Nature-based solutions and carbon dioxide removal

Joseluis Samaniego | Santiago Lorenzo | Estefani Rondón Toro
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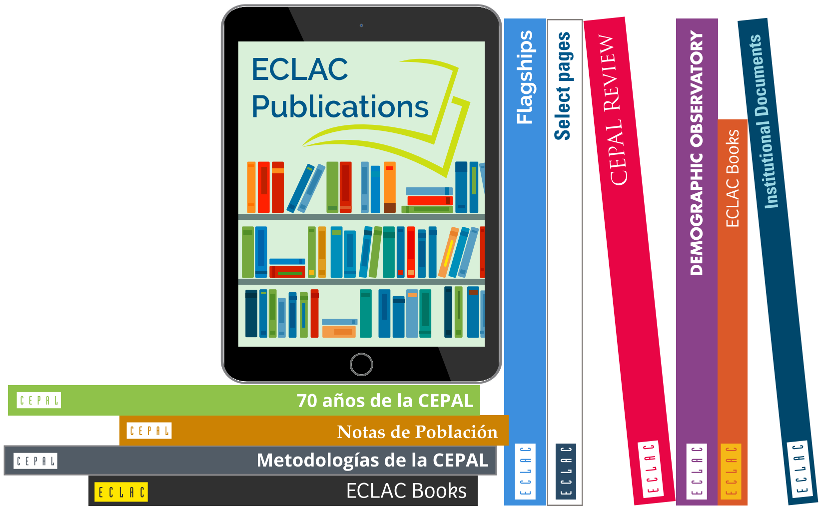

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Abstract

The negative impacts of climate change require an urgent global response to mitigate emissions and strengthen the adaptive capacity of our social, economic, and environmental structures. In Latin America and the Caribbean (LAC), within the context of high vulnerability and with the three crises affecting the region simultaneously, a transformation of development models that lead to a sustainable transition are needed. During this process, national and local policies must be able to take full advantage of the potential of climate action through the adoption of new technologies, innovation, productive reorganization, and the identification of synergies. For this reason, nature-based solutions (NbS) and carbon dioxide removal (CDR) measures and technologies become particularly relevant as a complement to the achievement of climate goals. Under this scenario, this paper examines the opportunities and challenges of large-scale implementation of these measures in the LAC region, emphasizing the need to accelerate the efforts already made, expand the research frontier, and manage risks. The results allow us to recognize the existing limitations and links between objectives, policies, and tools, as well as the co-benefits for their implementation, which can contribute to a major push towards sustainability.

Introduction

Climate change is emerging as an unprecedented problem with the capacity to distort social, economic, and environmental structures worldwide. Scientific evidence confirms the magnitude of the crisis and conveys a sense of urgency to implement action. It also helps to recognize the interdependence between climate variables, ecosystems, and human societies, thus, revealing the multidimensional nature of the problem. From a global and local context, this implies a profound transformation of development models, an accelerated adjustment process, and a sustainable transition towards decarbonization. Therefore, climate policy focuses on mitigating the potential effects of climate change and adapting to already existing risks, based on a holistic view of the problems.

However, climate and socioeconomic vulnerabilities fully determine the extent of these negative impacts. Variation in climate patterns and the intensification of extreme weather events relate to other structures in a complex way. Levels of vulnerability differ strongly between regions, people, and ecosystems. In addition, risks are addressed according to context and location. For example, in Latin America and the Caribbean (LAC), climate change is embedded in a context of low relative emissions, high climate vulnerability, social inequality, and fragile economic structures, which makes increasing resilience and strengthening adaptive capacity a high priority for the region.

Against this backdrop, it is essential to harness the potential of climate action, technological innovation, and ecosystem-based adaptation. It is necessary to explore appropriate and viable alternatives to minimize socioeconomic costs and address the most urgent environmental needs, considering synergies between mitigation and adaptation measures, social inequities, and policy complementarity.

With regard to synergies, measures that simultaneously address mitigation and adaptation objectives constitute a comparative advantage for LAC, and an opportunity to implement comprehensive actions to protect ecosystems, reduce net greenhouse gas (GHG) emissions, and improve the well-being of local communities.

On the other hand, many negative effects of climate change are irreversible. In such cases, mitigation measures are insufficient and adaptation policies become particularly important. Once climate variables exceed planetary boundaries, negative emissions technologies and carbon sinks will be needed. As such, nature-based solutions (NbS) and carbon dioxide removal (CDR) measures and technologies emerge as an option for increasing climate resilience in a regional context, and for building ecosystem-based adaptation.

Currently, CDR measures are in the early stages of the implementation process and there is much uncertainty about their costs, and potential risks and benefits, so it is important to examine in detail the consequences of their implementation at the global level and in the LAC region. In addition, it would be necessary to create international cooperation mechanisms to transfer institutional capacities, financial resources, and innovation.

As background on the development of this topic, during the year 2021 the Economic Commission for Latin America and the Caribbean (ECLAC), the Carnegie Climate Governance Initiative (C2G), and the Torcuato Di Tella Foundation (FTDT) conducted a study to establish the impact that implementing CDR measures and technologies would have on the Sustainable Development Goals (SDGs) in the LAC region (Samaniego et al., 2021). The study identified knowledge gaps for the formulation of recommendations that would allow regional governments to consider the incorporation of CDR measures in national climate change strategies, such as Nationally Determined Contributions (NDCs).

Based on the study conducted by Samaniego et al. (2021), a modeling tool was subsequently developed by CEPAL and C2G (2022) that includes four (4) CDR technologies relevant to the LAC region, allowing for the estimation of the potential economic, social, and environmental impacts that CDR options could have in a given country, particularly with regards to key indicators.

The objective of this document is to broaden the discussion by reflecting on the need to implement ecosystem-based adaptation measures in the LAC region, and the synergies between adaptation and mitigation, based on the measures identified as CDR. This document also discusses GHG emission reduction targets related to the insufficiency of NDCs and global climate targets deriving in the importance of CDR measures in this context. A case study on the problem of desertification in the region is added, making evident the need for solutions to address this problem. Existing CDR measures and technologies in the literature are developed, as well as their implications for governance.

Based on a general context, ECLAC has been working specifically to create an appropriate combination of social and environmental policies together with economic, technological, and industrial policies to contribute to the development of LAC. These policies and their combinations are called the "Great Boost for Sustainability" (CEPAL, 2020). They make it possible to increase investment in high-productivity sectors without increasing vulnerability in the balance of payments and, in turn, generate benefits for environmental conservation, the creation of jobs, and in bringing about the radical transformation of production and consumption patterns that ensure the technological revolution is also at the service of the new development model. Based on this Great Impulse, eight technologically mature and innovative sectors that can be produced within the region and can generate co-benefits, with contributions to employment and a smaller environmental footprint, have been identified:

(i) Transformation of the energy matrix based on renewable energies

(ii) Sustainable mobility and urban spaces

(iii) The digital revolution for sustainability

(iv) The health manufacturing industry

(v) The city industry

(vi) Bioeconomy and NbS

(vii) Circular economy

(viii) Sustainable tourism

Given that agriculture, livestock, and land-use change represent 42% of the total emissions in the LAC region (Bárcena et al., 2021), NbS would represent a mitigation opportunity. NbS are also an important tool for increasing the region's adaptive capacity, as they reduce exposure and sensitivity to the impacts of climate change. For example, the protection, restoration, or management of natural forests and wetlands in watersheds can secure and regulate water supply and reduce the risk of floods and landslides, as well as soil erosion. Likewise, mangrove restoration, among other environmental services, can maintain a protective barrier for coastal communities against flooding, reducing storm damage, and coastal erosion.

In this way, NbS could replace, complement, or reduce large investments in carbon-intensive infrastructure, while being flexible and easily adaptable to long-term changes such as sea level rise, with lower conservation costs.

Restoring natural heritage through reforestation is also a key step towards decarbonizing economies. These investments are low-cost and safe for storing carbon and providing a global service to humanity. In addition, it is an effective way to generate employment, recover ecosystem services that are vital to reduce vulnerabilities (such as water supply and land use), and avoid ecological disasters.

This document is organized into five chapters that describe the context of the research. In Chapter I, the global climate goals and national commitments derived from the Paris Agreement are described, as well as the regional context of mitigation and adaptation and the level of ambition of the current NDCs. Chapter II delves into how CDRs are embedded in climate strategies and their importance for the region. Chapter III addresses the problem of soil desertification in the global context and in LAC. Chapter IV describes the CDR measures and technologies present in the literature that have reached certain levels of development or implementation. In this same chapter, some governance agendas on CDR measures at the global level are presented. Finally, Chapter V summarizes the impact of CDR measures and technologies on the SDGs, as a case study for LAC.

I. Greenhouse gas emission reduction targets and Nationally Determined Contributions. The problem of insufficiency and global climate targets

This chapter describes the importance of NDCs in meeting the global targets of the Paris Agreement. It indicates the main elements of NDCs needed to achieve an emissions trajectory consistent with the commitments made, and to adapt to the effects of climate change emphasizing on local capabilities, constraints, and the multidimensional view of the problem. Subsequently, the case of LAC and the problem of insufficiency of the NDCs to meet the targets established in the Paris Agreement are presented.

A. The Paris Agreement and national commitments to meet climate goals

Climate change emerges as a global problem that produces collective challenges and requires coordinated actions among countries. At the individual level, anthropogenic activities generate a series of negative effects that are transmitted globally through diverse and complex channels with serious environmental, economic, and social consequences. Specifically, GHG emissions generate permanent and fundamental changes in the earth's global climate and in the intensity and frequency of extreme weather events. Moreover, the environmental dimensions of the problem interact closely with economic and social considerations of equity, inclusion, sustainable development, and justice, which represents an additional challenge and requires efforts of a holistic nature.

For this reason, the Paris Agreement on climate change was proposed and adopted in 2015 as an international mechanism to mitigate GHG emissions and build adaptive capacity to respond to the impacts of the climate crisis worldwide. Based on concrete actions at different time horizons, the signatory countries commit to keep the global temperature increase below 2°C, with respect to pre-industrial levels, and to make efforts to limit this increase to 1.5°C (UNFCCC, 2015).

According to climate projections by the Intergovernmental Panel on Climate Change (IPCC), the commitments made in the Paris Agreement, under a future scenario of strict emissions reductions (RCP 2.6),[1] put the global average temperature on track to meet the proposed targets by the end of the century. However, the current emissions trajectory, under the RCP 8.5 scenario, leads to a change in global average temperature well above these targets, with an increase greater than or equal to 4°C, which would generate devastating consequences on ecosystems, the economic structure, and the social fabric (IPCC, 2013). For the LAC region the historical trend is similar, and the negative effects of the environmental crisis are already present, with increasing intensity and frequency of extreme phenomena throughout the territory (Magrin, 2014). Similarly, climate models and future trajectories reveal the fragility of our ecosystems and the interdependence between regions. Behind the global goals there are local responsibilities and complementary objectives among the signatory countries, therefore, the effective implementation of the Paris Agreement requires an approach that recognizes these elements.

B. The NDCs: the main mechanism to create binding plans and meeting global targets

Based on the above, countries are encouraged to design and implement ambitious mitigation and adaptation policies, so that the Paris Agreement commitments are translated into precise and binding activities. Thus, the NDCs are the main mechanism for establishing individual commitments and national efforts to mitigate GHG emissions and adapt to the effects of climate change in a specific context. Therefore, NDCs embody the present conditions and capabilities that LAC countries have in contributing to the achievement of the Paris Agreement climate objectives (Samaniego et al., 2019).

Every five years, members must report progress and propose progressively more ambitious targets. Commitments and actions are reported, after going through a rigorous institutional planning and implementation process, where strategies related to financing, monitoring and reporting, governance, and the creation of environmental programs and plans are set. Priority sectors and international assistance requirements are also established.

Based on this process, countries build a roadmap to achieve carbon neutrality by the mid 21st century and to contribute to the reduction of global average temperature by mitigating their emissions. Once the NDCs of the signatory countries are reported, the true capability of the Paris Agreement to achieve the proposed goals at a given moment in time is revealed, since it is only through national plans that binding climate pacts are created (Samaniego et al., 2019).

As part of the collective effort enshrined in the Paris Agreement, it is recognized that NDCs are framed in a national context, where mitigation and adaptation targets are weighted according to local needs, and the economic and social conjuncture. In this sense, the ambition of the objectives considers a broad set of factors that are inserted in the climate sectors and produce impacts on other dimensions such as poverty, inequality, growth, and inclusion, so that the NDCs are configured differently in developed and developing countries. It is therefore a matter of articulating individual plans through a full appreciation of national conditions and cross-country linkages.

This recognition, rather than limiting local climate action, makes it possible to maximize the transformative potential of policies and identify the main drivers of change. From this, the participatory elaboration of NDCs is sought incorporating the opinions, needs, rights, and aspirations of society as a whole, so that the design and implementation are relevant, timely, transparent, and inclusive (Muñoz Ávila, 2016). According to the Paris Agreement recommendations, countries should include the following

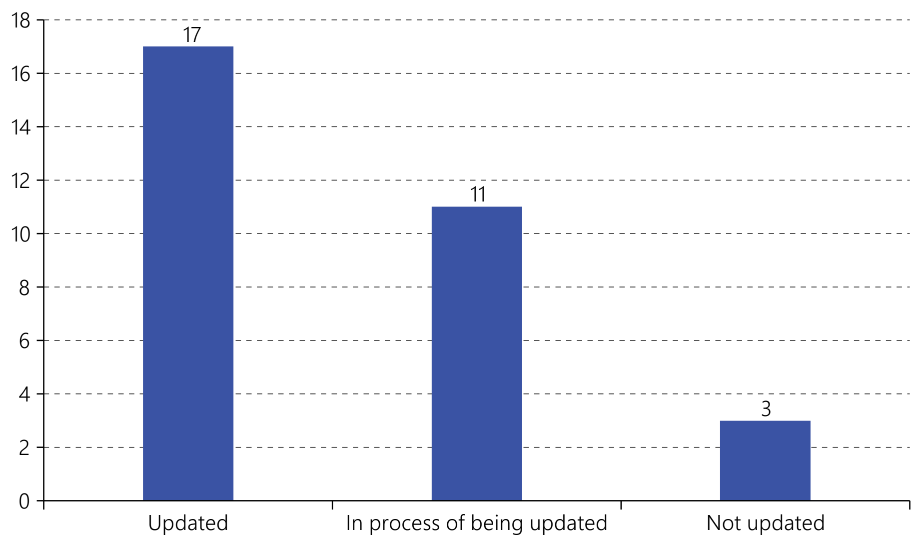
---

[1] Representative concentration trajectories (RCPs) are future scenarios of GHG concentrations and emissions, and function as a guide for monitoring compliance with the Paris Agreement targets. They are plausible scenarios that provide insight into the potential consequences of climate policies (IPCC, 2018).

information in their NDCs: planning process; sources of quantifiable information; implementation timelines; scope and coverage; assumptions and methodological approaches; equity and ambition considerations of the NDC; and details on the achievement of the UNFCCC objectives (Bakkegaard, 2015).

