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Mangrove restoration in Colombia: Trends and lessons learned

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ABSTRACT

Loss and degradation of mangroves in Colombia has motivated the development of restoration efforts since the 1990s. Many experiences have been accumulated; however, there is no general balance to evaluate approaches, techniques, and results from which best practices and public policy, and a long-term national mangrove restoration plan can be proposed. To fill this gap, a review of the scientific literature and unpublished reports was complemented with surveys to build a database "MANRESCO v. 1.0" released with paper. Analysis made it possible to describe the historical and geographical trends and to identify the relative success of the many actions, according to restoration types, mangroves types and specific techniques we documented. 163 actions between 1995 and 2018 on six biophysical typologies of mangroves, four restoration types and ten techniques to face deforestation, hydrological alteration, and oil spills were recorded. A Chi-square test was used to found relationship between relative succeed and some variables. No relationship was found between biophysical mangrove types and the relative success (p-value = 0.11), but success largely depended on the type of restoration and the technique used. Most effective type of restoration was the Community Based Ecological Mangrove Restoration. Techniques involving hydrological restoration had more highly successful cases than others (15%). The most widely used and common technique was the sowing of seedlings and propagules, which have been commonly used regardless of anthropic threat, but with a low level of success. According to the results of the largest mangrove restoration program in Latin America (Ciénaga Grande de Santa Marta), the techniques can be complemented in scale and time, resulting in a 69% of mangrove cover at a cost of 4115US $/ha. However, techniques need to be chosen on proper knowledge of socioecological systems to improve the cost-benefit estimation. Lesson learned and gaps identified can be useful to other countries carrying on mangrove restoration programs.

1. Introduction

Mangroves are dominant ecosystems on the tropical and subtropical coasts of Africa, America, Asia, and Australia. They are present in 123 countries, occupying approximately 13,760,000 ha (Bunting et al., 2018) and 0.7% of the world's total tropical forests (Spalding et al., 2010). The production of critical ecosystem services has been widely documented, including the supply of fuel, wood, tannins (Carrere, 2002), shelter, trophic subsidies to various biological groups (Lee, 1995; Lee et al., 2014), and climate regulation trough carbon sequestration and storage (Donato et al., 2011). Mangroves functions as links between terrestrial and marine environments, regulate the water quality of adjacent ecosystems (Feller et al., 2010), mitigate coastal erosion and compensate for rising sea levels (Mcleod et al., 2011).

In recent years, mangroves have received increasing attention from governments and non-governmental organizations around the world. However, this attention contrasts with their stability in many regions, as they are threatened by continuous disturbances of anthropic origin (Abuodha and Kairo, 2001; Ellison and Farnsworth, 1996; Carrere, 2002) Global estimates reveal that annual deforestation rate between 2000 and 2012 was 0.16–0.39% (Hamilton and Casey, 2016); due to urban sprawl, aquaculture, agriculture and over extraction of forest products. Also, extreme weather events are an important cause of mangrove loss, representing 27% of all losses (Friess et al., 2019; Goldberg et al., 2020).

The global loss of mangroves has generated negative environmental,

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climatic and social impacts, promoting the development of restoration actions. In this work, we use the term "restoration" not as a return to previously existing conditions to a disturbance, but to as a process to improved mangrove to states previously defined (Lewis, 1999). Although this term is usually called "rehabilitation", we used the term "restoration" because its strong ascendancy in the published literature (López-Portillo et al., 2017). The implementation and scope of restoration to provide environmental services will depend on the complexity of the system and includes activities or actions that promote environmental remediation(for example, cleaning of soils and water contaminated by spills); and actions to recovery or repair (e.g., reforestation) structure, composition, function, and services (Aronson et al., 2017; Bosire et al., 2008; Lewis et al., 2016).

According to Ellison et al. (2020), different mangrove restoration types, have been used over time based on the objective, the way to perform the restoration and the discourse or approach. Before the 1980s, actions focused on silviculture and reforestation. The promotion of natural regeneration gained relevance with the Ecological Mangrove Restoration (EMR) approach, which gave greater emphasis to the management of hydrology and topography (Lewis, 2005). Later, communities and other actors were added as a central element in the planning and implementation of actions (Community Based Ecological Mangrove Restoration -CBEMR) (Brown et al., 2014). Recently, ecological engineering and ecosystem design approaches have gained greater attention to address human problems and needs, in particular for coastal risk reduction and adaptation to climate change (Cheong et al., 2013). Additionally, enhancement, reallocation, or replacement (R/R) was proposed by Kaly and Jones, (1998) as a type of restoration in which the establishment of an alternative ecosystem is sought instead of an existing or damaged one.

In Colombia, mangroves develop along both the Caribbean and Pacific coastlines, covering an area of 289,122 ha (Rodríguez-Rodríguez et al., 2016). Despite their ecological and economic importance to traditional communities, the loss and degradation of mangroves persist in the country. This has motivated the development of restoration efforts from the 1990s to the present. One of the most notable is the one carried out in the Ciénaga Grande de Santa Marta (CGSM), the largest lagoon-coastal complex in the Colombian Caribbean, recognized as the most productive in tropical latitudes (Gocke et al., 2003; Rivera-Monroy et al., 2011; Rodríguez-Rodríguez et al., 2018). The massive death of the mangrove on CGSM due to the loss of hydrological connectivity and the subsequent restoration activities is an important experience and a reference to similar situations. Other than the reasonably documented CGSM case (Botero and Mancera, 1996; Botero and Salzwedel, 1999; Jaramillo et al., 2018a, 2018b; Rodríguez-Rodríguez et al., 2018), there is still no overview of mangrove restoration projects in Colombia to evaluate approaches, techniques, and results, from which public policy and a long-term national mangrove restoration plan can be oriented, so is needed a systematically collected information a national level.

In this paper we provided a synthesis of more than 25 years of mangrove restoration in Colombia, describing and analyzing the historical and geographical trends, types of approach, and restoration techniques used, as well as their relative success. Updated data on one of the most important mangrove restoration processes in Latin America (CGSM case) were included. The review offers reflections and lessons learned, providing inputs for mangrove restoration protocols according to cause of deterioration and identifying priorities and better practices that could be applied in other countries with similar types of mangrove and threats.

2. Methodology

2.1. Data extraction

To describe the historical and geographical trends, the types of approach (restoration type as we mention in this review), and the techniques used in the restoration of mangroves in Colombia, the scientific literature available through Scopus was reviewed using the Boolean equation "Manglar OR Mangrove And Restauración OR Rehabilitation OR Reforestation OR Recovery And Colombia ". The coincidence of these words in the abstract and keywords was considered, and the specific restoration action was sought in the text. In Google Scholar, only documents whose title contained the following words in English or Spanish were included: "Mangrove/Mangroves And Colombia And Restoration/Reforestation/Rehabilitation/Recovery". Since some of the information was not available in digital media, printed documents were consulted in local libraries. For the inclusion of documents as sources of information, the search focused on actions that helped the recovery or establishment of the mangrove between 1990 and 2018 in the coastal municipalities of Colombia.

