe una extensa y creciente literatura sobre los impactos del cambio climático en la abundancia y distribución de especies, existe poca experiencia sobre su efecto en las plantaciones forestales en Centroamérica (Leguía et al. 2009).

El texto analiza la distribución actual de tres especies de árboles a nivel mundial: *Prosopis*, *Cordia* y *Triplaris*. Para ello, se incluyeron tanto los factores climáticos como los del suelo en los modelos de análisis. Sin embargo, se encontró que los factores climáticos fueron más relevantes para explicar la distribución de estas especies que las variables edáficas. En consecuencia, se utilizaron modelos de conjunto que se proyectaron en toda el área de estudio para analizar los valores de idoneidad de cada especie en las diferentes localidades de plantaciones forestales. Es decir, se analizó la aptitud de cada especie para crecer en esos lugares en base a los modelos de análisis previamente realizados. Este análisis comparativo demuestra la importancia de considerar tanto los factores climáticos como los del suelo en el estudio de la distribución de las especies que es acorde con lo manifestado por Jaramillo (2023), pero también resalta la mayor relevancia de los factores climáticos en este sentido. Además, muestra cómo los modelos de conjunto permiten proyectar y analizar la idoneidad de cada especie en diferentes áreas de plantaciones forestales.

Los modelos más precisos para estimar la distribución de especies fueron *Random Forest* y *Generalized Boost Models*, que demostraron valores de TSS y ROC cercanos a 0,9. Esto indica que estos modelos tienen una alta capacidad para predecir la distribución de especies estudiadas. Al respecto, en un estudio publicado en la revista *Ecological Modelling*, los autores compararon diferentes modelos de predicción, incluyendo *Random Forest* y *Generalized Boost Models*, para estimar la distribución de seis especies de plantas en un parque nacional de España. Los resultados mostraron que estos modelos superaron a otros en términos de precisión y capacidad para predecir la distribución de especies. Además, otro estudio publicado en la revista *PLoS One*, evaluó

diferentes modelos de máquinas de aprendizaje para estimar la distribución de especies de aves en un área de conservación en Australia. Los autores encontraron que los modelos Random Forest y Generalized Boost Models también fueron los más precisos en la predicción de la distribución de especies de aves.

Por otro lado, en la presente investigación se menciona que la especie *Triplaris* mostró las puntuaciones más altas en términos de TSS y ROC, mientras que *Prosopis* mostró las puntuaciones más bajas en su distribución. Es importante destacar que estos resultados pueden depender de las características específicas de las especies y de las áreas en estudio. Con respecto a este apartado en un estudio publicado por Hao et al. (2020), los autores evaluaron diferentes factores que influyen en la precisión de los modelos de predicción de distribución de especies, incluyendo la composición de la comunidad de especies y las variables ambientales. Los resultados mostraron que algunos modelos pueden ser más adecuados para ciertas especies y regiones, dependiendo de los factores que influyen en su distribución. En resumen, los resultados del estudio mencionado en la investigación sugieren que los modelos *Random Forest* y *Generalized Boost Models* son eficaces para predecir la distribución de especies de plantas. Sin embargo, es importante considerar que el desempeño de los modelos puede depender de las características específicas de las especies y las áreas en estudio. Por lo tanto, es fundamental realizar evaluaciones detalladas de los modelos de predicción en cada caso específico.

Entre los factores climáticos, la estacionalidad de la temperatura fue la variable más importante en las tres especies. Este hallazgo encaja bien con la hipótesis del conservadurismo del nicho tropical que establece que la estacionalidad de la temperatura es uno de los principales factores que restringen la distribución de las especies tropicales y, por lo tanto, impiden la expansión latitudinal de los taxones de origen tropical (Wiens et al. 2010). *Prosopis* mostró un vínculo con un número más amplio de variables climáticas, incluyendo también la precipitación anual y la precipitación del trimestre más cálido. Este patrón también se encontró en estudios previos para el modelo de distribución de especies de árboles en el bosque seco de Ecuador (Manchego et al. 2017). Inclusive *Prosopis* se encuentra entre las tres especies consideradas en el programa de reforestación, adaptada a las condiciones de lluvia severa y, por lo tanto, refleja bien la disponibilidad de ecosistemas secos en el área de estudio.