More than five years after the ratification of the Paris Agreement, countries face the challenge of strengthening their national plans and accelerating the implementation of mitigation and adaptation policies. According to the latest UNFCCC NDC synthesis report, 164 plans out of 191 Parties are available in their most recent version, with 86 new or updated commitments, and representing 93.1% of total global emissions in 2019 (UNFCCC, 2021). In LAC, 17 of the 33 Parties that signed the Agreement submitted their updated plans in August 2021, representing more than 83% of the region's emissions (Samaniego et al. 2022).

Figure 1
Status of NDCs in Latin America and the Caribbean
(Number of countries)



Source: Samaniego et al. (2022).

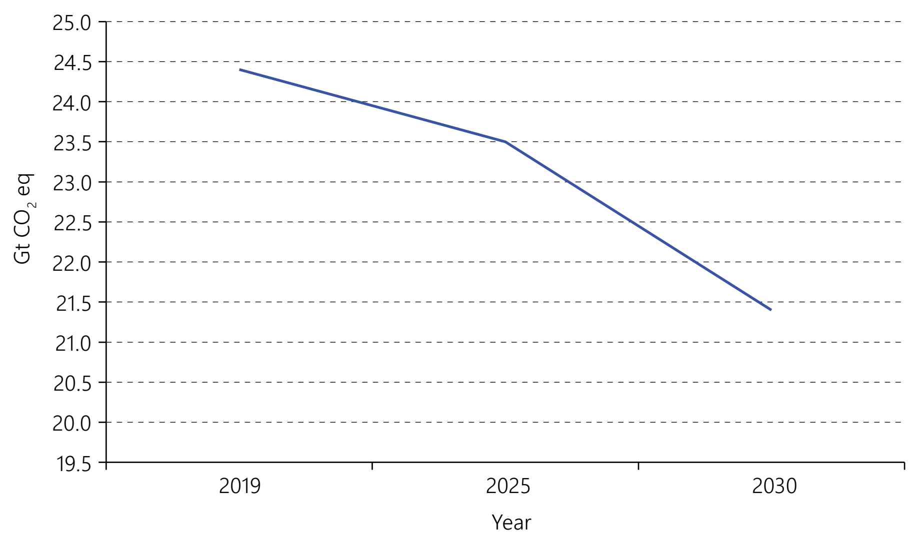
C. The ambition of the national goals and the problem of insufficiency

Globally, the poorest countries and most vulnerable regions are leading the way in implementing increasingly ambitious NDCs, either by updating their mitigation targets or introducing new adaptation actions. In 2021, Least Developed Countries and Small Island Developing States lead the way in increasing NDC ambition, with 86% of these countries increasing their emission reduction targets. Nevertheless, it is necessary to increase the efforts of the developed countries of the G20 (Group of Twenty), which emit more than 75% of GHGs worldwide and account for about 80% of gross domestic product (GDP). Currently, 16 of the member countries have communicated revised versions of their NDCs, and five of these have not increased the ambition of their targets (UNDP, 2021).

Under the current state of the NDCs, the sum of national commitments would lead to a 3°C increase in the global average temperature of the earth in 2100, relative to pre-industrial values, and the maximum level would be reached by 2030. It is estimated that total GHG emissions in the countries that submitted their updated NDCs would be around 23.5 Gt CO_2 eq in 2025 and 21.4 Gt CO_2 eq in 2030, compared to 2019 emissions of 24.4 Gt CO_2 eq. On the other hand, when the outdated NDCs are included, emissions from all Parties would be 54.8 and 55.1, respectively (UNFCCC, 2021). However, the IPCC's 1.5°C Special Report on Global Warming suggests that countries should commit to more pronounced reductions in GHG emissions.

Specifically, net anthropogenic CO_2 emissions are expected to be reduced globally by 45%, relative to 2010 levels by 2030, and to reach carbon neutrality by 2050, so that the increase in the earth's average temperature does not exceed 1.5°C (IPCC, 2018). Regarding the carbon budget, the most recent NDCs would use 89% in the 2020-2030 period, leaving only 55 Gt of CO_2 to limit the temperature increase to 1.5°C, with a 50% probability. Based on the above, to comply with the Paris Agreement it is imperative to increase the ambition levels of the NDCs to align emissions with the trajectories considered by the IPCC (UNFCCC, 2021).

Figure 2
Projected CO_2 emissions with the implementation of the updated NDCs



Source: Own elaboration based on UNFCCC (2021).

In the LAC region, and according to a study conducted by ECLAC in 2019 (Samaniego et al., 2019), unconditional mitigation commitments in the NDCs would lead to a 13% reduction in GHG emissions by 2030, with respect to an inertial scenario. The reduction would amount to 23% with conditional targets, which is insufficient to achieve the 1.5°C goal, although it is moderately close to the 2°C target. Based on the updated study presented in 2022 (Samaniego et al., 2022), the unconditional commitments would lead to an emissions reduction of 22% with respect to an inertial scenario, while with the conditional targets the reduction amounts to 28%. This implies an increase in climate ambition of 400 $MtCO_2eq_2$, with respect to the NDCs presented in 2015. However, countries would need to set commitments to reduce emissions by 39% and 55%, respectively, to meet the 2°C and 1.5°C target of the Paris Agreement. To move towards a trajectory consistent with the Paris Agreement, the countries of the region would need to triple the speed of decarbonization in the next 10 years. However, it should be noted that approximately 60% of LAC emissions are concentrated in three countries: Argentina, Brazil and Mexico.

On the other hand, most of the NDCs worldwide report other goals to redirect their economies towards a sustainable, low-carbon, and resilient path. The environmental, economic, and social dimension of the problem and their link to the SDGs are mentioned. Nearly 20% of the NDCs submitted analyze the relationship between the climate policies in their plans and the SDGs, emphasizing the links identified in each of the 17 goals. For example, the presence of gender considerations in almost half of the plans, through the development of policies, programs, targets, and indicators stands out. In addition, the NDCs updated to 2021 make greater efforts to incorporate the opinion of civil society, the private sector, NGOs, and government agencies, which increases the level of ambition in mitigation and adaptation policies (UNDP, 2021).

Mechanisms for incorporating NDCs into national legislative and regulatory processes, so that countries have the real capacity to implement policies, are also mentioned. It includes information on institutional arrangements, allocation of responsibilities, and existing gaps in the legal framework. From this process, national commitments begin to acquire a binding character that guarantees compliance with the Paris Agreement in the long term.

While there is currently scientific knowledge and a comprehensive set of tools to fight climate change, financing is one of the main obstacles in increasing ambition. According to IPCC (2018), between $1.6 trillion and $3.8 trillion per year is required between now and 2050 to meet the energy supply side. NDCs also expect to have between $3.5 trillion and $4.4 trillion to meet their emission reduction commitments, which is far from the available climate capital (UNDP, 2021).

On the other hand, the conditional commitments of developing countries will depend on access to financial resources, the speed with which these resources are allocated, and the alignment of their own capital markets with the Paris Agreement objectives. In both 2019 and 2021, countries recognize finance as the main barrier in accelerating implementation of their NDCs. According to the survey conducted by the United Nations Development Programme (UNDP) in the "State of Climate Ambition", only 15% of countries have a defined financing strategy in their updated plans. Furthermore, resources come mainly from the public sector, which can be risky for poor countries with fragile fiscal systems, reduced fiscal space, and little access to international markets (UNDP, 2021). In this regard, it is vital to highlight the importance the private sector has in closing the resource gap and designing sustainable financing strategies over time (CEPAL, 2021).

At the same time, the viability of NDCs will depend on factors related to institutional capacity building and technology transfer. Once the countries have the financial capital to implement their plans, it will be necessary to eliminate climate governance barriers and create coordination mechanisms between the organizations in charge of implementing the plan, so that the potential of the prioritized actions is maximized.

D. The problem of climate change and national commitments in Latin America and the Caribbean

For the LAC region, information on NDCs is largely available on the Ministry of Environment's official website for each country, with details of the citizen participation process and other elements of planning, implementation, and monitoring. In addition, the NDC LAC tool, developed by United Nations agencies and other organizations, compiles relevant information on commitments, the status of compliance with NDCs, policies developed, and key monitoring indicators (CEPAL, n.d.). More information on the NDC LAC tool is specified in box 1.

The process of developing NDCs in the region would require taking into account the factors that characterize the climate change problem and the socioeconomic contexts of the countries. At a general level, the LAC region suffers from a marked asymmetry between contribution to global GHG emissions and climate vulnerability (Bárcena et al., 2020).

The negative effects of climate change are transmitted to LAC countries in a heterogeneous and non-linear manner, with consequences for the productive sectors and other rural and urban sectors. It is estimated that, by 2050, economic losses due to climate change will range between 1.5% and 5% of regional gross domestic product (GDP) (Bárcena et al., 2020).

Box 1
NDC Latin America and the Caribbean

The NDC LAC is an information tool for sharing commitments, progress, and the status of compliance with the Nationally Determined Contributions (NDCs) in Latin American and Caribbean countries. This is an initiative developed by ECLAC, in conjunction with EUROCLIMA+, the Inter-American Development Bank (IDB), the United Nations Development Programme (UNDP), the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), the Avina Foundation and the LEDS LAC Regional Platform, which seeks to generate synergies to improve the effectiveness and accelerate the implementation of the Paris Agreement in the region. With transparent access to this information, the aim is to provide feedback to the process of designing climate plans, policies, and projects, based on past experiences and scientific evidence. Based on the recognition of gaps, challenges, and strengths the platform allows visualizing the current status of NDCs in the region and outlining the next steps to increase the ambition of the goals.

The NDC LAC consolidates, in one place, information from three complementary efforts:

(i) The systematization and analysis work of the Peer Dialogue —an action financed by EUROCLIMA+, and executed through a strategic alliance between GIZ and ECLAC, with support from the Avina Foundation.

(ii) The study with an overview of NDCs in the region carried out by ECLAC.

(iii) The LEDSenLAC report conducted by the LEDS LAC platform with support from IDB and UNDP.

Source: Own elaboration based on CEPAL (n.d.).

It is essential that LAC countries include a broad portfolio of adaptation policies in their national sustainable development strategies, particularly in their NDCs. According to the World Bank estimates, the economic cost of these policies in developing countries for the middle of the 21st century is approximately 0.12% of GDP. For the region in particular, the estimated cost is less than 0.5% of GDP, and is concentrated in the agriculture, water resources, coastal zones, health, and biodiversity sectors (World Bank, 2010). In addition, and according to the UNFCCC, financial resources of approximately US$ 23 billion are needed to implement adaptation policies in the water resources sector by 2030, and between US$ 570 and 680 million in the coastal zone sector, in both cases for the construction of resilient infrastructure and "hard" adaptation measures (UNFCCC, 2007).

However, this adaptation process, although essential, entails great challenges and limitations. While solutions to climate change must be global, adaptation strategies are based on local needs and capacities, as each country is responsible for and benefits from adjusting their structures to respond to the environmental crisis. Adaptation measures have fewer global co-benefits (or externalities), compared to mitigation measures, as systems are reshaped in a specific geographical area (CEPAL, 2015). Nevertheless, the IPCC proposes the simultaneous implementation of mitigation and adaptation policies in national plans, recognizing their complementarity and interconnection (Magrin, 2014). Likewise, it is important to ensure international cooperation so that the transition to a low-carbon economy is uniform throughout the world.

Based on the above and on the updated information presented by Samaniego et al. (2022), most NDCs in the region prioritize adaptation sectors and actions, with 32 of 33 countries including these strategies in their national plans, which leaves in evidence the importance of responding to changes in climate conditions (table 1). In addition, 70% of LAC countries include both adaptation and mitigation measures in their NDCs, in accordance with the commitments made in the Paris Agreement. With respect to the NDCs updated in 2021, 14 of the 17 new documents strengthen the adaptation component.

Table 1
Mitigation and adaptation measures distributed by sector in the NDCs. Sectors included are only for countries that submitted their updated plan

Country	Energy	AFOLU	Water	Transportation	Waste	Industries	Buildings	Agriculture	Health	Biodiversity, forests and EbA	Infrastructure	Cities, HS, and LuP	Oceans and coastal zones	Risk management	Tourism	Education	Social development
Argentina	●▲	●	▲	●▲	●	●	●	●▲	▲	▲	▲	▲	▲	▲	▲	▲	
Brazil	●	●	▲	●▲		●		●	▲		▲	▲		▲			
Chile	●▲	●	▲	●▲	●	●	●	●▲	▲	▲	▲	▲	▲	▲	▲		
Colombia	●▲	●	▲	●▲	●	●	●	●▲	▲	▲	▲	▲	▲	▲			▲
Costa Rica	▲		▲	▲				▲	▲	▲	▲	▲	▲	▲	▲	▲	
Cuba	●	●	▲	●▲				●▲	▲	▲	▲	▲	▲	▲	▲		
Grenada	●	●		●	●	●		▲		▲					▲		
Honduras	●▲	●	▲	●▲	●	●		●▲	▲	▲	▲	▲					▲
Jamaica	●▲	●	▲	●▲	●			●▲	▲	▲	▲	▲	▲	▲	▲		
Mexico	●	●	▲	●▲	●	●	●	●▲	▲	▲	▲	▲	▲	▲			
Nicaragua	●	●	▲	●▲				●▲	▲	▲	▲	▲					
Panama	●▲	●	▲	●▲	●			●▲	▲	▲	▲	▲	▲	▲			
Paraguay	●▲	●	▲	●▲	●	●		●▲	▲	▲	▲	▲		▲			
Peru	●	●	▲	▲	●	●		●▲	▲	▲	▲		▲	▲	▲		
Dominican Republic	●	●	▲	●	●	●		●▲	▲	▲		▲	▲	▲	▲	▲	
Saint Lucia	●		▲	●▲				▲	▲	▲	▲	▲	▲		▲	▲	
Suriname	●	●	▲	●▲				●▲	▲	▲	▲		▲				

Mitigation ● Adaptation ▲

AFOLU: Agriculture, Forestry, and other Land-use
EbA: Ecosystem-based Adaptation

HS: Human Settlements
LuP: Land-use Planning

Source: Own elaboration based on Samaniego et al. (2022).