A "restoration action" was considered as the set of techniques used to help the mangrove recovery in a particular site and time. Those initiatives of experimental nature or that intended to test some propagation techniques were not considered as restoration actions and were excluded from the analysis. To complement the information, the report of the actions carried out by the coastal environmental authorities (Areas of Regional Administrative Environmental Planning -CARs and National Parks) between 2010 and 2018 were requested by conducting online surveys, some of them sent technical reports that were analyzed to extract the information. Each restoration action reported in the available information sources was considered a record. In the end, actions that had already been reported by other sources of information were excluded.

For each registered restoration action, the following information was included in the database: geographical coordinates, year of implementation, municipality of implementation, area intervened by the action, causes of degradation, mangrove type according to the biophysical classification proposed by Worthington et al. (2020) (Deltaic, Estuarine, Lagoon or Open coasts; dominated by terrigenous (T) or carbonate (C) sedimentation); "restoration type", according to Ellison et al., 2020 and Kaly and Jones (1998), techniques used (Practical activity carried out in the field to improve site conditions) and costs. In the case of reforestation actions, the species used were specified. Monitoring (<1 year, between 1 and 5 years, >5 years); and monitored variables (Survival, Coverage, Plant Development, Function) also was considering. See supplementary material to review levels used to classify each restoration action in a type and restoration techniques and their definitions.

Not all the information required for each action was directly and explicitly available from the information sources, so it was derived from the interpretation of the texts or by consulting experts and restoration professionals familiar with the actions identified to complete as many fields as possible. In some cases, no coordinates were found, so were assigned according to the reported site name.

A total of 163 records were documented, and included in the database "MANRESCO V 1.0: Mangrove Restoration Action of Mangroves in Colombia, version 1" which is available in https://doi.org/10.17632/tf8p6n8c7d.1 Book, theses, online surveys, and technical reports were the information resources that contributed the most to the records (Table 1).

Table 1
Information sources reporting mangrove restoration actions in Colombia, and remaining actions after removing duplicates. Number of restoration actions or records are shown in each one.

Information source	Total sources	# Actions	# Actions after removing duplicates
Article (Scopus)	8	29	5
Article (Google Scholar)	1	1	0
Books or theses	75	75	75
Technical reports	11	40	40
Online Survey	12	46	43
Total			163

Because not all surveys sent were answered (12/17), it is possible that the final number of action restoration were biased by the number of retrieved final reports and the variables in them.

2.2. Evaluation of the restoration "success"

Considering the little monitoring information available on the restoration actions of this study, we established the restoration success for each action, based on the qualitative evaluation carried out by a mangrove expert, who visited the restoration sites. This evaluation was based on the perception of an apparent increase in two criteria (Table 2). Some sites were visited at the beginning and years after the implementation of the action by a mangrove expert who based on their own judgment assigned to each site a qualification between 3 (high), 2 (medium), and 1 (low) considering (a) the increase of natural regeneration and forest structure and (b) the increase of mangrove coverage. To evaluate whether the type biophysical mangrove, the restoration type, and the techniques influenced the success of the actions, a Chi-square test (X^2) was used. To check the strength of the association between the variables, Pearson's contingency coefficient was calculated. For CGSM, long-term monitoring data about survival, coverage, plan development and costs was accessible, then, it was selected as a case study in depth. For CGSM, success was evaluated comparing structure variables (basal area) and salinity between a reference forest and a restoration forest and relation with restoration costs and area recovery.

3. Results and discussion

3.1. Historical trends and restoration types

Mangrove restoration efforts in Colombia date back to before 1990, when experimental field approaches, searched methods and techniques for the management of seedlings, and transplants of individuals (Álvarez-León, 2003). Between 1995 and 2005, the International Tropical Timber Organization (ITTO), funded the "Manglares de Colombia" project. A diagnosis and zoning of mangrove to guide their use and establish of nurseries and restore degraded areas (Sánchez-Páez et al., 2004, 2000, 1998). New actions were recorded found in 2009 when ecological restoration began to have greater attention in the country (Fig. 1).

Four mangrove restoration types were identified in Colombia. The afforestation and reforestation (REF) approach reached its peak in the 1990s and has been losing importance compared to other approaches that emphasized the understanding of the biophysical attributes of the system and its relationship with local communities. Although multiple reforestation practices were done in the second period (1990–2005), the involvement of communities in the planning and execution of activities, prioritizing hydrology, gained importance through the "Manglares de Colombia" project and PROCIENAGA project (this last made for CGSM restoration). For the more recent period (2005–2018), although reforestation practices continued, the recovery of biophysical characteristics (EMR) and community approaches (CBEMR) are more prevalent (Fig. 1).

Table 2
Criteria used to judgment qualitative the success of the restoration on 82 actions visited.

Criteria	Success		
	High (Value 3)	Medium (Value 2)	Low (Value 1)
Seedling survival or increased natural regeneration and forest structure	100–70%	60–40%	30–0%
Relative increase in mangrove cover	>30%	30–5%	< 5%

3.2. Geographic trends

Most restoration actions were done in deltaic mangroves (n = 69), followed by carbonate open coast mangroves (n = 40), estuaries (n = 30), terrigenous open coast (n = 17), and in the lagoon (n = 7) (Fig. 1).

Of the 163 registered actions, 73.5% were in the Caribbean and 26.5% in the Pacific. On a review about trends in Mangrove research in Colombia, Castellanos-Galindo et al. (2020) also found preference for mangroves of the Caribbean coast. These lesser efforts in the Pacific could be related with less security, and high logistic costs. Greater attention to the Caribbean could be related to a higher coverage loss and CGSM, a delta type mangrove with a known history of deterioration. The municipality of Sitio Nuevo in CGSM registered the highest number of actions in the entire country (# restoration actions = 26). Other municipalities that registered a significant number of actions were Cartagena de Indias (# restoration actions = 20) and San Antero (# restoration actions = 18), while in the Pacific, were Buenaventura and Tumaco (# restoration actions = 21 and 7, respectively) (Fig. 2).

3.3. Types and techniques of restoration implemented in response to different anthropic threats

Changes in land use and degradation produced by the extraction of forest resources, coastal development that alters water dynamics, and spills of pollutants were the anthropic threats for which restoration experiences were recorded. The loss of hydrologic connectivity in the mangroves of Caribbean coast is recurrent and associated with a higher level of infrastructure development, compared to Colombian Pacific where restoration actions have been more recurrent to address problems of deforestation and selective logging (Fig. 3).

Four restoration types (Fig. 4) and multiple techniques have been used to restore mangrove ecosystems in Colombia in response to these anthropic threats.

The most widely used techniques have been the sowing of seedlings and propagules that have been commonly used to treat hydrological alterations (n = 29) and deforestation or selective logging (n = 27). Faced with hydrological problems, the manual or mechanical opening of channels (n = 24 actions) has been carried out under the CBEMR and EMR approaches to regain connectivity with freshwater sources and in some cases, after hydrological reconnection, seedlings have been planted directly or on sediment elevations (n = 26).