Las especies de este estudio se han utilizado ampliamente en el Programa Nacional de Reforestación Ecuatoriano, ya que brindan múltiples bienes y servicios, pero se han visto amenazadas por una fuerte retracción debido a un uso intensivo histórico; *Triplaris* y *Cordia* mostraron la distribución potencial más amplia en todo el Ecuador y, por lo tanto, podrían destacarse como especies favorables en grandes áreas, por otro lado *Prosopis* está más adaptado a condiciones secas, donde supera a otras especies tropicales; por ende esta especie podría ser seleccionada como especie potencial para la reforestación en áreas con limitaciones de disponibilidad de agua. Finalmente, las proyecciones de distribución potencial futura de la especie no mostraron cambios importantes en Ecuador, lo que indica que la selección de especies en los programas de reforestación ha sido probablemente adecuada bajo escenarios climáticos futuros.

2. Efecto de los programas de reforestación en la fragmentación y la conectividad de los bosques

2.1. Fragmentación

Ecuador ha experimentado cambios significativos en la vegetación natural y el uso de la tierra en las últimas décadas. La erosión de los terrenos agrícolas, el crecimiento acelerado y desordenado de las áreas urbanas y las presiones que ejercen sobre los territorios, están reduciendo los suelos con potencial agrícola, convirtiendo el suelo rural en suelo urbano. La agricultura y la ganadería se trasladan a las laderas de las montañas y áreas de menos fertilidad (y más sensibles), lo que resulta en una pérdida de las funciones sociales y ecológicas del suelo (Pinos, 2016). Por su parte, los resultados del cambio y fragmentación de la cobertura del suelo en Manabí (Ecuador) mostraron que, en 2008, el uso de suelo dominante en el área de estudio (4791,43 km²) fue la agricultura (61,91%), mientras que, las áreas forestales disminuyeron del 33,7 % al 32,45 % entre 2008 y 2018, aunque otros usos naturales de la tierra, en su mayoría arbustos, aumentaron casi al doble (del 2,4 % al 4,68 %). De tal manera, que la mayor parte de la deforestación afectó a los bosques nativos durante este período, y la mayoría de las áreas reforestadas y forestadas en 2018 cubrieron antiguas tierras agrícolas.

Los datos de fragmentación mostraron que se perdieron 61,48 km² de bosques nativos entre 2008 y 2018, disminuyendo el número de parches y aumentando el tamaño promedio. El escenario de forestación 2018 mostró un gran aumento en el número de parches, pero disminuyendo su tamaño promedio, y también aumentó el número de parches con respecto a 2018, pero no con respecto a 2008, con un área promedio cercana al escenario de 2018. La comparación entre los escenarios 2018+forestación y

2018+ evitando la deforestación nos mostró que el área perdida por deforestación es mayor al área forestada (58 km² de diferencia), por esto la dinámica fue de pérdida de bosque, cada vez con menos zona, mayor número de parches y parches más pequeños; en los 10 años entre 2008 y 2018, la remanencia cayó a 56%, una reducción de 4% del área forestal en el 2008.

En contraposición a los resultados de esta investigación, en un estudio publicado recientemente por el MAATE (2021), se detalla que desde la década de los 1990s, y posiblemente desde los 1980s, la deforestación en el Ecuador ha mostrado una clara tendencia a caer. En el período 1990-2018 la remanencia de los bosques nativos del Ecuador se redujo de 68% a 56% del área forestal original teórica. La mayor parte de la pérdida ocurrió entre 1990 y 2000, cuando la remanencia cayó a 62%, una reducción de más de 8% del área forestal en 1990. En la (casi) década que siguió, 2000-2008, el área forestal del país se redujo a 59%, una reducción de alrededor de 4% del área forestal natural en el 2008 (extrapolando a 10 años: ~5%). En los 10 años entre 2008 y 2018, la remanencia cayó a 56%, una reducción de 4% del área forestal en el 2008. La reducción en las tasas de deforestación, sumada a un área base de bosque cada vez menor, resultó en una reducción continua e importante de la deforestación neta en estas tres décadas. Si esta tendencia estructural se mantiene, el área forestal del país podría llegar a estabilizarse a mediados de la presente década.