In the case of mitigation, the most important sectors (according to their potential to reduce GHG emissions) are energy, transport, agriculture, and AFOLU (Agriculture, forestry and other land use) and focus on renewable energy deployment, sustainable biodiversity management, climate-smart agriculture (CSA), and regulation. This trend is consistent with the sectoral structure of emissions in the region, where 29% of total emissions come from the energy sector, 26% from the agriculture sector, 20% from the AFOLU sector and 15% from the transport sector. Moreover, updating the NDCs made it possible to include other sectors, such as waste management, biodiversity, and the housing sector, and to introduce a multisector approach.

With regards to adaptation, policies focus on reducing or eliminating vulnerability in the sectors that are most exposed. In the NDCs of the LAC region, the most important adaptation sector is water resources, which includes actions for sustainability and water security, sustainable watershed management, wastewater sanitation, and implementation of a regulatory framework for water use and agricultural activities. The health, biodiversity, and agriculture sectors also stand out, which are present in most of the commitments in the region. On the other hand, the sectors of tourism, infrastructure, resilient cities, and coastal zones are limited to a small number of countries with particular conditions, and where the proposed measures depend on the development structure and the anticipated impacts of climate change.

1. Nature-based solutions (NbS) and the NDCs

Globally, NDCs project 25% emission reductions in the AFOLU sector (Grassi, 2017), and NbSs are estimated to have the potential to globally reduce 30% of the emissions needed to meet Paris Agreement targets by 2030 (Seddon, 2020).

Of the new NDCs submitted globally, 21% include wetland management as a mitigation strategy, while reforestation measures and forest management are in at least 55% of the commitments. Likewise, NbS are introduced in these documents as tools for coastal restoration and disaster prevention in areas exposed to sea level rise and ocean acidification, as well as for the construction of resilient infrastructure. It is equally important to have these alternatives available to address the challenges of forced displacement of human settlements vulnerable to climate change risks (UNFCCC, 2021). From this systemic approach, countries can generate larger, cross-sectoral impacts.

In the case of LAC, the updated NDCs also reveal significant progress in the NbS. Measures related to forest conservation and reforestation stand out, which favor carbon sequestration, reduce vulnerability to extreme events, and protect the environment. For example, countries such as Costa Rica, Colombia, Chile, Mexico, and Panama include actions to conserve forests and reforest the territory. For LAC, these solutions bring environmental, economic, and social benefits, and increase the countries' adaptive capacity. For example, Cuba, in its NDC, seeks to protect beaches, reefs, mangroves, and their ecosystems in order to reduce the human and economic impact of hurricanes (Samaniego et al., 2022).

2. Carbon dioxide removal (CDR) measures and technologies, and NDCs

The mitigation strategies considered by the IPCC in the construction of future trajectories incorporate CDR measures and technologies (also called negative emissions), to achieve the Paris Agreement goals. According to the projected scenarios, the use of these should range between 100 and 1,000 Gt CO_2 during the 21st century, so that the earth's global temperature does not exceed 1.5°C. Therefore, these strategies could prove essential to stabilizing CO_2 emissions in sectors experiencing challenges in decarbonization. However, the adoption of these measures and technologies is subject to sustainability and feasibility constraints, as they are at an early stage of implementation (IPCC, 2018).

CDR measures and technologies correspond to a set of techniques or processes to remove CO_2 from the atmosphere and offset residual emissions. These technologies can be classified into two types: those that enhance natural processes that remove CO_2 from the atmosphere such as trees, wetlands, or other carbon sinks, or those that use chemical processes to directly capture CO_2 and store it.[2]

Currently, CDR measures and technologies are not significantly present in the national strategies of the Paris Agreement, as they remain an exploratory field with uncertainty about costs, risks, and expected impacts. In LAC, the NDCs include few measures or lines of action on these technologies and are not part of a priority plan to strengthen adaptive capacity or reduce emissions. Only isolated actions are identified, such as the use of new energy generation, storage, transmission, and distribution technologies, but no concrete policies are developed to promote the adoption of CDR measures and technologies (Samaniego et al., 2022). Therefore, it is essential to develop research and innovation processes to evaluate the expected effects of implementing these technologies in LAC countries. This would make it possible to establish the steps prior to the design of a roadmap, through its consideration in the NDCs, which will contribute to overcoming the aforementioned obstacles.

2 Chapter IV of this document describes the CDR measures and technologies found in the literature that have some degree of development or implementation worldwide.

II. Carbon dioxide removal measures and technologies, and their relevance to Latin America and the Caribbean: regional overview, challenges, and opportunities

This chapter introduces CDR measures and technologies as an alternative for meeting global climate goals, which can be complementary to the sectors identified in the NDCs. It discusses the challenges, opportunities, and the need to move towards their implementation in the LAC context.

According to the future climate scenarios constructed by the IPCC, all trajectories consistent with meeting the Paris Agreement targets project the use of CDR measures, whether in the short, medium, or long term. In the event that global temperature rise temporarily exceeds 1.5°C, the amount of CO_2 removed from the atmosphere will be required to exceed the amount entering, resulting in "negative net emissions." Given fragile climatic conditions, these technologies function as a stabilizing mechanism to respond to unexpected shocks, thereby increasing the adaptive capacity of countries. As biological ecosystems approach planetary boundaries and their tipping points, further deployment of CDR measures will be necessary to redirect emissions to sustainable trajectories (IPCC, 2018).

LAC is characterized by asymmetry between low emissions and high vulnerability, since the region contributes a small fraction to GHGs globally but suffers disproportionately from the effects of climate change (Bárcena et al., 2020). This scenario imposes additional pressures to improve adaptive capacity and resort to other types of solutions, such as, for example, more related and/or nature-based CDR measures (Samaniego et al., 2021).

The productive sectors that have opportunities for mitigation and adaptation in LAC are particularly vulnerable to climate change impacts, both due to physical and transitional risks. For example, the agricultural sector plays a strategic role in the countries of the region accounting for nearly 5% of GDP, 20% of the employed population, and 25% of exports. However, its activities are particularly sensitive to climate change, which is expected to produce permanent changes in crop cycles, field productivity, structure, and yields. In fact, it is estimated that agricultural productivity in LAC may fall between 12.9% and 24.3% as a result of climate change, with heterogeneous impacts depending on the socioeconomic, geographical, climatic, and technological conditions of the countries (Bárcena et al., 2018).

On the other hand, the region's energy sector accounts for less than 5% of global emissions, but it is highly exposed to shocks in the electricity generation system due to global climate variations and the intensification of extreme weather phenomena. In this sense, it is important to modify energy demand sustainably and redistribute sources (Bárcena et al., 2018).

Similarly, the region is characterized by great richness in biodiversity as well as in terrestrial and marine ecosystems. Globally, LAC concentrates 24% of the world's terrestrial ecoregions, 18% of the world's marine ecoregions and a third of the planet's water resources (UNEP, 2022; BID, 2018). This generates the potential to naturally absorb CO_2 through carbon sinks such as wetlands, forests, oceans, mangroves, and paramos. In addition, 20% of jobs in LAC depend heavily on ecosystem services and 12% of housing is built with forest-derived products (CEPAL and OIT, 2018; Hickey and Wellenstein, 2020).

Table 2
Biodiversity data in Latin America and the Caribbean

24%	of the world's terrestrial ecoregions are in Latin America and the Caribbean
18%	of the world's marine ecoregions are in Latin America and the Caribbean
1/3	of water resources are located in the region
20%	of jobs in Latin America and the Caribbean depend heavily on ecosystem services
12%	of homes are built with forest-derived products

Source: Own elaboration based on UNEP (2022); BID (2018); CEPAL and OIT (2018); and Hickey and Wellenstein (2020).

Therefore, the management, regeneration, and use of these ecosystems allows LAC countries to increase mitigation and adaptation capacity in a sustainable manner and conserve the region's heritage. In addition, the management of carbon sinks directly involves community participation and simultaneously allows to address other social and economic objectives (BID and DDPLAC, 2019). Box 2 presents the summary of a study on the potential positive impacts of mangrove conservation to manage climate risks in coastal ecosystems.

Box 2
Mangrove restoration as an adaptation tool in coastal ecosystems

Mangroves are coastal ecosystems that integrate the marine and terrestrial environment and produce great benefits for climate adaptation. In addition to being powerful carbon sinks and promoting biodiversity conservation, mangroves have great potential to protect coasts by reducing waves, erosion, and the intensity of extreme weather events. In this sense, sustainable management and restoration of mangroves stands out as a nature-based solution to increase adaptive capacity, mitigate CO_2 emissions, and protect communities.

With this in mind, researchers from the Institute of Environmental Hydraulics of the University of Cantabria conducted a study to estimate the capacity of mangroves to attenuate ocean waves and protect coasts, through a new methodological approach that identifies the causal relationship between mangrove age and wave attenuation. The study is based on Rhizophora mangrove species in Vietnam, Australia, and Japan, considering ecosystem characteristics, wave properties (height and period), tree morphology, forest density, and water depth levels, without using calibrations. The available data and the estimation method help to calculate the attenuation capacity throughout the life cycle of the mangroves, which makes it possible to determine the time expected for protection and restoration measures to have an effect on the waves.

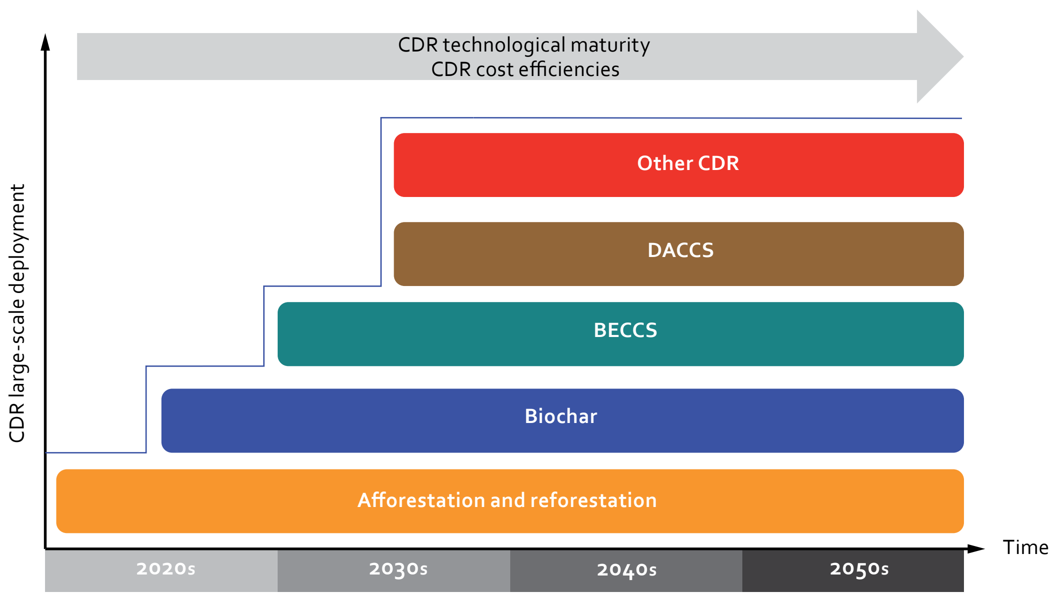
The study finds that after restoration, the mangrove takes 5 years to obtain maximum coastal protection capacity and maintains it for the rest of its life. These results incentivize the restoration and sustainable management of mangroves, as they provide accurate estimates of the expected time horizon for perceiving the maximum potential of the policy, facilitating decision-making and accelerating the adoption of nature-based solutions in coastal management.

Source: Own elaboration based on Maza et al. (2021).

Based on the above, CDR measures and technologies would emerge as an alternative response to climate, economic, and social challenges of the region, so that future trajectories are consistent with the goals of the Paris Agreement. However, it is equally important to understand the expected impacts of the deployment or implementation of CDR measures and technologies from a multidimensional approach, considering the negative side effects that could manifest directly or indirectly.

Based on the above, the study entitled "Impact of CDR measures and/or technologies on the Sustainable Development Goals (SDGs) in selected countries in Latin America and the Caribbean," conducted by Samaniego et al. (2021) and summarized as a case study in Chapter V, rigorously assesses the potential benefits and impacts of large-scale implementation of CDR measures and technologies in the LAC region. The results highlight the importance of advancing research and implementation of pilot projects on these measures and technologies in the short, medium, and long term, prioritizing according to technological maturity and cost efficiency. These processes should begin well in advance of the large-scale implementation phase, in order to achieve adequate technological development and optimize financial costs. Diagram 1 presents a proposed process for large-scale implementation of CDR measures and technologies in LAC countries, as suggested in Samaniego et al. (2021).

Diagram 1
Suggested phasing of large-scale CDR deployment in Latin America and the Caribbean countries



Source: Own elaboration based on Samaniego et al. (2021).

Generally speaking, the transition must recognize the links formed between the countries' productive system and the natural resources that coexist in the same geographical area, so that the process is integrated, transformative, and inclusive, since neither the environment nor the socioeconomic structures operate in independently in the territory. Rather, they are part of an environment that is completely interrelated and sensitive to change. This raises the need to understand in detail the problems related to the use and management of natural resources. For this reason, the following chapter delves into the problem of soil desertification in LAC and how NbS, especially nature-based CDR measures such as afforestation and reforestation can contribute to meeting environmental, economic, and social objectives.

III. The problem of land degradation and desertification. Deforestation: the global context with a focus on Latin America and the Caribbean

The need to propose sustainable paths for the economy of Latin America and the Caribbean that are consistent with the acute challenges of the 21st century, calls for the insertion of our economy into the limits, potentials, and productivity of our ecosystems. Prosperity, democracy, security, and the well-being of our communities cannot be achieved without our environmental system and its biophysical limits being deeply considered by regional economic development strategies. In the same way, productive chains, jobs, and income generation must be developed based on the sustainable functioning of ecosystems, maximizing the productivity offered by their goods and services. We, therefore, need a set of policies that are articulated and consistent with the challenges of our time, and that will enable us to overcome the constraints on the necessary transition towards sustainability imposed by current land use in LAC.