In the presence of species such as *Acrostichum aureum* as a consequence of selective logging (n = 21); and *Typha domingensis* (n = 7), which could compete with the mangrove for their establishment, the actions have included their removal and subsequent planting of seedlings or propagules, in the latter case to favor mangrove habitats (Restoration Type: Relocation or Replacement).

The isolation of areas with barbwire was used to promote natural recovery in two areas affected by livestock. In four sites more, affected by livestock, hydrological improvement was carried out with community participation (Tinoco and Rodríguez-Rodríguez, unpublished results). Active collection of the liquid or washing (n = 4) (eg. Ibáñez, 1995), and move emitting source to promote natural recovery (n = 1), was carried out after chemical spills and contamination. In 18 cases when reforestation was carried out, the cause of the deterioration was not reported. This was the type of action most used against different causes of loss or degradation (Fig. 4).

Regarding the actions that reported planting, 77.1% used only *Rhizophora mangle*, 2.3% *Mora oleifera* and 0.8% *Pelliciera rhizophorae*, while 19.8% of the actions used several species. Reforestations carried out with a single species in areas with hydrological problems could be unable to functionally reproduce a natural mangrove swamp (Rahmania et al., 2019). Mangroves can provide different ecosystem services that vary in type, quality, and quantity depending on the species (Wu et al., 2020). In Colombia, the preference for the use of *R. mangle* in reforestation actions may be related to the ease of management and availability

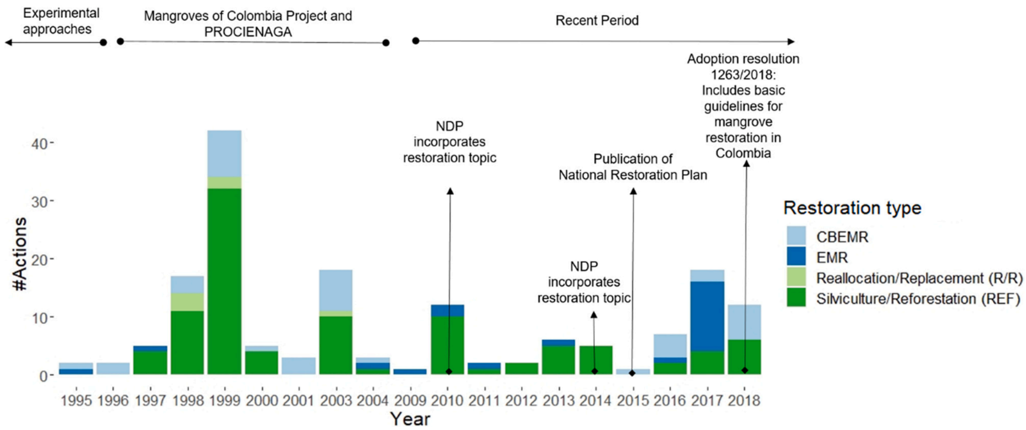

Fig. 1. Mangrove restoration types and the main milestone in Colombia. NDP: National Development Plan. CBEMR: Community Based Ecological Restoration of Mangroves, EMR: Ecological Mangrove Restoration, R/R: Relocation/Replacement, REF: Silviculture/Reforestation.

of propagules and its presence along the two coasts of the country (Sánchez-Páez et al., 2004, 1998). Other countries also have found *R. mangle* preference in restoration programs, but reported low survival rate due to incorrect selecting planting site (Wodehouse and Rayment, 2019). Then, heterogeneity of the forests according to their physiographic type and objectives of restoration actions require a thorough analysis to design and implement actions.

3.4. Success of restoration actions

Since in most cases there are no monitoring programs which allow us to quantitatively evaluate their success (85 actions do not report monitoring programs or were unknown); we evaluate relative success of 82 actions with qualitative criteria based on expert judgment.

Only 24% of the actions were considered to have a high relative success level, 53% have a medium success level, and 20% low (Table 3). According to the type of mangrove, the deltas presented a level of success between intermediate (40%) and high (35.5%). On the open coast in a carbonated environment, it there was a medium level compared to terrigenous environment (45% and 16.6%, respectively) (Fig. 4). Only 24% of the actions were considered to have a high relative level of success, 53% have a medium, and 20% low level of success (Table 3). According to the type of mangrove, the deltas presented a level of success between intermediate (40%) and high (35,5%); while, in the open coast, a carbonate setting had more medium level success than in a terrigenous setting (45% and 16,6%, respectively) (Fig. 5).

No relationship was found between biophysical typology of mangrove and the level of success (x^2, $p = 0.106$). However, success largely depended on both the restoration type and the technique used ($p = <0.001$ - contingency coefficient: 0.473; $p = <0.001$; contingency coefficient: 0.671) (Table 3, Fig. 6). The most effective approach was CBEMR compared to others. The actions implemented under the CBEMR approach have taken place in areas where the cause of degradation has been hydrological and had the support and participation of small farmers and fishermen who live with the mangrove and derive their resources from it (Municipalities of San Antero and Pueblo Viejo). The results showed that the largest number of successful restoration actions were concentrated in the delta typology. However, these results should be considered with caution, given that the different mangrove typologies could not be evaluated with the same effort.

The reforestation with sapling or propagules that was used as a technique against deforestation, selective logging, or hydrological problems, have low ($n = 15$) and medium success ($n = 11$). Globally, reforestation is one of the most common action in mangrove restoration projects. However, the long-term success has been low due to the lack of consideration of associated biophysical, political, economic, and social variables with no management in changes in land use and governance (Lee et al., 2019; Lovelock and Brown, 2019). To overcome these issues, Colombian government has been establishing strategic lines on policy instruments, in order to improve: i) mangrove management process and coordination with sectoral and territorial planning, ii) governance schemes (co-management) between institutions and the local community (ethnic minorities and peasants), and iii) comprehensive long-term mangrove restoration proposals with a landscape. Implementation of these and other strategic lines has made it possible to consolidate in a few specific places approach integral management of the mangrove, mitigating some of the anthropic threat (eg. Cispata bay case that recently got a certificate blue carbon program); however, this is still a challenging to majority mangrove forest in Colombia.

Including seedlings and propagules planting after hydrological restoration ($n = 12$), was more successful than if hydrological restoration did not include planting of individuals ($n = 5$ in medium class). Only the removal of *A. aureum* and the planting of seedlings, propagules, was relatively successful against logging (Fig. 6). Concerning spills, active collection, low-pressure sediment washing, or relocation of the pollutant source, had a relatively high success, even increasing the initial cover of the mangrove (Hoff and Michel, 2014). These examples showed that the removal of barriers to regeneration and the promotion of natural regeneration are possible mechanisms to accelerate the restoration process after physical and chemical barriers in the ecosystem have been overcome (Lewis, 2005).