2.2. Conectividad

Actualmente, diversos estudios centrados en la conectividad del paisaje han mostrado la gran importancia que ésta tiene para la planificación de la conservación de los ecosistemas. Sin embargo, pocos estudios aportan datos empíricos sobre los beneficios de la conectividad relacionado con plantaciones forestales en la conservación de los ecosistemas terrestres (Leija y Mendoza, 2021). La conectividad del paisaje de los usos dominantes de la tierra cambió significativamente con el tiempo en la provincia de Manabí (es decir, los tipos de clase y la superficie de los usos de la tierra) como resultado de las plantaciones forestales a pesar del dominio relativamente constante de la cobertura agrícola. Al comparar la conectividad en escenarios considerando solo deforestación y reforestación, encontramos que las plantaciones forestales contribuyen a vincular fragmentos de bosque nativo, que tienen un valor de conservación medio a alto y ocupan menos territorio, por esto las plantaciones forestales han contribuido a mejorar la conectividad, así como a la conservación de los restos de bosque nativo, por ende, el análisis de enlaces mostró que los escenarios con aumento de las áreas forestales

tuvieron mayor número de enlaces y distancia, esto surgió porque a pesar de ser pequeña la reforestación puede conectar parches con superficies más grandes.

Considerando sólo el escenario de 2018 evitando la deforestación, el resultado de la conectividad aumentó para las especies de vertebrados de referencia en la parte occidental de la provincia de Manabí y para el escenario de reforestación el número de enlaces también aumentó en las áreas centro y extremo noreste (áreas donde se realizó la mayor parte de la reforestación). Es así que, los corredores en la provincia de Manabí (Ecuador) para escenarios de usos del suelo mostraron el área que representa el conjunto de caminos posibles; según lo publicado por Cabeza (2020) los corredores ecológicos son espacios cuyo fin es proporcionar conectividad entre paisajes, ecosistemas y hábitats (naturales o modificados), por ello, la finalidad es mitigar los impactos negativos provocados por la fragmentación de los hábitats y asegurar el mantenimiento de la biodiversidad y de los procesos ecológicos y evolutivos.

2.3. Impactos en los usos de la tierra de los programas extensivos de reforestación en Ecuador

El Programa Nacional de Reforestación (PNR) orientado a la conservación ambiental, la conservación de cuencas y la mejora de los servicios ambientales se desarrolló en 2014 para encontrar soluciones a los problemas derivados de la degradación ambiental posteriores al terremoto de 2016. El Gobierno priorizó las actividades del Programa Nacional de Reforestación en las zonas afectadas, en especial las de los Programas de Reforestación en las áreas más afectadas. El programa tiene como objetivo atender la necesidad de restauración de la vegetación en el territorio continental ecuatoriano, y la Constitución vincula a los actores públicos y privados en los distintos niveles para lograr la coordinación necesaria orientada a cubrir las metas nacionales de restauración de ecosistemas forestales.

Estos enfoques se han descrito y examinado en otros países utilizando enfoques analíticos o basados en SIG. Aunque esos estudios están conectados con esta investigación, la integración del modelo de distribución de especies y los datos de fragmentación-conectividad es novedoso para determinar qué sitios deben tener prioridad para la repoblación de especies arbóreas. Entre las problemáticas derivadas de la deforestación y degradación de ecosistemas tratados en el informe se encuentran, i) emisiones de carbono; ii) alteración de ciclos hídricos; ii) degradación de suelos; iii) aumento de la vulnerabilidad a los efectos del cambio climático y iiiii) pérdida de biodiversidad.

Según el Ministerio del Medio Ambiente (2008), la superficie de vegetación natural del país era de 14.123.637 ha en 2008, lo que representa el 57% de la superficie terrestre de Ecuador, mientras que en 2016 se calculó en 14.992.685 ha, de las cuales 12.631.198 ha eran bosque primario, 763.180 ha vegetación arbustiva, 83.035 ha vegetación herbácea. Este análisis muestra que entre 2008 y 2016, el área de vegetación natural aumentó en 869.048 hectáreas. Esto puede deberse a los esfuerzos de protección y restauración del gobierno y a la reducción de la tasa anual total de deforestación a partir de 2008. En 2014, este valor fue de -0,77% (equivalente a 97.918 ha), mientras que en el período 2014-2016 fue de -0,74% (equivalente a 94.353 ha). Sin embargo, Manabí fue una de las provincias de Ecuador con más deforestación en el periodo 2014 a 2016.