The generation of new jobs and income should consider new, more sustainable production and consumption processes that facilitate innovation in the urban environment, promoting the maintenance of agro/silvo/pastoral systems' productive capacity and a strong transition towards renewable energies. The strategy of action should prioritize sectors that have the potential to disseminate impacts on the economy in a synergetic manner and that, therefore, constitute initial conditions for advancing/producing a great environmental impulse.

Efficient management of the links between water, soil, and biodiversity must find expression in a new rurality where integrated agroforestry systems and bioeconomic processes promote new forms of organization of value chains associated with natural resources (bio-chains) and the generation of circular economy flows. The identification/selection of the best landscape management strategies allows for increased productivity (animal and by area), smaller environmental footprints, and the recovery of degraded areas with negative emissions. The environmental conversion of agricultural production, therefore, allows the creation of wealth and employment with a wide distribution of economic and social benefits.

A. The state of forests in Latin America and the Caribbean

From fighting poverty and hunger to mitigating climate change and conserving biodiversity, the impacts of forests and trees contribute to multiple goals and targets of the 2030 Agenda. Managing forests sustainably brings benefits to both urban and rural communities, as forests have indispensable economic and environmental functions for society.

Their provision of environmental goods and services, such as water quality, is directly related to forest management. Changes in land cover, land use, and land management have serious impacts on the water supply of a country. The economic dimension of this contribution to society is not fully captured by the current economic measurement systems.

The FAO (2018) indicates that three-quarters of the planet's accessible freshwater comes from forested watersheds, and research highlights that 40% of the world's 230 most important watersheds have lost more than half of their original tree cover. Despite this, forest area designated for soil and water conservation has increased globally over the past 25 years and, in 2015, a quarter of forests were managed for soil or water conservation. For example, the cloud forests of La Tigra National Park in Honduras, provide more than 40% of Tegucigalpa's water supply, while in Ecuador, 80% of Quito's population receives drinking water from two protected areas (UNCCD, 2017).

The energy sector (in addition to water production for hydropower) also receives strong contributions from forests. About one-third of the world's population, that is, about 2.4 billion people, use wood for basic energy services such as cooking, boiling water, and the heating of homes (FAO, 2018). The same study notes that forests supply approximately 40% of the world's renewable energy in the form of woodfuel; this is equivalent to solar, hydro, and wind combined. Attention must now turn to a more sustainable production of woodfuel to reduce forest degradation, as well as a cleaner and more efficient production to improve the health of millions of people, particularly women and children.

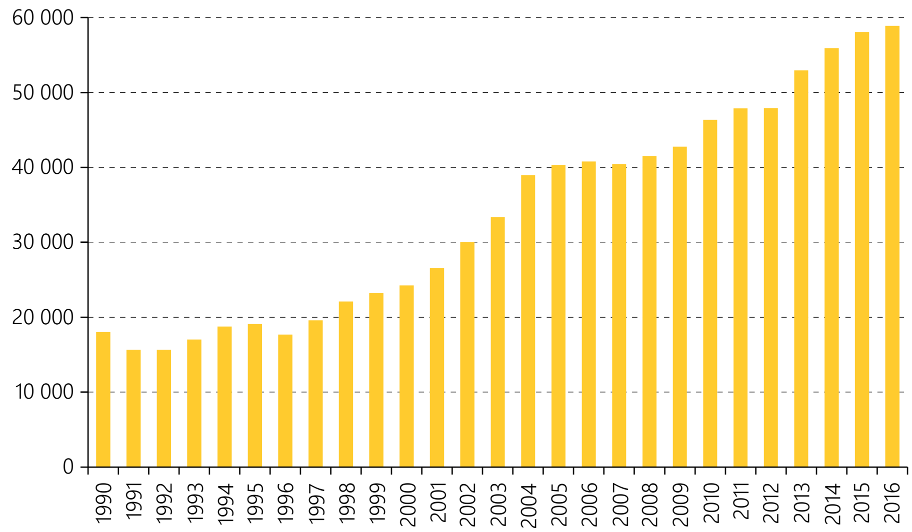
Modernizing the traditional forest energy sector offers the potential to improve livelihoods, create sustainable value chains, and free up resources for investments in sustainable forest management. In LAC, 15% of the population still relies on firewood and charcoal for cooking and water sterilization (FAO, 2017).

The progressive loss of forest cover is, therefore, a strong threat to the economic process. In global terms, from 2001 to 2018 there was a total loss of 361 million hectares of forest cover, equivalent to a 9% decrease in cover since 2000 and a total 98.7Gt of CO_2 emitted (World Resources Institute, n.d.). In a similar period of years (1999-2016), LAC lost 59 million hectares of forest cover, equivalent to a 6% decrease (FAO, 2019).

The drivers of this process have been identified by Hosonuma et al. (2012). Two processes affect forests: deforestation and degradation. Deforestation is the removal of forest cover and its conversion to other uses, such as for agriculture and livestock. Forest degradation occurs through timber extraction, for example, resulting in losses of carbon, biodiversity, and forest structures. In the case of LAC, the agribusiness (agriculture and livestock) is responsible for 68% of deforestation, while timber extraction (often done illegally) is responsible for more than 70% of forest degradation (Hosonuma et al., 2012). Traditionally in South American tropical forests, degradation by timber extraction is the initial process of land use change, followed by clear-cutting (degradation) resulting from livestock and commercial agriculture practices (Fearnside, 2005).

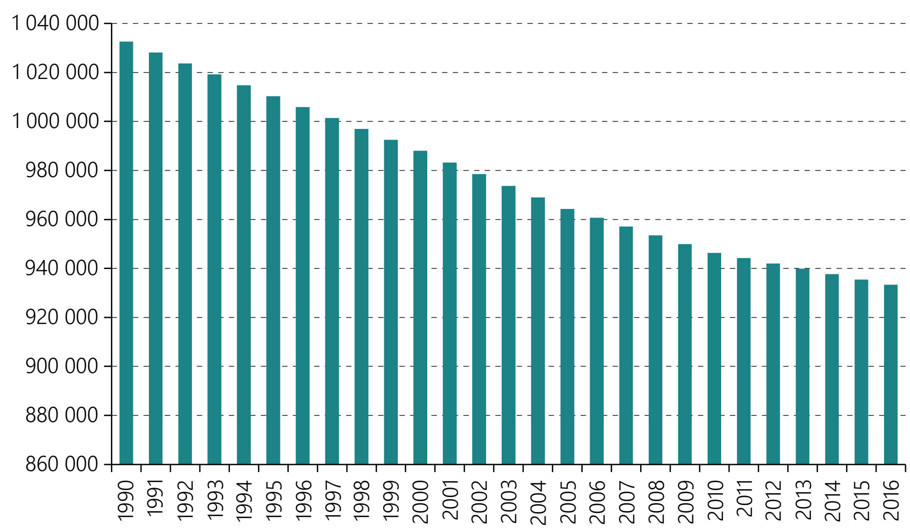
In LAC, soybeans have been the main product of commercial agriculture for export, representing approximately 3.6% of the region's total exports in 2017, after oil (6.1%), motor vehicles (5.7%), and copper ore and concentrates (3.9%) (CEPAL, 2019). Having forest conversion as an expansion mechanism —following the example of other cash crops for export—, soybean harvest area has increased by 40.8 million ha in the period from 1990 to 2016 (CEPAL, 2019) (figure 3), and land dedicated to permanent pasture (5 years or more) has increased by 20.6 million ha (FAO, 2019). At the same time, there has been a loss of 99.2 million ha of forest cover in the same period (FAO, 2019) (figure 4).

Figure 3
Latin America and the Caribbean: evolution of soybean cultivated area
(In thousands of ha)



Source: CEPAL (2019).

Figure 4
Latin America and the Caribbean: evolution of forest cover
(In thousands of ha)



Source: FAO (2019).

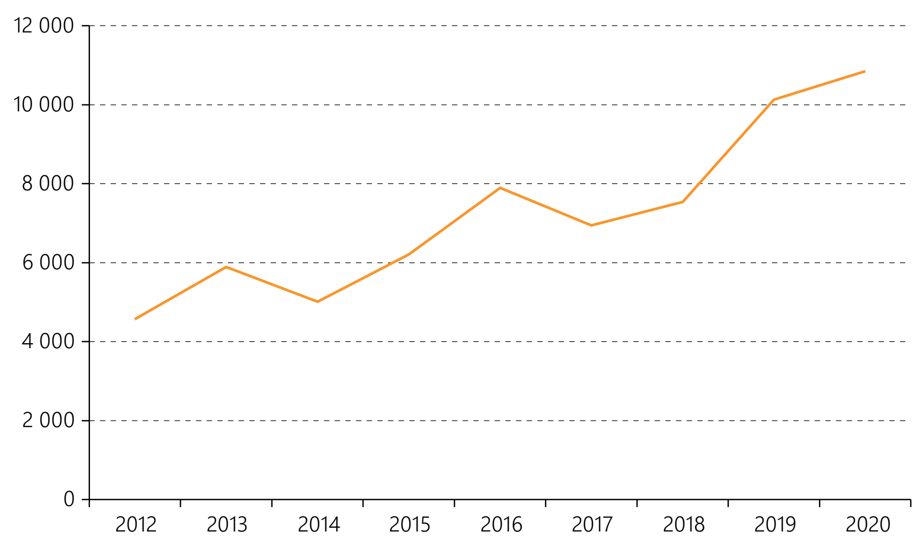
All forests and trees outside forests influence hydrology, but the loss of tropical and subtropical forests can be disproportionately important (FAO, 2018). Recent research suggests that tropical and subtropical forests play a key role in the transport of atmospheric moisture by providing a global circulation system that influences cloud cover and precipitation on a regional scale (Ellison et al., 2017). In the Amazon basin, this effect is referred to as "flying rivers". Van der Ent et al. (2010) indicated that more than 70% of the precipitation in the La Plata River basin originates in the Amazon rainforest. The weakening of the "flying rivers" would have a devastating effect on the South American economy. Similarly, large-scale loss of these huge contiguous rainforests has been linked to declining regional precipitation (Donato Nobre, 2014; Ellison et al., 2017).

However, the Amazon rainforest is going through rapid deforestation. The estimate of deforestation in Brazil's Legal Amazon was 11,088 km2 for 2020, after reaching 10,120 km^2 in 2019 (INPE, 2020). The estimate includes the so-called "clear-cutting", i.e., areas with total forest cover suppression, and represents an annual increase of 9.5% over the previous year. The PRODES system, used to measure deforestation, uses LANDSAT satellite images (20 to 30 meters of spatial resolution and a revisit rate of 16 days). Figure 5 shows the progressive increase in deforestation in this biome.

Research conducted by relevant Brazilian organizations (Instituto Centro de Vida (ICV), Instituto de Manejo e Certificação Florestal e Agrícola (Imaflora), and Universidade Federal de Minas Gerais (UFMG)) concluded that 94% of deforestation in the Brazilian Amazon and in Cerrado are associated with illegal deforestation, (without authorization of vegetation suppression), with significant economic risk implications for the commodities market, producers, and investors. For the states of Acre, Amapá, Amazonas, Maranhão, Piauí, and Roraima, the data refers to the 2018 to 2020 period. Similar reports occur in the rest of the Amazon countries.

High rates of deforestation and illegal logging result in sharp declines in the abundance of mammal, bird, reptile, and amphibian populations. According to the Living Planet Index, in LAC there was a 94% decline in species abundance between 1970 and 2016 (WWF, 2020). The main cause was habitat loss. It is important to note that the underlying causes of the COVID-19 pandemic are the same as those driving climate change and biodiversity loss (IPBES, 2020). These include changes in land use, deforestation, and agricultural intensification that disrupt natural interactions between species and increase contact between wildlife, humans, and pathogens, which have generated almost all pandemics with annual global costs of more than USD 1 trillion (IPBES, 2020).

Figure 5
Deforestation monitoring of the Brazilian Amazon forest by satellite: rate PRODES Amazonia, 2012–2020
(In km^2)



Source: INPE (2020).

Another region of concern in terms of deforestation is the Gran Chaco, which is the largest dry forest in South America and covers 100 million hectares in Argentina, Paraguay, Bolivia, and Brazil, with high rates of biodiversity. From 2000 to 2012, the Argentine, Paraguayan and Bolivian Chaco suffered the highest rate of tropical forest loss in the world, reaching 1973 hectares per day in August 2013 (Hansen et al., 2013). From 2010 to 2012, approximately 1.1 million hectares were cleared in these countries, three quarters of them in Paraguay (Cardozo et al., 2013). From 2012 to July 2018, approximately 2.9 million more hectares of land were detected as cleared for change of use in the Gran Chaco due to deforestation. In 2012, peaks in clearing activity were observed with 539,233 ha cleared and a minimum of 375,290 ha in 2016. In June of 2018, 33,959 ha were detected as changes in natural cover in the Gran Chaco Americano, corresponding to an average of 1,095 ha/day (with 80% of clearing occurring in Argentina) (Arévalos et al., 2018).

B. Land degradation

Our ability to manage landscapes will determine the future of land resources (soil, water, and biodiversity) and will determine the success or failure in poverty reduction, food and water security, and climate change mitigation and adaptation. Indeed, integrated land and water management is recognized as an accelerator for achieving most of the Sustainable Development Goals.

Land degradation is a complex phenomenon, usually involving the loss of some or all the following factors: productivity, soil, vegetation cover, biomass, biodiversity, ecosystem services, and environmental resilience (UNCCD, 2017). Degradation is commonly caused by mismanagement or overexploitation of land resources, such as vegetation removal; nutrient depletion; overgrazing; inadequate irrigation; excessive use of agrochemicals; urban sprawl; pollution; or other direct impacts, such as mining, quarrying, trampling, or vehicle travel. Land-use change is not the same as degradation, and some land-use changes can be net positive in terms of benefits to humanity. However, in the current context of declining natural ecosystems, coupled with increasing pressures on land resources, land-use change is often associated with degradation that reduces biodiversity and ecosystem services.

According to the Economics of Land Degradation (ELD) Initiative, 52% of land used for agriculture, globally, is moderately or severely affected by land degradation, with the loss of ecosystem services generated by degradation, costing between US$6.3 and 10.6 billion per year (equivalent to 10-17% of global GDP) (ELD Initiative, 2015). These costs are unevenly distributed, with negative impacts mainly affecting local communities and the rural poor. The same initiative estimates 1.4 billion people are directly affected/impacted by land degradation.