Without attempting to evaluate the benefits of converting other systems to mangroves, we reported that the removal of *T. domingensis* was very successful in allowing afforestation of newly formed alluvial beaches with mangroves, accelerating plant succession, and creating newly available habitats (Sánchez-Páez et al., 2000). Although it was an efficient technique, its use has not been extensive (Fig. 2). A recent study conducted in India and Bangladesh showed the facilitating role of halotolerant grasses in mangrove restoration projects (Begam et al., 2017). The rhizospheres of grasses participate in the decomposition cycle, releasing nutrients and serving as a substrate for cyclic bacteria, which leads to the recovery and stabilization of soils. Likewise, the synthesis of osmolytes protects mangrove species by facilitating their colonization and dissemination (Begam et al., 2017). In Neotropical mangroves, the establishment of herbaceous species such as *Sesuvium protulacastrum* or *Distichilis spicata* before reforestation actions, improves the physicochemical conditions of the sediment (reduction of salinity, temperature, oxygenation) (McKee et al., 2007), acting as a facilitator mangrove development.

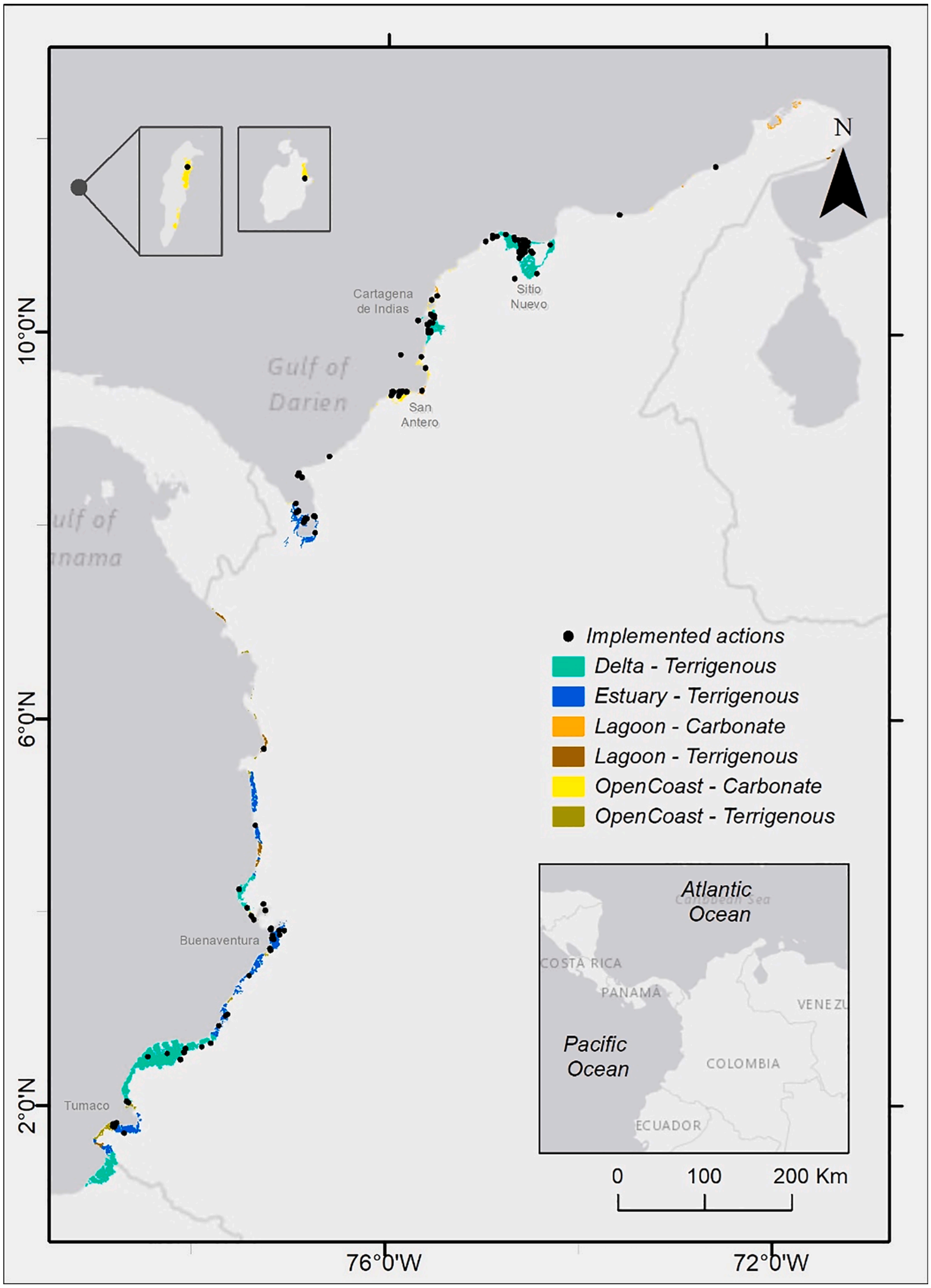

Fig. 2. Distribution of mangrove restoration actions identified in Colombia by the biophysical typology proposed by Worthington et al. (2020).

3.5. Case study: Restoration types and techniques in a delta-type mangrove - Ciénaga Grande de Santa Marta (CGSM)

Different techniques of mangrove restoration have been applied in CGSM (Fig. 7) which is a study model for the derivation of best practices and restoration protocols in Delta-type mangroves with hydrological alterations.

The CGSM is a deltaic plain of the Magdalena river with a coastal lagoon of 132,100 ha located in the Colombian Caribbean, whose original mangrove cover for 1956 (51,150 ha) was degraded by the loss of hydrological connectivity caused by, among other reasons, the coastal infrastructure, reaching 22,580 ha in 1995 (INVEMAR, 2019). The PROCIENAGA project was designed to rehabilitate the hydrology of the lagoon complex as a starting point for the restoration of mangroves, water quality, and fishing supply. The strategy sought to empower local communities in the management of fauna and flora resources, generate agreements and strengthen the institutional framework (CBEMR Approach). Between 1996 and 1998, the Magdalena River was reconnected with its delta through mechanical dredging of more than 3.35 $\times$ 10^6 m^3 distributed in 5 main channels with an total length of 82 km ($\overline{X}$ = 20.5 $\pm$ 11.5 Km) (Jaramillo et al., 2018a, 2018b; Salzwedel et al., 2016). With the flow of freshwater to the system, to the intention was to reduce the levels of edaphic salinity, the main cause of death of the mangroves (Botero and Salzwedel, 1999). The initial cost of the restoration works amounted to 20,111,386 USD (2020) (18,511,000 USD-2016 prices) (Salzwedel et al., 2016).