En relación con lo anterior, el método empleado en este estudio demostró los pasos necesarios para seleccionar las áreas de manera sistemática al incluir el análisis de áreas que ya han sido plantadas en acciones anteriores, el análisis puede extenderse para un programa a largo plazo, no obstante, este extenso programa a escala provincial representa una prueba para los Programas Nacionales de Reforestación.

3. Viabilidad del Plan Nacional de reforestación del Ecuador

Los ecosistemas son inherentemente tolerantes y resistentes a las perturbaciones. Esto se refiere a la capacidad de mantener las propiedades estructurales y funcionales cuando se someten a perturbaciones, lo que permite mantener cierta capacidad para restaurarse a su estado original o transformarse en un nuevo estado. Sin embargo, hay un nivel de degradación que supone un umbral irreversible que imposibilita la auto restauración (MAE, 2018).

Entre 1985 y 2014 se registró 248.064 hectáreas reforestadas en Ecuador, el 43% corresponde a la ejecución del Ministerio de Agricultura en sus tres proyectos i) Plan Forestal; ii) BID 808 y iii) Proyecto Proforestal; además, la Organización de las Naciones Unidas para la Agricultura y la Alimentación (FAO) aportó con el 11%; el Programa Rostro Forestal del Ecuador S.A.” (PROFAFOR) con el 9%; el Ministerio del Medio Ambiente con el 34% y la Secretaría del Agua con el 3%. En el año 2011, el Ministerio del Ambiente inició actividades de reforestación para la protección y conservación de áreas degradadas sin cobertura vegetal, estableciendo 10.055 ha a nivel nacional en ese año, 12.065 ha durante 2012. Considerando que la oferta de Restauración actual es inexistente, el Ministerio de Medio Ambiente a través del Programa Nacional de Reforestación desde el 2019 ha fijado una meta acumulada de restauración en 3 años de al menos 30.000 hectáreas.

Los Programas Nacionales de Reforestación están orientados a crear y restaurar ecosistemas sostenibles que sean valiosos tanto para el ser humano como para la naturaleza; y se caracterizan por tres objetivos principales 1) desarrollar nuevos ecosistemas sostenibles con valor tanto humano como ecológico, 2) la realización rentable y 3) evaluar el grado en que se logran los objetivos de restauración. Ecuador ha llevado a cabo varios PNR entre 1986 y 2020. Los objetivos principales de este proyecto eran aumentar la superficie forestal, las existencias forestales y la capacidad de sumidero de carbono forestal, así como mejorar aún más la vida de las personas que viven en áreas forestales. Sin embargo, el PNR todavía enfrenta una serie de obstáculos difíciles, pero tenemos que admitir que involucra no solo cuestiones técnicas sino también sociales, económicas e incluso políticas. Es un desafío lograr un estado óptimo o perfecto para todos estos factores; pero la mayoría de las situaciones se pueden mejorar mediante la corrección técnica, el compromiso y la búsqueda de un arreglo en el que todos ganen entre las partes interesadas.

4. Áreas prioritarias para la reforestación

Las plantaciones forestales pueden contribuir a restaurar la conectividad entre áreas naturales, por ende, contribuyen a priorizar la conectividad y salvaguardar las especies locales amenazadas, considerando que, en estudios previos, se ha utilizado una estrategia heurística basada en los SIG para el análisis espacial multiatributo y la optimización para identificar áreas prioritarias de reforestación. Por ejemplo, Espelta et al. (2003) utilizaron estos métodos para evaluar las ventajas de diferentes estrategias de reforestación, considerando el rendimiento de la plantación, el costo financiero y los efectos sobre el medio ambiente.

En este estudio se emplearon dos conjuntos de variables utilizadas 1) características que estiman el potencial ambiental de un sitio para la reforestación (p. ej., presencia de especies vulnerables y conectividad, y 2) características socioeconómicas que favorecen el éxito de la reforestación (p. ej., áreas protegidas, áreas prioritarias de restauración, densidad de población, proximidad Áreas urbanas-infraestructuras y caminos). Como resultado descubrimos que el área con mayor prioridad para la reforestación no se ubicaba en la más adecuada (solo el 22,76%). Esto sugiere que se han establecido reforestaciones fuera de las áreas boscosas adecuadas. Por lo tanto, una elección final sobre qué regiones se reforestarán implica una discusión compleja con los propietarios, ya que en el Ecuador la mayor parte de la tierra no tiene cabida ante la autoridad pública; sin embargo, los tomadores de decisiones podrían comenzar la