This is the context for the UNCCD’s Land Degradation Neutrality (LDN) initiative, which aims to halt the ongoing loss of fertile land to degradation. Unlike past approaches, LDN sets a degradation management goal to promote a two-track strategy, with measures to avoid or reduce land degradation combined with measures to reverse past degradation. In other words, it is a matter of balancing losses with gains, to reach a state where there is no net loss of fertile and productive land.

In LAC, the large systems that dominate the region’s arid, semi-arid, and dry sub-humid lands and that cover large extensions within a country, or involve two or more countries, are represented by the diverse dry zones and deserts of Mexico; the Central American dry corridor or arc; the arid and semi-arid zones of La Guajira region in the Colombian Caribbean that borders Venezuela; the plains of Colombia and Venezuela; the Northeast of Brazil; the Gran Chaco region shared by Argentina, Bolivia and Paraguay; the high altitude ecosystems in Argentina, Bolivia, Chile, and Peru; the arid and hyper-arid coastal zones extending from southern Ecuador, along Peru and into Chile; and the Patagonian steppe in Chile and Argentina that reaches as far as Tierra del Fuego. In this context, it is also worth mentioning the semi-arid and dry sub-humid lands of minor Caribbean systems, which, although not very significant from the perspective of the subcontinent, are significant in the island territories; the arid and semi-arid zones in some islands of the Netherlands Antilles and Aruba, Hispaniola, Cuba, and some minor islands stand out (UNCCD, 2019).

In addition, although under different climatic conditions, other systems that are under intense pressure from the expansion and intensification of agricultural activities should be considered, such as the Amazon basin, the Brazilian Cerrado and grasslands, the Uruguayan savannah, and the humid pampas of Argentina.

The Central American Dry Corridor is another example of one of the ecoregions most susceptible to degradation and climate change in LAC (Central American Bank for Economic Integration & FAO, 2019). It is 1,600 kilometers long and 100 to 400 kilometers wide stretch of land that covers the lowlands of the Pacific coastal zone and most of the Central Range region of Chiapas (in Mexico), Guatemala, El Salvador, Honduras, and Nicaragua, as well as the Guanacaste province in Costa Rica, and the Arco Seco of Panama. It is an ecoregion of dry tropical forest that covers almost a third of Central America's territory and is characterized by periods of heatwaves or intense rainfall, exacerbated by the influence of the El Niño-Southern Oscillation (ENSO) phenomenon. This vast territory is home to more than 45 million inhabitants, 40% of whom live in rural areas. Poverty affects more than half of the region's inhabitants, and approximately 20% live in extreme poverty. It is estimated that about 10% of the population in the region suffer from undernourishment, especially in periods of emergency and rehabilitation resulting from recurrent droughts and floods, which have significant consequences on the livelihoods and development of the countries (Central American Bank for Economic Integration & FAO, 2019).

To assess the degree of land degradation in LAC —and to guide public policies at national and regional levels— the development of a single indicator or index to represent or map such degradation poses a major challenge. The United Nations Convention to Combat Desertification (2019) used the land degradation assessment methodology of the World Atlas of Desertification (Cherlet et al., 2018), which is based on a systematic framework that provides a "sum of evidence" on human interactions with the environment and is appropriate to the reality of LAC. This allows for the identification of thematic pathways and geographic patterns of overlapping processes that can potentially contribute to land degradation. Neither decreasing trends in productivity per se imply land degradation, nor increasing trends imply recovery.

Thus, the United Nations Convention to Combat Desertification (2019) analyzed the main variables that can affect land degradation in eight LAC countries: Mexico, Guatemala, Dominican Republic, Ecuador, Peru, Paraguay, Brazil, and Argentina. To carry out the analysis, the database with which the World Desertification Map was developed (Cherlet et al., 2018) was processed, following their developed methodology called Convergence Analysis of Relevant Variables. The variables considered for the analysis were the following: Soil Organic Carbon, Aridity, Water Stress, Primary Productivity Decline, Land Cover Change and Deforestation, including all 64 possible combinations among them. All the variables indicated are in historical series of at least ten years and with a resolution of 1 km^2.

Despite the differences between and within countries, LAC has many shared characteristics and similarities in its land degradation processes. In all countries, the degraded area is a significant proportion of the national territory and in all cases the main variables affecting this process are recurring with great frequency. Deforestation is present in all countries, both as an individual variable and in combination with other variables. The same is true of soils with low carbon content and declining productivity, although on a smaller scale. The aridity variable appears in most of the countries, though it is of greater importance in Mexico and Peru. Table 3 presents a summary of the most relevant characteristics of the countries analyzed, extracted from the satellite database. For each of them, the degradation variables that most frequently affect the territory are indicated, as well as the most affected Departments or Provinces.

It is important to highlight the relationship between high levels of degradation and land productivity. In the case of degraded rangelands in Brazil, for example, Strassburg et al. (2014) demonstrated that a more sustainable use of these lands could meet the projected increase in demand for meat, crops, timber, and biofuels to 2040 without the use of new areas and recovering the current ones. They concluded that current productivity is at 32-34% of its potential and that sustainable intensification could raise this productivity to 49-52%, providing an adequate supply of these goods until at least 2040, without further land or ecosystem degradation and with notable benefits for carbon storage. They further identified that, if the recovery of degraded grasslands is deepened, which would raise productivity to 70% of its potential, 36 million hectares could be released from production.

Table 3
Land degradation in selected countries as a percentage of the territory and its degradation drivers

Country	Estimated degradation *(Percentage of land area)*	Main degradation factors	Most affected territories
Mexico	**32.9**	Water Stress, Aridity, Deforestation, and Low Soil Carbon Content	Baja California Sur, Chihuahua, Sonora, Guanajuato, and Zacatecas
Guatemala	**55.6**	Deforestation and Productivity Decline	Peten, Alta Verapaz, Chiquimula
Dominican Republic	**59.9**	Deforestation, Water Stress and Low Soil Carbon Content	Monseñor Nouel, Santiago, La Vega, and Samana Provinces
Brazil	**36.0**	Deforestation, Productivity Decline, and Low Soil Carbon Content	States in the northern region linked to the Amazon and the Cerrado
Argentina	**40.0**	Productivity Decline, Low Soil Carbon Content, and Land Cover Change	Santa Cruz, San Luis, and Santa Fe Provinces
Paraguay	**62.3**	Deforestation, Lower Productivity, Plant Cover Change, and Loss of Productivity	Departments of San Pedro, Ñeembecú, Guairá, Caaguazú, and Alto Paraná
Peru	**58.1**	Deforestation, Aridity, Water Stress, and Low Soil Carbon Content	Departments of Ucayali, Pasco y Callao, Madre de Dios, Apurimac, and Moquegua
Ecuador	**49.9**	Deforestation, Low Soil Carbon Content, and Land Cover Change	Provinces of the East region (Morona Santiago, Sucumbíos, Orellana, Zamora Chinchipe, and Napo)

Source: Own elaboration based on United Nations Convention to Combat Desertification (2019).

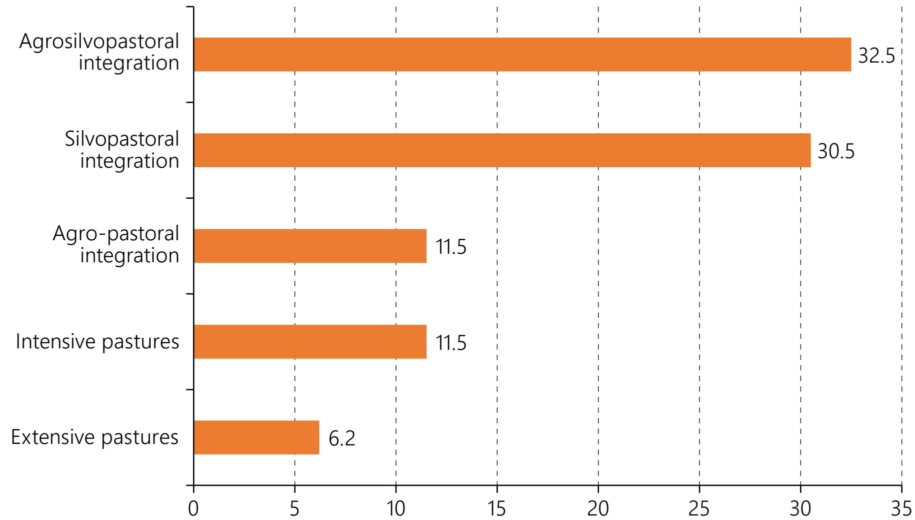
With new sustainable production methods, agricultural production can, in fact, work in the opposite direction from what it has done so far: it can reduce emissions, add carbon to the soil and recover it, adding value and productivity at the same time.

Among the methods already evaluated economically and environmentally are silvopastoral systems, which are agroforestry arrangements that combine forage plants, grasses, and legumes, with shrubs and trees for animal feed, and other complementary uses (Chará et al., 2019). These productive systems allow the intensification of production based on natural processes, being considered a more sustainable use of land compared to conventional land use. Ecological interactions increase productivity, efficiency, the provision of environmental services and, finally, the economic performance of properties. They directly contribute to increased income from timber, animals, animal products and agricultural products sales, and indirectly add the benefits of soil conservation, provision of environmental services, provision of shelter for animals and improvement of their welfare (Peri et al., 2016). Changes in this direction will be necessary throughout the rural production chain, aiming at a new rurality —especially in our region, where agricultural goods are a strong component of the economy and exports. Integrated agrosilvopastoral systems therefore have an important role to play in the future of rural production chains.

Chará et al. (2019), highlights that the benefits appear in the form of better-quality forage, reducing the need for supplementation from external sources and increasing up to 4 times the number of livestock per hectare. In addition, it provides increased carbon absorption in soil and in plants; better availability of nutrients due to improved soil conditions and more nitrogen fixation; improved water infiltration capacity and regulation of the hydrological cycle; increased biodiversity of birds and insects improving pollination and pest control. Different names are used in the literature to identify the variations in the method, but the most common are agrosilvopastoral systems, silvopastoral integration, and agriculture-livestock integration, depending on the characteristics of each initiative.

Similarly, Oliveira et al. (2018) evaluated carbon sequestration in different cattle productive systems (figure 6) in southeastern Brazil, in homogeneous area from the point of view of relief and edaphic, where a greater incorporation of carbon in soils and plants is perceived in integrated systems.

Figure 6
Carbon sequestered in different beef cattle production systems in Brazil
(Ton CO_2 eq/ha/year)



Source: Own elaboration based on Oliveira et al. (2018).

A large-scale agricultural intensification experience in Brazil should also be analyzed, due to its dimension and potential for change in the production system. It is the ABC Plan - Low Carbon Agriculture (Observatório ABC, 2017). The recovery of pastures and implementation of integrated systems, 15 + 4 million hectares respectively, allow increase in land use efficiency and productivity. Based on the results so far, this change would allow the reduction of up to 1.4 million hectares in plant cultures and between 4 to 5 million hectares in pastures, which could be removed from the production system, allowing the recovery of forests. This increase in productivity is also revealed in the increase in the animal load per hectare. While in degraded areas the rate is 0.7 AU/ha, in recovered areas it is 1.5 AU/ha and in areas with silvopastoral integration it is 2.5 AU/ha.

Finally, as long as policies focused on forest restoration and recovery of degraded areas are not applied on a massive scale, the population living in degraded areas tends to increase. Between 2000 and 2010, an increase of 12.4% of people living in degraded areas worldwide was recorded (Barbier and Hochard, 2016), while in LAC this increase was 18.4%, only behind the increase of populations in degraded areas in Sub-Saharan Africa (table 4). Barbier & Hochard (2016) estimated for the year 2000 a population of 1.33 billion living in degraded areas, of which 1.26 billion in developing countries.

There is no doubt that the high concentration of population in degraded areas is a strong obstacle to poverty reduction and economic growth in developing countries, as persistent land degradation reduces the productivity of the agricultural systems on which the rural poor depend.

Table 4
People living on Degraded Agricultural Land (DAL) as percentages of the rural population

Region	Rural population in DAL–year 2000	Variation of rural population in DAL for 2000–2010
World	34.0	+12.4
Developed countries	17.9	-2.8
Developing countries	32.4	+13.3
Latin America and the Caribbean	13.0	+18.4
East Asia and the Pacific	50.8	+8.4
Europe and Central Asia	38.5	+1.0
Middle East and North Africa	22.3	+14.3
South Asia	26.2	+17.8
Sub-Saharan Africa	20.6	+37.8

Source: Own elaboration based on Barbier and Hochard (2016).

C. A resilient, low-carbon post-pandemic economic recovery

Generally speaking, according to the IPCC (2018), both the 1.5°C and 2°C targets will require that we reach zero net carbon dioxide equivalent (CO_2e) emissions by 2050, and with sharp reductions by 2030. Zero net emissions means that anthropogenic CO_2e emissions are balanced globally with the removal of anthropogenic CO_2 through CO_2e capture activities such as afforestation.

Therefore, bearing in mind the sharp reductions required by 2030, an economic recovery with the same environmental effects as we had before the pandemic will lead us to a deepening of the climate and water crises, with long-term effects on our ability to maintain a healthy and productive economic and social process. In other words, we would be emerging from one crisis to enter another of an even more global nature, much longer term and with much more lasting and deleterious impacts. Economic recovery must then focus on low-carbon sectors that generate jobs and environmental resilience while strengthening the social capacity to generate prosperity. How do we respond regionally to these challenges?

Latin America and the Caribbean possesses a significant portion of the planet's natural wealth, and its economy and exports are largely dependent on that natural resource base. At the same time, the future of the regional economy and the region's ability to deal with inequalities and economic growth will depend not only on the maintenance of its natural resource base and environmental services, but also on the recovery of the productive capacity of already degraded resources, i.e., increasing resilience. Effective public policies for the management of low-carbon economic sectors will therefore be key to ensure a new cycle of development, growth, and employment in the region for post-pandemic recovery.

It is also important to note the high dependence of jobs on the natural resource base. Approximately 64 million jobs in LAC (19% of employment) depend directly on ecosystem services. Agriculture and livestock, as well as food, beverage, and tobacco processing, are the sectors with the largest number of workers dependent on ecosystem services (with more than 40 million and 10 million workers, respectively). Other sectors that also depend on the natural environment are textile, chemical and paper manufacturing, as well as environmental tourism (CEPAL & OIT, 2018). This indicates that the maintenance and recovery of the material/natural base of the economy is fundamental in economic recovery.