Due to the high sediment load of the Magdalena River (7000 m^3 s^{-1}, Restrepo and Kjerfve, 2000) and the constant sedimentation of the main

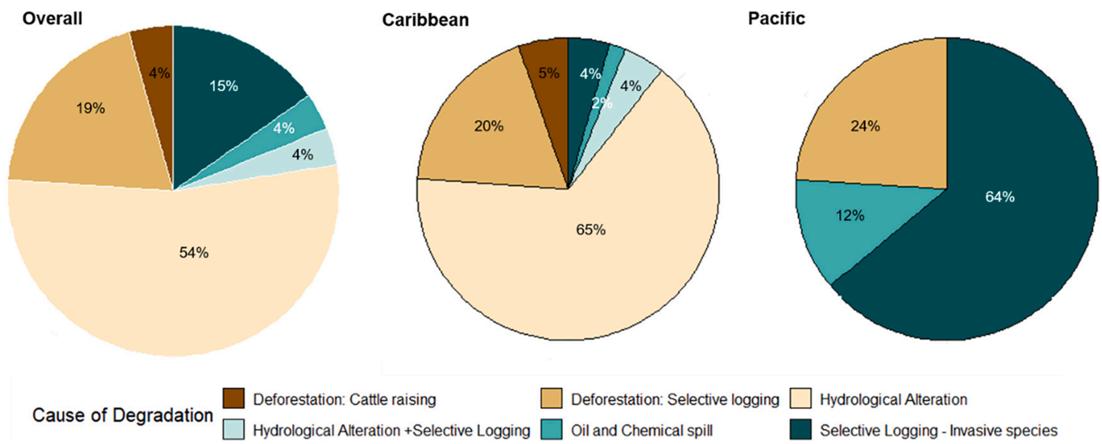

Fig. 3. Main anthropic threats that motivated mangrove restoration actions in Colombia.

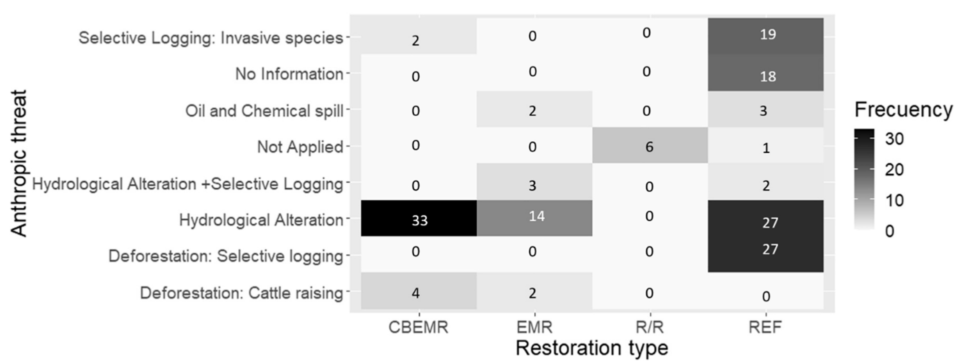

Fig. 4. Frequency in the use of restoration types in response to different mangrove threats between 1990 and 2018. CBEMR: Community-Based Ecological Mangrove Restoration; EMR: Ecological Mangrove Restoration.; R/R: relocation or replacement; REF: Silviculture/Reforestation. The "Not Applied" category includes cases in which secondary succession was accelerated by the elimination of Typha domingensis. 163 actions are reported.

Table 3
Actions are recorded at each success level according to the restoration type. The number of shares is shown in percentages and parentheses. The most common level of success for each restoration type is highlighted in bold. CBEMR: Community-Based Ecological Mangrove Restoration; EMR: Ecological Mangrove Restoration. n = number of actions.

Restoration type	Success level			n
	Low (1)	Medium (2)	High (3)	
CBEMR	4.8 (1)	**47.6 (10)**	**47.6 (10)**	21
EMR	0 (0)	**66.6 (1)**	33.3 (2)	3
Silviculture/Reforestation	36.5 (19)	**55.8 (29)**	7.7(4)	52
Reallocation/Replacement	0 (0)	50 (3)	50 (3)	6

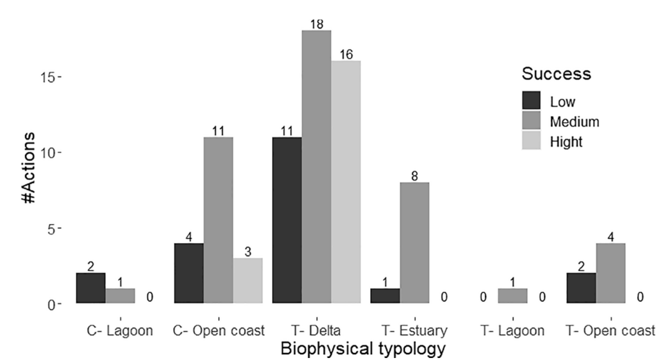

Fig. 5. Success of restoration actions according to the typology of mangrove. The sedimentary setting is indicated as C: Carbonate; T: Terrigenous. 82 actions are reported.

communication channels, it has been necessary to dredge again from 2006 to the present. However, dredging did not maintain the CBEMR approach and was done without incorporating community participation. Additionally, in 2000 reforestations were carried out at different points of the CGSM. In the northeast (Ciénaga Sevillano) the mass tree mortality in the 1990s led to mangrove peat collapse. Between 2000 and 2004, the local community participated in the planning and execution of restoration through the manual opening of three channels (total length = 1.1 km) (Sánchez-Páez et al., 2000), allowing the circulation of water, and then the surface was raised and seedlings were planted. Since 2017, due to the increase in salinity, in the northwest sector, additional mechanical dredging was done in more than 72.9 km of channels. From 1994 to 2018, around US $ 48,410,611 were invested in CGSM, mainly in hydrological rehabilitation (Table 4).

Along with Clarin, one of the channels frequently dredged since 1996, the mangrove cover gain was 450 ha, between 2001 and 2013. In Sevillano, until 2013 the gain was 750 ha, 300 ha more than Clarín, where the hydrological rehabilitation was mechanical and did not incorporate topographic management (Table 4, Fig. 7).

The planting of seedlings in CGSM had variable results. Lack of community empowerment and institutional arrangements in Cuatro Bocas led to the destruction of the planted seedlings by the community (Table 4. Ortiz, 2004). Participation schemes and adequate social arrangements are required before the implementation of actions and must be maintained over time. In other cases, seedlings' survival was low after two years of implementation, compare to a reference stand (Table 4). Overflooded soils, direct solar radiation, and high salinities in