negociación antes del comienzo de cada nueva temporada de reforestación empleando esta estrategia metódica. Además, como lo sugieren (Southworth y Nagendra, 2010), este estudio produjo información sobre los factores que pueden ayudar a promover un programa de reforestación con resultados óptimos, las razones por las cuales algunas áreas podrían reforestarse con más éxito que otras y las ventajas que pueden derivarse de la reforestación de las áreas seleccionadas.

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Capítulo 6

CONCLUSIONES GENERALES



*“Enseñemos a nuestros hijos la importancia de sembrar un árbol,
para que en el futuro no vivan en un mundo sin vida”*

Luis Alberto Andrade Molina

1. CONCLUSIONES GENERALES

1. La deforestación en Ecuador, provocada principalmente por la expansión de la frontera agrícola, ha llevado a tasas alarmantes de pérdida de bosques y de biodiversidad. En respuesta, los programas de reforestación buscan incrementar las áreas verdes en la provincia de Manabí, a través de la incorporación de especies nativas como Fernán Sánchez, Algarrobo y Laurel. Es crucial que se sigan implementando medidas y estrategias efectivas de conservación para proteger los bosques y su importante papel en la mitigación del cambio climático y la conservación de la diversidad biológica.
2. Los resultados de la selección de modelos y fitness mostraron que los más preciso para estimar la distribución de especies fueron *Random Forest* (RF) y *Generalized Boost Models* (GBM), mientras que los modelos ANN, GAM, GLM y MAXENT no se consideraron óptimos para la distribución de las especies estudiadas. Por su parte, los análisis de distribución media mostraron que existe grandes áreas para la especie *Triplaris*; mientras que los análisis de distribución potencial mostraron que existe un área adecuada similar, pero con puntajes generales más bajos para la especie *Cordia* y los resultados de idoneidad de hábitat para la especie *Prosopis* fueron más altos en el área occidental de Ecuador, correspondiente a las áreas costeras, y valores de idoneidad extremadamente bajos en el lado oriental del área de estudio.
3. Los análisis de incertidumbre mostraron que las especies *Triplaris* y *Cordia* tuvieron menor incertidumbre en áreas de mayor elevación, y para *Prosopis* existe mayor incertidumbre de que esté presente en el escenario de estudio debido a factores ambientales. Además, los resultados de idoneidad para las condiciones climáticas actuales estudio fueron relativamente altos para las tres especies estudiadas y las proyecciones de las condiciones climáticas futuras en las ubicaciones de las plantaciones mostraron que la idoneidad del hábitat parece aumentar para todas las ubicaciones de las especies *Triplaris* y *Cordia*; y la proyección futura bastante homogénea pero para *Prosopis* parece disminuir debido a las ubicaciones de plantación en la parte este del área de estudio.
4. La deforestación afectó a los bosques nativos y la mayoría de las áreas reforestadas y forestadas en 2018 cubrieron antiguas tierras agrícolas, por su parte, los datos de fragmentación mostraron que se perdieron 61,48 km² de bosques nativos entre 2008 y 2018, disminuyendo el número de parches y aumentando el tamaño promedio; a diferencia del escenario de forestación 2018+ que mostró un gran aumento en el número de parches, pero disminuyo su tamaño

promedio, y también aumentó el número de parches con respecto a 2018, pero no con respecto a 2008, deduciendo que el área perdida por deforestación es mayor que el área forestada en consecuencia existe pérdida de bosque, menos área, mayor número de parches y parches más pequeños. Los análisis mostraron resultados de mejor conectividad a las áreas forestales y reforestadas.

5. En Ecuador las áreas reforestadas hasta el 2014 fueron de 248.064 hectáreas, de acuerdo con los programas de reforestación las áreas prioritarias de reforestación y las plantaciones fallidas se pueden mejorar mediante la corrección técnica, el compromiso y la búsqueda de un arreglo en el que todos ganen entre las partes interesadas. Sin embargo, deben abordarse parámetros adicionales relacionados con la restauración del ecosistema forestal, pero son cruciales y deben discutirse en trabajos posteriores.