The IDB elaborates on the issue of jobs in a zero net emissions future in Latin America and the Caribbean (Saget et al., 2020), using the decarbonization scenario that is based on the "below 2°C "2 scenario published by the IEA in 2017 (IEA, 2017). Such a scenario would put the world on a path to zero net carbon emissions by 2060 and contribute to climate stabilization at the level of 1.75 °C above pre-industrial levels, which is the midpoint of the Paris Agreement target range. The high-emissions scenario —which we use as a benchmark for comparison— is based on the IEA's "Reference Technology Scenario" (RTS) in the same publication, in which global carbon emissions, instead of decreasing, increase by 15% compared to current levels by 2040.

According to the IDB, the figures confirm that decarbonization can create net jobs. Simulations show that, compared to the high emissions scenario, GHG emissions are reduced by 35% and 15 million jobs are created by 2030 (representing 4% of total employment in the region). Net jobs hide the winners and losers. The decarbonization scenario has 22.5 million more jobs in the plant-based food, construction, manufacturing, renewable electric power, and forestry sectors, and 7.5 million fewer jobs in the animal-based food, mining and fossil fuel extraction, and fossil fuel-based power generation sectors.

Agriculture that is more sustainable dominates job creation. The sector employs 19 million more employees, equivalent to full-time in the decarbonization scenario for 2030 compared to the high-emissions scenario, an increase of 54% over the high-emissions scenario.

It should be noted that the number of jobs that could be created in the forestry sector in a decarbonization scenario is underestimated. In fact, this is based on the typical labor intensity of existing forestry work in the region. But reforestation efforts would be much more labor intensive than current forest harvesting. For example, if countries planted forests on a large scale as a green recovery measure, many more jobs could be created in the short term.

In conclusion, the decarbonization of the economy, in a transformative recovery process, could be a real driver of economic reactivation while promoting a low-carbon and resilient economy, thus avoiding new future crises, and overcoming the negative effects of the COVID-19 crises. Therefore, to develop an intelligent transition towards sustainability as the basis for a new economic development cycle in LAC, it is necessary to consider the interrelationships between productive systems and their natural resource bases in the different geographical areas. Based on this analysis and taking into account the immediate reality of the COVID-19 pandemic, transition planning will be needed, promoting progressive changes in order to overcome initial barriers, articulate key actors and create virtuous circles/flows with increasing benefits.

Post-pandemic economic recovery packages should include conditionalities for changing the agricultural production system in LAC towards the integration of agroforestry and pastoral production. The degradation of forests, land, and water resources undermines the potential for economic development and deepens inequality. The provision of environmental goods and services, such as water supply, are directly related to sustainable forest and land management. The challenge in LAC is to build sustainable agricultural production processes, since degradation affects productivity and employment and, therefore, the regional economy.

IV. Carbon Dioxide Removal: techniques and rationales

Recent assessments by the Intergovernmental Panel on Climate Change (IPCC, 2021; 2018) indicate that large-scale Carbon Dioxide Removal (CDR) is required in all pathways to limit global warming to 1.5–2 degrees Celsius (°C) with limited or no overshoot. In this chapter, the main CDR techniques covered in the scientific literature are described. The relative strengths and weaknesses of each are explored and the socio-economic and governance issues pertinent to these large-scale interventions are discussed.

A. An introduction to Carbon Dioxide Removal

Carbon Dioxide Removal (CDR) is defined by the Intergovernmental Panel on Climate Change (IPCC) as "Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products" (IPCC, 2018). It is also known as carbon removal, carbon drawdown or anthropogenic CO_2 removal. Negative Emissions Technologies (NETS) and Greenhouse Gas Removal (GGR) are terms that encompass CDR, but which also include other greenhouse gases such as methane. It should be noted that there are currently no well-developed methods for removal of non-CO_2 greenhouse gases (GHGs).

There is often confusion between CDR and Carbon Capture and Storage (CCS). CCS entails capturing CO_2 emissions at source (such as a fossil fuel power plant) and then durably storing it. Attached to a fossil fuel power plant, this could be considered part of cutting emissions by avoiding new emissions being released into the atmosphere. Therefore, CCS stops the volume of CO_2 in the atmosphere growing, whilst CDR removes CO_2 that has already been emitted, reducing the total volume of CO_2 in the atmosphere.

CDR techniques may use a range of different approaches to remove and store carbon. Some would use engineering techniques to remove carbon directly from the air around us, some would use a combination of natural systems in conjunction with engineering and others would use nature-based approaches, for example the growing of trees or changing land use management practices to improve carbon uptake.

B. Why should we be discussing CDR now?

Five years after the Paris Agreement on climate change entered into force (UNFCCC, 2015), recognition is growing that without a rapid acceleration in action, limiting global average temperature rise to 1.5–2°C will not be possible. Indeed, the World Metrological Organisation finds there is a 40% chance of the annual average global temperature reaching 1.5°C above preindustrial levels in at least one of the next five years (WMO, 2021), posing significant risk to natural and human systems and our ability to delivery sustainable development (IPCC, 2018).

Progress towards achieving the Paris Agreement goals has been slow. Even if all the current Nationally Determined Contributions (NDCs) under the Paris Agreement were implemented, the Earth is still expected to warm by 3°C by the end of the century (range 3.0–3.5 C° with 66% probability) (UNEP, 2020).

This collective failure to adequately respond to global warming is reflected in the emission pathways presented in the IPCC Special Report on Global Warming of 1.5°C (IPCC, 2018). These all require the removal of CO_2 from the atmosphere using CDR, if warming is to be limited to 1.5°C. These scenarios indicate the need to remove between 100 billion and 1,000 billion tonnes (Gt) of CO_2 by the year 2100 (IPCC, 2018), demonstrating the necessity of rapid and unprecedented global action. In the most recent IPCC report, only two of the five scenarios assessed indicate the possibility to limit average global temperature rise to 1.5–2°C, with both relying on transformational emissions reductions and CDR to reach net zero and subsequently net negative emissions (IPCC, 2021). It is in this context that CDR options are increasingly being proposed (UNEP, 2019), but, removing and permanently storing CO_2 is not a new idea, it has been embedded in global climate agreements since at least 1992, when the United Nations Framework Convention on Climate Change (UNFCCC) established that mitigation included both emission reductions and removals (UN, 1992). What is new is the scale and pace with which these removals are now required to avoid 1.5-2°C warming (IPCC, 2021; Mace et al, 2021).

If CDR were ever implemented at a multiple Gigatonnes scale, it would be expected to have climate cooling effects, but only over decadal times scales. Such effects are modelled in the IPCC pathways (IPCC, 2021; 2018). If global net negative CO_2 emissions were achieved and sustained, global surface temperature increase would be gradually reversed but other climate changes (such as sea-level rise) would continue in their current direction for decades to millennia (IPCC, 2021).

Many of the techniques explored in this chapter are either theoretical, or in very early stages of development and unless affordable and environmentally and socially acceptable CDR becomes feasible and available at scale well before 2050, 1.5°C-consistent pathways will be difficult to realize (IPCC, 2018). Considerable uncertainties remain about many of the techniques regarding, for example, their potential for carbon removal over time, any potential climate scale impacts they may have and the likely environmental, social and economic costs of deployment. These uncertainties are compounded by researchers' divergent choices regarding a complex range of factors including, for example, decisions about likely future adaptation strategies, climate change scenario choices, innovation timelines, opportunity costs and future innovation cost discounting. All of which are likely to affect the outcomes of their assessments. Pending more research, through which more rigorous assessments may become available, this chapter recognises these challenges and therefore provides ranges for costs, carbon removal (sequestration) potentials and other factors for each technique, reflecting the evidence in current literature. The techniques are summarised in table 5.

In addition to the uncertainties about CDR techniques, there is considerable debate about the appropriateness of available governance for both CDR generically, and for each of the individual techniques. Florin, et al. (2020) have produced in-depth overviews of international law and governance relevant to CDR and the Carnegie Climate Governance Initiative (C2G) has explored governance issues in a range of briefings and educational materials (C2G, 2021) for those who wish this explore further.

Table 5
Overview of CDR techniques[a]

	Technique	Range of theorectical sequestration capacity (gigatonnes/year[a])	Estimated cost USD ($) per tonne sequestered CO_2	Permanency of sequestration	Readiness	Active research area	Governance framework	Social acceptability[b]
Afforestation and reforestation	Planting of forests and restoration of ecosystems that result in long-term storage of carbon.	1–18 Gt.	$15 to $30 although the IPCC give a range of 5 to 50, but only for abatement.	Medium term.	Already widely practiced. Could be deployed at scale with little further development.	Yes. Exploring gas fluxes from trees, land use change effects and albedo changes.	The United Nations Framework Convention on Climate Change (UNFCCC), Kyoto Protocol, Paris Agreement, the Food & Agricultural Organization (FAO). Questions remain regarding social justice (i.e., land use issues). A requirement for better monitoring, verification and reporting.	Competing demands for land use need governance. A lack of financial incentives to encourage afforestation.
Artificial upwelling	Pumping oceanic waters from deep waters to enhance carbon uptake.	Potentially counterproductive in some circumstances–and no more than a maximum 20 Gt by 2100.	Unknown.	Long term.	Not currently practical, even in principle in engineering terms, to deliver cooling.	Limited research activity exploring engineering challenges.	Unresolved.	Unknown.
Biochar	Biomass burning under low-oxygen conditions (pyrolysis) creates "biochar", which is then added to the soil to enhance soil carbon levels.	0.3 to 35 Gt.	$18 to $166.	Long term.	A well-established technique with an evolving market.	Yes, explorations of decomposition rates and the relationship with feedstock and temperature.	State and customary law, UNFCCC and FAO. Better monitoring, reporting and verification (MRV) is required. A transboundary trade in biochar may require international agreement regarding carbon credit allocation.	No major social concerns.
Bioenergy with carbon capture and storage (beccs)	Feedstock is burnt producing energy or heat. Gases released from combustion are then captured.	1 to 85 Gt.	$65 to $240, although most costs are below $200.	Dependent on location-potentially permanent.	An established technology.	Yes, whole systems analysis, feedstock production & combustion techniques.	Unresolved. The UNFCCC, Paris Agreement and FAO. Land use trade-offs. A requirement for better MRV of achieved sequestration.	Land-use change issues may create tensions.
Carbon sequestration in soils	Land management changes that increase soil's carbon concentration.	1 to 11 Gt.	$12.	Medium to long term.	No significant barriers. Limited knowledge technique in the agriculture community.	Yes. A better understanding of gas fluxes from enhanced soil is required.	The UNFCCC and Paris Agreement, the FAO and the 4p 100 initiative. A requirement for better MRV of achieved sequestration.	No major social concerns.

	Technique	Range of theorectical sequestration capacity (gigatonnes/year[a])	Estimated cost USD ($) per tonne sequestered co$_2$	Permanency of sequestration	Readiness	Active research area	Governance framework	Social acceptability[b]
Crop residue oceanic carbon sequestration	Crop residues and biomass are gathered and deposited into the ocean to sink.	Up to 1 Gt.	Uncertain.	Long term.	No technical constraints to deployment. Scale up and infrastructure developments required.	Not an active area of research. More evidence regarding environmental impact is required.	Covered by the London Protocol and the Convention on Biological Diversity (CBD).	It is uncertain how publics would respond to this technique.
Direct air capture with carbon storage (DACCS)	Chemical processes that separate CO_2 from air for subsequent storage.	0.5 to 5 Gt (by 2050).	$20 to $1 000.	Dependent on location–potentially permanent.	No technical constraints to deployment aside from scale up and energy supply/use.	Yes. Demonstrator projects improving energy, heat and water efficiency. Modelling to understand scale up needed.	With amendments may be relevant to UNFCCC, Kyoto Protocol and Paris Agreement.	It is uncertain how publics would respond to this technique.
Enhancing ocean alkalinity	Additional alkalinity in ocean surfaces will increase the uptake of CO_2.	3,500 Gt.	$50 to $450.	Permanent.	Reduction of carbon and energy footprint required.	Very limited.	Would be subject to the United Nations Convention on the Law of the Sea (UNCLOS) and the London Protocol in the future, if named in annex 4. The CBD.	Limited research on broadly similar techniques suggest it is unlikely to be welcomed.
Enhanched terrestrial weathering	Minerals added to the land which react with the atmosphere and remove carbon.	0.72 to 92 Gt.	$15 to $3,460.	Permanent.	No technical constraints to deployment.	Yes. Limited research underway.	Subject to nation state law. May be relevant to UNFCCC, Kyoto Protocol and Paris Agreement and the London Protocol.	Limited evidence regarding how publics would respond to this technique.
Macroalgal cultivation	Intensive farming of microalgae.	With 9% global coverage 12 Gt pa of bio digested methane could be captured. If burned for power, with gas capture, a maximum of 34 Gt equivalent may be captured.	Not available.	With robust CCS, potentially long-term.	Technologies are readily available. Development may be required to maximise methane and CO_2 capture and use.	Yes. Limited research underway.	Dependent on the location of cultivation which could be in in-shore or off-shore waters.	As an extant farming method, a proliferation of the technique may pose insurmountable challenges.