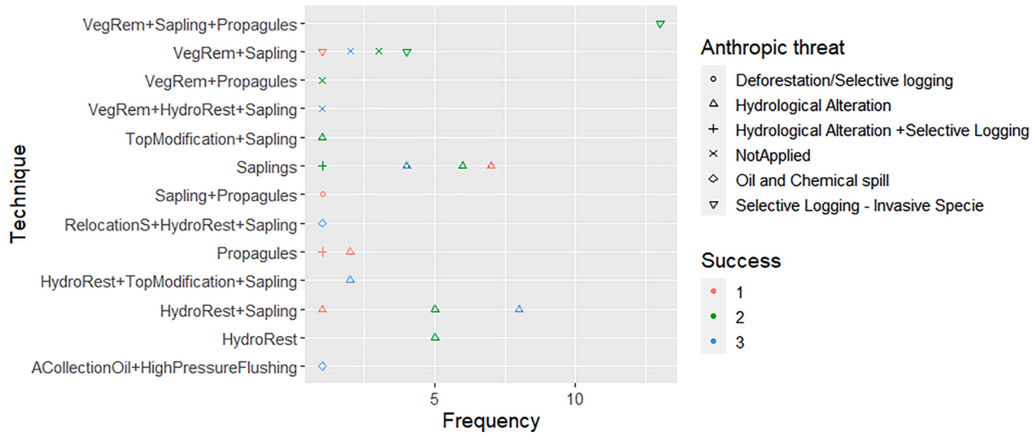

Fig. 6. Relative success of restoration techniques used in response to different causes of deterioration. Success: 1. low; 2. medium; 3. High. Technique: TopModification: Topography modification through surface elevation; Seedling: Planting seedlings, VegRem: vegetation removal; Propagules: Planting propagules; HydroRest: Hydrological restoration; Relocation: relocation of the source of contamination; ACollectionOil: Active Collection Oil Spill.

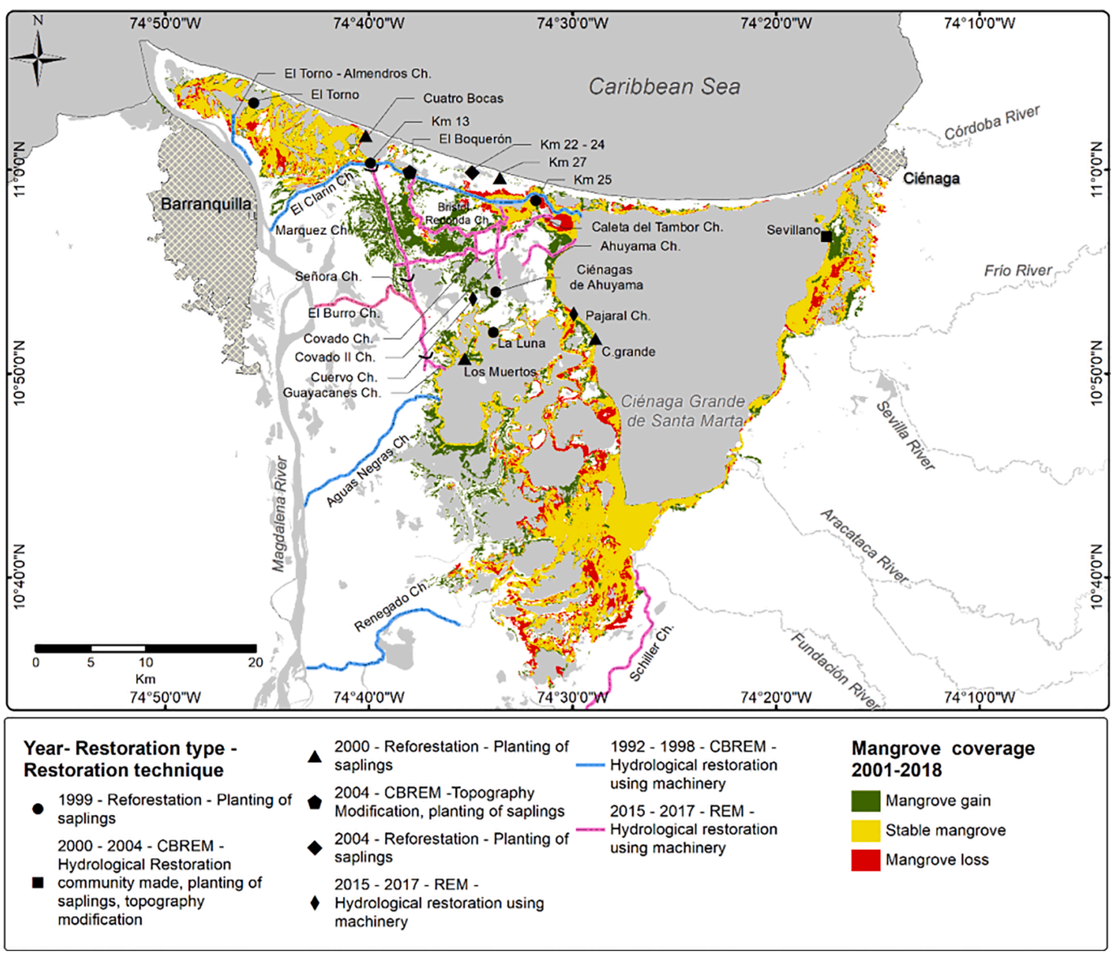

Fig. 7. Mangrove restoration techniques and actions in Ciénaga Grande de Santa Marta (CGSM) since the 1990s. The figure shows the year of execution, the restoration type, and the technique used.

the areas selected for reforestation were the main causes of failure (Elster, 2000). This confirms the importance of guaranteeing adequate biophysical conditions before reforestation (e.g. Los Muertos). In fact, in Caño Grande, where intertidal water salinity was close to the reference stand over time, reforestation actions were highly successful to recover structure forest (Fig. 8). High survival rates of *R. mangle* were recorded after two years of planting (Table 4) and high forest mass was recoved after 17 years (Basal Area = 21 m^2/ha^{-1}). Logging events have been reported in the last 3 years, decreasing values of forest mass (Fig. 8). A site with hydrological rehabilitation done with a dredge (Clarin – Km 22) showed a faster increase of basal area than a site where the reforestation technique, reaching 27.49 m^2/ha^{-1} in 17 years, showing the usefulness of the technique. In recent years, interstitial water salinity has risen to the interior of the forests, generating massive tree deaths

Table 4
Some restoration actions carried out in CGSM and relevant data. Natural regeneration and seedling survival percentage (S%) in reforestation techniques after two years of implementation. Approximate action costs in dollars (2020) are shown. CBEMR: Community-Based Ecological Mangrove Restoration; EMR: Ecological Mangrove Restoration; REF: Silvicultural/Reforestation: AHR: Artisanal hydrological restoration; MacHR: Hydrological restoration performed with machinery (dredge). TM: Modification of the topography through elevation of the surface; Sapling: Plant of a sapling. Rm: *R. mangle*; Lr: *L. racemosa*. a. INVEMAR, 2019; b. It Includes PROCIENAGA Project (Salzwedel et al., 2016), maintenance costs and new hydrological restoration carried out by machinery - Data provided by CORPAMAG; c: Sánchez-Páez et al., 2004; d: Salzwedel et al., 2016; e: Ortiz, 2004; f: Elster, 1998. All actions identified to CGSM are shown in Supplementary Material Figure B.