	Technique	Range of theorectical sequestration capacity (gigatonnes/year[a])	Estimated cost USD ($) per tonne sequestered co_2	Permanency of sequestration	Readiness	Active research area	Governance framework	Social acceptability[b]
Ocean carbon capture and storage (OCSS)	The chemical removal of dissolved inorganic carbon which is taken to storage sites.	Uncertain.	Not available.	Long term.	The principles are well understood. Chemical engineering research is required before a viable technology becomes available for testing.	Mainly technical and economic modelling.	If conducted EEZ waters, OCSS would be subject to nation state terms. On the high seas, the storage of CO_2 beneath the seabed would be covered by the London Protocol.	There is no evidence to indicate the nature and scale of any responses.
Ocean fertilisation	Placing iron in ocean surface water encourages plankton growth, which takes up CO_2 during growth.	IPCC include estimates up to 44 Gt whilst other later assessments suggest 3.7 Gt.	$2 to $457.	Long term.	Technically feasible and the industrial infrastructure required is well understood.	Yes. Environmental impacts and capacity to uptake CO_2.	Research addressed under the London Protocol and UNCLOS. The CBD.	Limited research suggests it is not welcomed.
Ocean fertilisation with macro-nutrients	Placing nutrients in ocean surface water encourages plankton growth, which takes up CO_2 during growth.	Uncertain.	$20.	Long term.	Technically feasible and the industrial infrastructure required is well understood.	Yes. Environmental impacts and capacity to uptake CO_2.	Research addressed under the London Protocol and UNCLOS. The CBD.	Limited research suggests it is not welcomed.
Restoring wetlands	Rewetting and reclaiming of wetlands, e.g., peatlands to enhance carbon storage.	1.2 Gt.	$10 to $100 although costs per tonne of saltwater restoration are unavailable.	Medium term.	Requires little new technology.	Yes. Reducing methane release and its capture.	The UNFCCC, Kyoto Protocol, Paris Agreement the Ramsar Convention on Wetlands and FAO. Land use trade-offs. Better MRV required.	A key barrier may be the lack of financial incentives to encourage land-use change.

Source: Own elaboration.
Note: Key: Medium term–Multi Decadal; Long term: Multi Century.
[a] There is considerable uncertainty regarding potential removal capacity and costs reflecting a wide range of model and theoretical deployment assumptions (IPCC, 2018). This information should be treated with caution pending more rigorous comparative assessments which may become available if understandings of the techniques mature. Uncertainties in assessments is explored in the following text.
[b] It is important to note that most research evidence regarding social acceptability is based on European or North American citizens only.

C. Afforestation and reforestation

The intentional planting of new trees in places where they have not traditionally grown (afforestation), or replanting where they have been cropped, died, or been removed by other means (reforestation) that results in a net uptake of CO_2 as the trees grow, plays an important role in current climate change response measures (Doelman et al., 2020). However, once a tree or forest reaches maturity, the uptake of CO_2 slows (Houghton, 2013) and when a tree's life cycle is complete it decomposes, and CO_2 is returned to the atmosphere (Read et al., 2009). This release of CO_2 may be avoided through forest management, with mature trees being harvested and the biomass stored in long-lived wood products such as within buildings, McLaren (2012), for example, has suggested that between 0.5 and 1 $GtCO_2$ per annum of biomass could be sequestered into buildings for long term storage. Managed forestation by product may also be used for bioenergy or biochar (RS/RAE, 2018). Following harvesting, new planting and subsequent forest regrowth, or natural revegetation allows for continuing CO_2 removal.

The net removals capacity of forestation is uncertain and multiple issues regarding its efficiency, locational questions and effects remain, including effects on biodiversity and soils, changes to watersheds and water resource management. A better understanding of the balance of effects of planting trees between their carbon sequestration and warming effects is required. For example, shading by trees where dark leaved conifers predominate may have a net warming effect (Lundquist et al., 2013). More research on climate models is therefore required to better understand the full effects of changes to forestry cover (Winckler et al., 2019).

Griscom et al. (2017) suggests forestation removals capacity ranges from between 3 to 18 $GtCO_2$ per year, with the variation dependent on assumptions about the land available for planting ranging from 350-to 1780 million hectares (MHa). Earlier evidence which informs the IPCC estimate indicates a global capacity of 1 to 7 $GtCO_2$ per year by 2050 (IPCC, 2018). In a more conservative assessment Smith et al. (2015) estimate a maximum sequestration through forestation of 12 $GtCO_2$ per annum by the year 2100.

The cost estimates for afforestation and reforestation have been assessed at between USD $15 and $30 per tonne of CO_2 (Smith, 2015) whilst the IPCC only provide abatement costs of $5 to $50 per tonne, demonstrating the considerable uncertainty regarding potential costs that also remains.

The planting of forests will create trade-off tensions related to land use change, or future land use opportunities, including, for example, for food production and other approaches to removing CO_2. Policy trade-offs may therefore become an important future governance agenda of forestation (Hammad, 2020). A better understanding of how to balance trade-offs between, for example, land use options, such as biomass and bio-fuel production, cropping and grazing with forestation whilst also protecting the culture and rights of indigenous peoples in the most equitable, economically viable and socially acceptable way is required (Rouse, 2020).

No "one size fits all" approach can be taken to forestation and careful consideration of local circumstance may be important, before taking any decisions about where to afforest, or not (RS/RA, 2018). Importantly, planting may undermine capacity for landowners to generate income in the short term, meaning they may seek certainty regarding any payments to bridge the period between planting and harvest.

Currently, globally, forestation is planned to meet 25% of all committed NDCs mitigation to 2030 (UNFCCC, 2015). In addition, the Bonn Challenge (IUCN, 2011), a global effort to reforest 350 MHa of forest by 2030, has been endorsed and extended by the New York Declaration on Forests at the 2014 UN Climate Summit (UN, 2014). To date, the Declaration has been endorsed by 40 national governments, 56 companies, and more than 70 civil society and indigenous peoples' organisations.

The monitoring of rates of both afforestation and deforestation needs to be improved and a precise global accounting system agreed upon (IPCC, 2018). This is challenging and will require resourcing to be effective. Examples of monitoring challenges include the accounting for variable species uptake capability over time in multiple environments and with complex soil and irrigation differences, and the complexities of reporting and verifying gas fluxes across a sector that is, simultaneously, a sink for and source of CO_2 and other greenhouse gases from both natural and human sources (Welch, 2019).

D. Artificial ocean upwelling

Across much of the mid and low latitude oceans, nutrients are depleted in the surface waters, limiting biological production (Moore et al., 2013). Artificial upwelling would use engineering interventions to bring deeper, nutrient-rich waters up toward the surface stimulating phytoplankton growth and the absorption of carbon. Upwelled waters would be cooler than surface waters, and therefore cool the surface waters increasing their capacity for heat absorption from the atmosphere at local scales (i.e., providing "air-conditioning" for coastal cities nearby) (GESAMP, 2019).

There is no scalable technology available to date, although some field experiments, using very small scale devices have been successfully deployed for several months in Qiandao Lake, China and in one sea trial in the East China Sea (Pan, 2016). Other studies and field experiments (Aure et al., 2017, Fan et al., 2020) suggest a robust and efficient artificial upwelling device, utilising self-powered energy may be possible (Pan, 2016).

It has been estimated that the theoretical maximum carbon capture and storage of this technique would be less than 20 Gt by 2100 (GESAMP, 2019) whilst the IPCC (2019) have concluded that long-term large-scale interventions could be counterproductive in some circumstances. There has not been any experimental measurement of achieved carbon sequestration using the technique to date and the engineering challenges which must be surmounted to deliver meaningful carbon sequestration using this technique are substantial, including questions about the water transportation methods, and the design and construction of the tubes.

The extent of any environmental impacts of the technique are unknown but it is known that artificial upwelling may affect biomass productivity (GESAMP, 2019). In addition, there may be undesirable climatic consequences, including disruption of regional weather patterns and long-term warming rather than cooling, if enhanced upwelling is deployed at large scale (Kwiatkowski et al., 2015). In addition, some simulations suggest that if artificial upwelling were stopped, surface temperatures and atmospheric CO_2 concentrations would rise quickly (Oschlies et al., 2010).

How citizens might respond to the technique is unknown and how it might be governed is unresolved. It would likely be within the scope of the London Protocol and UNCLOS if outside Exclusive Economic Zones (EEZs). However, the London Convention and Protocol are unlikely to have a bearing on the technique as it doesn't include the dumping of materials. Were it to effect biodiversity, the Convention on Biological Diversity (CBD) may be applicable.

E. Biochar production and deposition

Biochar is a stable, long-lived form of carbon which is a well understood and established method. Biochar is formed, in pyrolysis, when biomass is heated in a closed container, with little or no available air, to above 250°C. In combination with sustainable biomass production, it can be carbon negative. If stored in soil for long periods biochar is expected to not only store carbon, but to also improve soil quality and crop yields (Lehmann, 2015), as well as water quality and nutrient levels (Smith, 2016).

It is suggested that a tonne of biochar may remove between 2.1 to 4.8 tCO_2 (Lehmann, 2015, Hammond et al., 2011), although uncertainty remains, for example, the IPCC estimate a global potential removal of between 0.3 and 35 $GtCO_2$ yr−1 in 2050 (IPCC, 2018) whilst others suggest a cumulative removals potential that ranges from between 78 and 477 $GtCO_2$ this century (ICRLP, 2018). Costs of biochar removal is also uncertain with Woolf et al. (2010) estimating cost ranges from $18 to $166 per tCO_2 produced and Fuss (2018) estimating a cost per tonne of between $90 and $120.

There is a wide range of on-going biochar research activity helping to better understand what constitutes "good" biochar in agronomic and environmental management applications. Areas of current research include exploring uncertainties associated with decomposition rates of the various types of biochar, depending upon the pyrolysis feedstock and temperature (Anderson, 2020).

There are not expected to be major social concerns with the deployment and scale up of biochar, although there may be some social reticence and concerns about any effects on forests or food supply (Smith et al., 2010). It may be important for those developing infrastructure, that they be clear to the wider local community about the nature of the combustion methods and its by-products.

The monitoring, reporting and verification of the take up and use of biochar may be difficult, both at the state and international level (RS/RAE, 2018). Improved accounting will, though, be important in the future and it is possible that biochar will, in the longer term, become subject to international governance mechanisms such as the CBD and UNFCCC.

F. Bioenergy with carbon capture and storage (BECCS)

BECCS entails burning biomass to generate electricity, heat, or liquid fuel. The CO_2 emitted during combustion is then captured and stored in long-term underground reservoirs, effectively removing it from the carbon cycle (RS/RA, 2018). Despite its widespread inclusion in the integrated assessment models assessed by the IPCC, BECCS remains a fledgling technology and although each part of the technology has been proven at demonstration and commercial scale, very few commercial-scale projects exist worldwide (Brack and King, 2020).

Successful BECCS relies on a secure, regular supply of biomass, which may be grown for the purpose or derived from waste, sourced locally to minimise emissions from transport. If cropped, it is important that the crop is quick growing, rapidly replaced and that the BECCS crop doesn't undermine cropping for secure food supply or other purposes (RS/RA, 2018).

The IPCC have identified estimates for BECCS total mitigation potentials by the year 2050 in the range 1 to 85 $GtCO_2$ (IPCC, 2018) whilst Fuss et al (2018) suggest that BECCS may have the potential to remove between 0.5 and 2 $GtCO_2$ per annum by 2050. Behave et al. (2017) suggest that costs are likely to be in the range $140 to $270 per tonne of CO_2 captured whilst the IPCC notes that most cost estimates are below $200 (IPCC, 2018).

BECCS at climate effecting scale will require land-use change (Fajardy and Mac Dowell, 2017) creating competition with food supply, potentially leading to increases in food prices or effects on food security (Hasegawa et al., 2018). In addition, fresh water and nutrients will be required to enable biomass crops to flourish potentially creating further tensions, including in relation to the Sustainable Development Goals (SDGs).

Land use change issues may create tensions and policy will need to find ways to balance the demands for land to support BECCS against needs for settlements, energy, carbon removal and food. Given several countries already have national policy commitments and bioenergy and BECCS deployment strategies (RS/RAE, 2019), these, and the environmental implications need urgent resolution.

BECCS governance is generally considered to comprise two elements, biomass production and usage and the CCS elements (Torvanger, 2019). The latter relates predominantly to capture and storage monitoring, reporting and validation (MRV), as well as the safety and permanence of long-term storage. The Biomass agenda encompasses accounting for sustainability and resource use related to biomass energy production, processing and use, and interactions with the global carbon cycle. Trade-offs between BECCS biomass production and competing land and water use will also require governance attention, normally at the local level (Torvanger, 2019).

G. Carbon sequestration in soils

Carbon can be captured and sequestrated in soil, depending on soil type, usage and resource availability and there are no significant technical barriers to soil carbon sequestration, the practices are understood and in some cases already in practice in farming (RS/RAE, 2018) and measures are already in play that aim to promote the method as a contributor to the climate change targets of the Paris Agreement including the "4 per 1000 initiative" (Soussana et al., 2019).

The technique can be undertaken in several ways (ICRLP, 2018, RS/RAE, 2018):

- improved crop varieties and changes in their rotation and cropping;
- the use of novel biotechnologies;
- managing nutrients and optimising fertiliser use though careful timing and precise applications;
- minimising tillage and maximising the retention of organic material;
- improving grasses, especially by promoting and planting those with deep roots, and grass density; and,
- improving grazing management, paying attention to feed sourcing/production and stock density.

Assessing the global capacity to sequester carbon in this way is complex, estimates derived from modeling are therefore varied, ranging from 1 to 11 $GtCO_2$ per annum ((Lal, 2011, Lal, 2013, Minasny, 2017). If we are to accurately quantify the volume of carbon sequestered and any non-carbon greenhouse gasses releases (Lal, 2011) through this approach, rapid and reliable methods are needed for the measurement of soil carbon and gas fluxes (RS/RAE, 2018).

Smith (2016) suggests taking forward the required practices has the potential to create profit of up to $3 per tonne of CO_2 through improved productivity. In other circumstances, dependent on soil and environmental conditions, Smith suggests deployment may cost up to $12 per tonne.

However, and importantly, the longer term the capacity to store additional carbon year on year will decline as soils become saturated and sequestration can only be expected to continue for approximately 20-years, after which it becomes impossible to sequester additional carbon through these types of intervention (Zomer et al., 2017).

There is a lack of knowledge about the benefits of the approach among some quarters of the farming/land management community, which will need to be overcome with education and training, if deployment is to be scaled up (Minasny, 2017).

H. Crop residue oceanic carbon sequestration

Crop waste or other biomass would be grown, gathered centrally and taken to appropriate ports for transport to be dumped into the deep ocean or off the deltas of large rivers. With suitable additional ballast, biochar, timber and other organic matter could also be deposited in the deep ocean seabed (GESAMP, 2019).

Allowing for an average land transport distance of 200 km, and a combined average river and ocean shipping distance of 4,000 km, Strand and Benford (2009) suggested that 30% of global annual crop residues of 2 Gt could be available sustainably without harming soils. However, Keith (2001) suggested that the use of such biomass to produce electricity in a power plant that captures the CO_2 and sequesters it in geological formations would be a more effective option. Lenton and Vaughan (2009) suggest that an annual sequestration rate of up to 1 Gt C of material per annum, half the global annual crop residues, would only make a very modest contribution to slowing climate change.