Site	Coordinates	Year	Type of Restoration	Technique	Hectares of mangrove (ha)					S (%)	Total cost (USD)
					1995	2001	2007	2013	2018		
Overall CGSM	–	1996–2018	CBEMR, REM, REF	AHR,TM, Sapling, MacHR	22,580[a]	29,139[a]	29,510[a]	39,535[a]	34,365[a]	–	108.447 X10^6
Rinconada	10°57′41.4″N-74°29′37,6″O	–	None. Reference stand	None. Reference stand	–	–	–	–	–	*Rm*: 86.6 (±13.1) *Lr*: 64.1 (±33.8)[f]	–
Sevillano - Chino	10°56′58.00″N-74°17′20.00″O	2002	CBEMR	AHR, TM Sapling	–	3005[b]	3034[b]	3755[b]	3274[b]	*Rm*: 70 Lr: 100[c]	11.849[c]
Clarín	10°56′54.77″N-74°36′23.95″O	1996	CBEMR	MacHR	–	1572[b]	1408[b]	2022[b]	1355[b]	–	2.922 × 10^3 [d]
Los Muertos	10°50′45.00″N-74°35′18.00″O	2000	REF	Sapling	–	–	–	–	–	*Rm*: 60 Lr: 8.3[e]	–
Km 27	10°59′37.00″N-74°33′34.00″O	2000	REF	Sapling	–	–	–	–	–	*Rm*: 100[e]	–
Caño Grande	10°51′42.80″N-74°28′52.90″O	2000	REF	Sapling	–	–	–	–	–	*Rm*: 95[e]	–
Cuatro Bocas	11° 1′40.84″N-74°40′9.92″O	2000	REF	Sapling	–	–	–	–	–	*Rm*: 0[e]	–

(Fig. 8).

The use of dredge has been useful for large-scale wetland restoration; however, some associated side effects have been reported. For example, with the impact on riparian soil properties (Unghire et al., 2011). In CGSM, the mechanical dredging of freshwater channels, as part of a large-scale hydrological restoration strategy, favored the recovery of the mangrove swamp (Jaramillo et al., 2018b); in fact, 41% of the lost coverage was recovered since 1995 (Table 4). However, the accumulation of sediments laterally at the edges of the channels left by the machines does not allow greater hydrological connectivity within the forest (Jaramillo et al., 2018a), limiting the effect of the action in the innermost areas; indeed, mangrove recovering has been seen mainly in margins (Fig. 7). These small- and medium-scale internal connection require manual modification by trained community work; for example, opening additional channels and dispersing the excavated sediment to the desired height so that seedlings are established, survive and grow; these activities would generate additional revenue and community ownership. The CBERM approach is based on the participation of local communities in the management of vital resources, the identification of needs, the choice and the adaptation of appropriate sustainable management practices (Datta et al., 2012). In Indonesia, CBERM community approaches were used to restore up to 400 ha and could to cover in larger areas (Brown et al., 2014). In Mexico, these approach was consolidating organizational capacities and environmental awareness in the local population and has influenced forest environmental policy (Zaldívar-Jiménez et al., 2017).

Additionally, although in the 1990s the need for continuous maintenance of the dredged channels was needed to maintain acceptable levels of salinity in the system, the channels are insufficient to guarantee the stability of the mangrove. Since 2017, CGSM's mangrove coverage has declined once again due to further increases in salinity (Table 4; Fig. 7), forcing urgent dredging of new channels in the northwest (Fig. 6). This situation is due to the high evapotranspiration of the wetland and its dependence on the climatic environment (Blanco et al., 2006). Also, human activities in the basins of the supplying rivers, leading to reduced inputs, blocked water flow and constant obstruction of channels (Botero and Mancera, 1996). Currently, the scarce hydrological knowledge of the estuary, (Jaramillo et al., 2018b), the use and regulation of water resources, limits the design of better techniques to rehabilitate the hydrological dynamics of the whole mangrove swamp system.

Since the first actions were done in 1996, there has been a recovery of 11,756 ha (INVEMAR, 2019), costing approximately 4115US $/ha. This value is below the estimated average for mangrove restoration projects in the world (10,663US $/ha (2020); 8961 at 2010 prices), and above the average for countries with emerging economies such as Colombia (1417 US $/ha (2020); 1191 (2010) prices)) (Bayraktarov et al., 2016). These costs comparatively with costs in other countries, the increasing on coverage (Table 4) and partial recovery of forest structure (Fig. 7) shows that this experience has been relatively successfully, although some practices and mechanisms can be improved, as we have discussed.

3.6. Gaps and lesson learned from mangrove restoration in Colombia

Most of the experiences between 1990 and 2005 were obtained from the Manglares de Colombia and PROCIENAGA project, so the analysis of the information was obtained mainly through technical reports and publications of these projects. For the period 2005–2018, the lack of documentation in the scientific literature and the difficulty in accessing information in gray literature or technical reports produced by entities responsible for mangrove restoration and independent organizations, limit the findings from this research to the recent period about the total number of actions and some preference of practitioners; however, considering the diversity of actors and resources that provided information; it is representative at the national level and supplied trends, letting a starting point to discuss better practices. Indeed, this study highlights the need to improve the reporting mechanism and strengthen the practice of open data. Likewise, the little existing literature only reports on successful projects, while unsuccessful ones are hardly published. Knowing the possible reasons for the failures of mangrove restoration projects would help improve these practices.

A central point for the success of the restoration is the availability of techniques and trained personnel (Lewis, 2005; Lewis and Brown, 2014; Lewis et al., 2016; Primavera et al., 2012). Based on the records, several restoration efforts have been carried out in Colombia and some on a large scale, mainly in the Caribbean, where experiences of hydrological restoration, the elevation of collapsed surfaces, and planting of seedlings

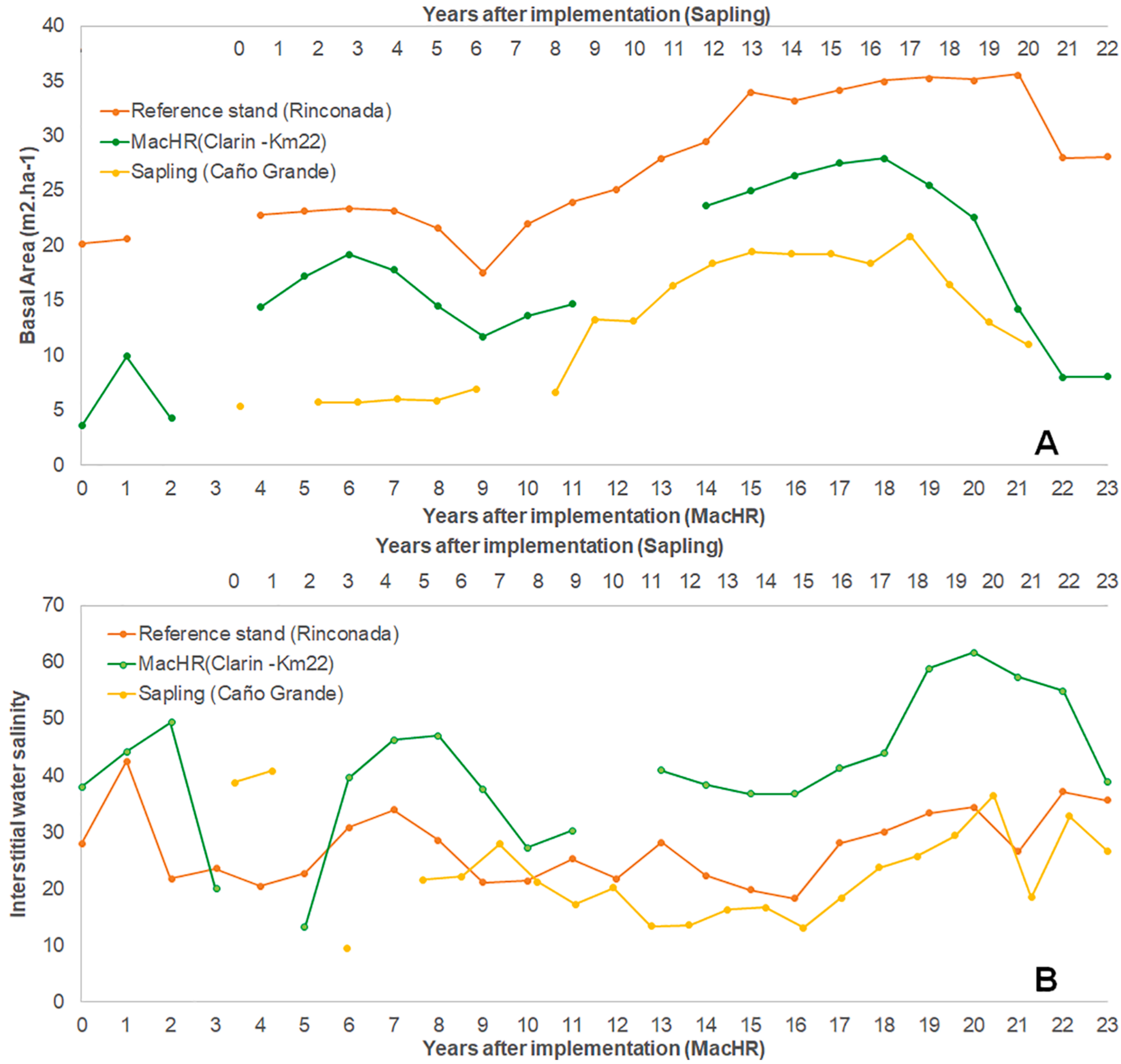

Fig. 8. Restoration trajectories of CGSM mangrove using different techniques. MacHR: Hydrological restoration performed with machinery. Sapling: Planting of *R. mangle*. Trajectories of Basal area (A) and Salinity (B).

or propagules following removal of physical barriers, under EMR and CBEMR approaches, have been developed. Likewise, pollutant removal mechanisms of emission sources have been successfully implemented to allow natural regeneration. Although accordingly to Goldberg et al., 2020, erosion is the main cause of mangrove loss in South America, this study did not record experiences to overcome it; therefore, an urgent need is the development of technical capacity and protocols applied to improve experiences in mangrove restoration when erosion is the main threat.

Experiences in a delta-type mangrove exposed to hydrological deterioration (CGSM) showed that under the EMR approach at the beginning of the restoration program, knowledge of the hydrology of wetlands and their connectivity problems at the landscape scale is require to guarantee a successful restoration. Urgent actions to restore the flow of the main channels in the wetland could be carried out on a large scale with the use of machinery, based on appropriate technical criteria including models of preferential flows based on micro topographical analyses (Pérez-Ceballos et al., 2020). However, the early incorporation of community approaches acknowledging the users of the system, including agreements for the use of water resources and the integral management of the supply basins, is essential. Once the reestablishment of the hydrological flow has been achieved, the areas to be restored should be prioritized, and small and medium-scale restoration actions designed with local communities (CBREM) to recover the connectivity within the mangrove swamp. After the hydrological or topographic barriers have been overcome at each site, reforestation actions should be evaluated and implemented successfully. The initial diagnosis and the permanent monitoring of the system in hydrological, ecological, and social attributes, will improve the knowledge of the system, better decision making, and strengthening of governance.

Finally, although the number of monitored actions may initially seem high, most were done for less than a year (84.5%), and only in 2.8% were lasted longer than 5 years. Few (21.2%) measured the survival rate of the seeded individuals as an indicator of success, and the remaining action (14.5%) reported, variables related to composition and vegetation structure, or fish habitat to assess improvement in function. Recent proposals, suggest the inclusion of (i) biodiversity analysis (fauna and flora); (ii) composition and structure of vegetation (iii) interaction of biotic and abiotic factors (Dubey et al., 2019); and (iv) potential for sustainable use, using natural sites (López-Portillo et al., 2017), to evaluate the success of restoration in mangrove (Bosire et al., 2008). Therefore, monitoring of mangrove restoration programs in Colombia must to be improved by including additional variables, comparisons with reference sites that need to be identified based on biophysical similarities and differences (e.g Worthington et al., 2020). Long-term monitoring programs of restoration actions with open data policies like those conducted in CGSM are needed to evaluate successes and failures of past, present and future restoration efforts. These programs should to be implemented with previously defined indicators and protocols to obtain standardized data at the national level. MANRESCO v.1 database (Rodríguez-Rodríguez et al., 2021) includes more than 160 restoration actions in Colombia released in this study and is a starting point for future analyses to improve mangrove restoration practices, will undoubtedly increase in this decade.

4. Conclusion

Colombia has almost three decades of experience in restoration actions to face deforestation and selective logging, hydrological alteration, and oil and chemical spill. Assessing the success of the restoration action is challenging now when considering the lack of systematic reports and long-term monitoring. So the general need is in achieving better mechanisms for monitoring, and recording experiences with quality standards, considering the potential to analyze successes and failures based on performance measurements, costs, and benefits of implementation. This study found that success largely depended on the restoration type and the technique used. Techniques that rely of removal of barriers so that natural regeneration can occur and that rely on community-based restoration strategies, seem to be successful and highly recommended.

The main experience in terrigenous delta mangroves with hydrological alteration shows that restoration techniques are complementary at different spatial and temporal scales. However, the choice of each technique needs to be supported by a clear knowledge of the hydrology and ecology of the system to avoid applying a trial and error dynamic and improve relation cost-benefit. Furthermore, sustaining agreements with local actors and community-based restoration approach over time, better governance schemes and mangrove management processes are needed consistently in all mangrove forests in Colombia to overcome challenges and make restoration practices sustainable in the future.

CRediT authorship contribution statement

Rodríguez-Rodríguez Jenny Alexandra: Conceptualization, Data curation, Formal analysis, Methodology, Investigation, Writing - original draft. **Mancera-Pineda José Ernesto:** Conceptualization, Methodology, Writing - review & editing. **H. Tavera:** Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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Further reading

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