The environmental impacts of depositing crop wastes in the deep ocean are uncertain. It is, though, known that, if deployed in shallow water (below 1,000 m), its impacts on ecosystem services could be more significant, particularly on deep-sea fisheries. In addition, long-term oxygen depletion and potential increases in hydrogen sulphide, methane, nitrous oxide and nutrients (nitrogen and phosphorus compounds) arising from the degradation of the organic matter would occur and could be regionally significant (GESAMP, 2019).

This potential technique is not currently subject to significant research, and it is uncertain how publics would respond to this technique. To deliver enough mass of material to the deep oceans to have a material effect a new, very large-scale infrastructure and market mechanism would need to be constructed

(GESAMP, 2019). How much material would be taken, and from where would require monitoring and regulation to protect soils and crop productions as well as to inform the market mechanism (GESAMP, 2019). In addition, crop residues provide multiple services within agricultural systems. This technique might then have important, unintended, and harmful consequences for those systems; however, this has not been subject to systematic research to date.

The technique may be permissible under the Organic Material of Natural Origin category in Annex 1 of the London Protocol and the Uncontaminated Organic Material of Natural Origin category in Annex I of the London Convention (IMO, 2016), subject to satisfactory assessments of the potential impacts (GESAMP, 2019).

I. Direct Air Carbon Capture & Storage (DACCS)

DACCS includes a family of technologies which use chemical engineering to remove CO_2 from the air around us. The carbon is then sequestrated in ways that will not contribute to global warming. Potential sequestration methods referenced in the literature (GESAMP, 2019; IPCC, 2005), include:

- injecting liquid CO_2 into the oceans;
- injecting into the seabed, seabed depressions, sediments or trenches; and,
- mineralisation of injected CO_2 within geologic structures.

Because the concentration of CO_2 around the world is in equilibrium (Goeppert, 2012) the location of DACCS units would not have to be tied to specific locations such as GHG emitting industrial infrastructure. DACCS plants could therefore be located near renewable or low emissions energy sources to power the process, over geological formations suitable for storing CO_2, and in areas that are neither environmentally sensitive nor densely populated (RA/RAE, 2018).

To extract CO_2, two DACCS approaches receive most attention in the literature. Adsorption, in which a chemical gathers molecule on to its surface from another substance, or absorption, in which CO_2 is taken up into the volume of another material, i.e., absorbed. Other emerging approaches include electro-swing, humidity-swing, carbonate looping, and membrane separation (Voskian and Hatton, 2019, Fasihi, 2019, Samari, 2019, Fujikawa et al., 2021).

Currently DACCS technologies are situated between the pilot plant stage and small scale or prototype demonstration in the field. Conservative assumptions, such as Viebahan et al. (2019), suggest that DACCS is unlikely to be available on a large-scale before 2030. Hanna et al., (2021) have suggested that investing 1.2 to 1.9% of global Gross Domestic Product (GDP) in DACCS would only lead to the removal of in the order of 2 $GtCO_2$ per annum.

Before the technologies can be scaled up, some outstanding issues, including energy requirements, the longevity of CO_2 storage, and the natural resource requirements, require resolution (RS/RAE, 2018). It is suggested that, in the long term, DACCS has a global sequestration potential of between 0.5 and 5 Gigatons of CO_2 per annum by 2050 (Fuss, 2018).

Both adsorption and absorption approaches have high heat or energy requirements to provide an air supply through the plant and to reactivate the agents and release the CO_2. Daggash et al. (2019) suggests that absorption based DACCS would require an energy input of 1500-2500 kWh for heat and a further 220-500 kWh of electricity per tonne of CO_2 removed. Adsorbent energy requirements are in the range 200-1000 kWh electricity and 640-1700 kWh for heat per tonne of CO_2 (Climeworks, 2020). Having extracted CO_2, sequestration, in whatever form is chosen, will have some additional energy resource demands. For example, for transportation to, and pumping into reservoirs.

To maximise the net carbon removal potential of DACCS, the energy required would be best drawn from low-carbon, low impact sources such as solar, wind and nuclear power or by co-locating plants with industrial processes that emit waste heat, such as gas power plants. However, if large scale

DACCS is to rely on renewable energy sources, greater efficiency and a step change in global renewables capacity is required. In addition to the energy and heat requirements, there are other costs that require consideration, for example:

- water resources–between 1 and 30 M^3 of water per tonne of CO_2 (Climeworks, 2019, Smith, 2016);
- natural resources-whilst DACCS does not require biomass and it would not harm ecosystems, a life cycle assessment of DACCS technologies is required (RS/RAE, 2018);
- sorbent replacement costs and other maintenance (Fuss, 2018);
- CO_2 sequestration costs–including preparation for deposition, transport and, depending on location and type of storage, storage costs; and,
- capital investment and opportunity costs.

Estimates of financial costs of scaled up DACCS range widely. For example, Sanz-Pérez et al., estimate costs at $30 to $1,000 per tonne of CO_2 captured (Sanz-Pérez, 2016) whilst Fuss et al. (2018) estimate a cost of between $100 and $300 per tonne. Small scale pilot projects are currently operating at less than $600 per tonne (Climeworks, 2019).

A reading of research needs assessments (Sandalow, 2018, Gambhir, 2019, NAS, 2019) suggests the following are key areas for DACCS research in the future, in no order of priority:

- Achieving greater energy, heat and water efficiency.
- Developing a better understanding of the sustainability impacts of DACCS.
- Resolving remaining carbon cycle uncertainties.
- Improving the production of synthetic renewable fuels using captured carbon.
- Gaining a better understanding of how to deliver environmentally neutral secure, permanent carbon removal and storage.
- The economics and policy of a DACCS compatible carbon market.
- The social acceptability of DACCS.
- Understanding interactions between DACCS and mitigation policy.
- Global carbon accounting and governance.

DACCS plants are likely to have a small footprint, compared to medium sized industrial facilities, and they will not create any threats regarding land availability, including to ecosystems services or food security (RS/RAE, 2018). Further, because DACCS plants are not geographically constrained, aside from having access to energy and water supplies, facilities need not be in sensitive areas or close to populations. The locating of DACCS plants is not then expected to give rise to significant social acceptability issues, aside from those that arise from the proposals for any medium-size industrial facility (RS/RAE, 2018).

J. Enhancing ocean alkalinity

Given the CO_2 absorbed in oceans is acidic, adding additional alkalinity to the surface of the ocean will result in an increased uptake of CO_2 by the ocean from the atmosphere. Enhancing alkalinity would also help reduce the effects of ocean acidification on the marine ecosystem (GESAMP, 2019).

No field trials have been undertaken, however, enhancing alkalinity would not require any novel or new technology —the raw materials required are already available from cement and other industries or naturally occurring minerals, or electrochemical enhancement of carbonate and silicate mineral weathering might be used using ships for distribution (RS/RAE, 2018). However, there is a very large carbon and energy footprint in the current manufacturing processes of some of the materials (RS/RA, 2018). These techniques can also be conducted on land (see *Enhanced Terrestrial Weathering* below), avoiding the costs of transport to and across the oceans.

The impacts of introducing particles from these materials into the oceanic environment are unknown suggesting further examination prior to implementation would be required (GESAMP, 2019).

The IPCC do not estimate a theoretical removals capacity for chemically enchaining alkalinity (IPCC, 2018) although theoretical studies have suggested that enhancing ocean alkalinity could remove as much as 3,500 $GtCO_2$ by 2100 (Gonzalez and Lilyina, 2016). Cost estimates range from \$50 to \$400 per tonne (GESAMP, 2019).

Currently, there is very limited research underway on the technique (Bach et al., 2019) and further research is required to develop understanding about which minerals or other materials would deliver the best net CO_2 return, the likely impacts on ocean ecosystems, the longevity of any sequestration, the economics and resource efficiency of the methods and how both deployment and its effects would be monitored (GESAMP, 2019). Corner et al. (2014) indicate that publics may not be supportive of ocean-based interventions of this nature, suggesting acceptability research about the technique may also be warranted.

The technique could fall under Annex 4 of the London Convention and London Protocol and UNCLOS (Hubert, 2020a). Other interested parties may include intergovernmental or civil society organisations and commercial interests related to chemical engineering.

K. Enhanced terrestrial weathering

The weathering of carbonate and silicate rocks, in which rocks react with CO_2 to form carbonates, removing carbon from the atmosphere, is the primary way in which CO_2 is removed from the atmosphere over geologic timescales (RS/REA, 2018). Enhanced weathering would seek to artificially replicate and accelerate this process through the spreading of minerals on to the surface or by adding them to soil used for agriculture. It is expected that current mining, grinding and farm machinery technology would be capable of extracting, preparing and distributing the mineral. However, a large scale up of available machinery and infrastructure globally would be required (Florin et al., 2020).

The underlying understanding of the chemistry of enhanced weathering of carbonate or silicate minerals to decrease CO_2 is very well understood (NAS, 2015) meaning the key barriers to deployment are questions about how to scale up, cost, possible environmental or other consequences alongside several governance issues rather than technical questions about method. It should be noted that, if a sufficient volume of minerals could be processed, distributed and deployed at large enough scale the capacity of enhanced weathering to contribute to CO_2 mitigation is virtually unlimited (IPCC, 2013). Smith et al. (2015) have estimated that if two-thirds of all croplands were treated with between 10 and 30 tonnes of material per hectare per annum, between 0.4 and 4 Gt could be removed by enhanced weathering by 2100.

The IPCC suggests a range for the potential to remove carbon of 0.72 to 95 $GtCO_2$ per annum (IPCC, 2018), whilst noting more evidence is required before estimates can be agreed. A recent enhanced weathering experiment has suggested the technique maybe up to three times less efficient than had been previously suggested (Amann, 2020).

A significant issue associated with enhanced weathering is the requirement to mine, grind-up, transport and spread very large quantities of material. The Royal Society and Royal Academy of Engineering (2018) have estimated that with a 100% efficient process, at least 7 km^3 per year of material, double the volume of all mined coal in 2018, would be required to remove as much CO_2 as we are currently emitting.

Cost estimates range from between \$15 and \$3,460 per tonne (McQueen et al., 2020, Beerling, 2020, IPCC, 2018 and Renforth, 2011). It is also suggested that enhanced weathering on the surface may have positive benefits on crop growth through changes in nutrient availability (De Oliveira, 2020).

The technique may have negative effects, from, for example, fine particulate pollution and nickel and chromium accumulation and release into aquatic and marine systems (Edwards et al., 2017) meaning additional environmental impact research is required in addition to recent proof of concept and small-scale field trials (McQueen et al., 2020; Kelemen, 2020; GGREW, 2020).

Despite low levels of understanding about the approach (Pidgeon and Spence, 2017, Wright et al., 2014) and whilst noting that what has been done has focussed on Europe and the United States, research has suggested that enhanced weathering may be seen as being too slow a response, although research in well controlled conditions is likely to be acceptable (Cox et al., 2020). Cox et al. (2020) also suggest that publics require greater clarity about the processes that would be involved and would wish to see evidence that the current scientific uncertainties can be resolved. Further, the study also indicates there may be a preference for the use of mine by-products for enhanced weathering rather than the sinking of new mines to access materials.

Given enhanced weathering on land would be conducted within the boundaries of countries, national law and other national governance norms would apply. However, were enhanced weathering to be deployed at a significant scale, new international mechanisms for monitoring, verification, and reporting, including mechanisms that account for transboundary effects of the approach would be required.

L. Macroalgal cultivation for sequestration

The large-scale farming at sea of macroalgae, or seaweed, to capture carbon through photosynthesis with subsequent harvest for sequestration or bio-fuel production with carbon capture could, theoretically, result in net CO_2 removal (N'Yeurt et al., 2012), and play a role in enhancing the biological pump, the ocean's natural biologically driven process of absorbing and circulating carbon dioxide to the deep ocean (Sigman, 2006).

Nearshore macroalgal aquaculture for food is a well-established industry globally (Pereira, 2013) and may already account for the accumulation of ~0.8 Mt of organic carbon annually in the Asia-Pacific region (Sondak, 2017). If scaled up, it has been estimated that, were 9% of the oceans converted to macroalgal aquaculture they could potentially generate 12 Gt per annum of bio digested methane (N'Yeurt et al., 2012). This could subsequently be burned as a substitute for natural gas. The biomass involved would capture 19 $GtCO_2$ and the CO_2 produced by burning the methane would be captured and sequestrated.

Research is underway exploring the effect of ocean acidification on macroalgae growth (Rodríguez, 2018), which may diminish the value of the technique if acidification continues, and the conversion of seaweed to bio-products which use captured carbon in ways to sequester it for the long term (BMRS, 2019).

As an extant farming method, it has been suggested that its proliferation in the Asia-Pacific region would not raise novel socio-economic challenges (Pereira, 2013). Pereira also suggests diversification to other regions is likely to be practical although scale up would require significant infrastructure investment and policy commitment (RS/RA, 2018). In addition to environmental benefits, the technique may have economic value from sale for nutrition, energy and fertiliser, although some of these uses may mean the approach does not capture GHGs in the long term and, as such, may not qualify as CDR (RS/RA, 2018). It is noteworthy that this technique would avoid the competition for land resources of other afforestation methods and, dependent on location, may not be in competition for marine resources and may, potentially, enhance them (GESAMP, 2019).

The FAO may be positioned to play a role in some aspects of the monitoring of macroalga production by building on its regular assessments of aquaculture, which include details on the global production of various types of aquatic plants (FAO, 2014). For waters outside EEZ, the technique would fall under customary international law, the London Protocol and the UNCLOS, within inshore waters, the approach would be a nation state governance issue.

M. Ocean carbon capture and storage (OCCS)

OCCS would remove dissolved inorganic carbon from the oceans to be taken to long term storage sites, increasing the capacity of the oceans to absorb CO_2 from the atmosphere driven by a natural return to equilibrium. The principles underlying the technique are well understood and are used at small scale in laboratories during sea water analysis (Willauer et al., 2017). However, many critical research issues remain, most importantly the feasibility of large-scale engineering development of OCCS and the associated costs and whether a scaled-up system would be suitable for climate mitigation (GESAMP, 2019).

It is unclear what incentives would be required to encourage up-take were a technology proven. Which institutions would develop this and why is unknown? It is also unknown where the captured carbon would be stored and at what opportunity cost, nor whether the technique would be socially acceptable. However, some limited technical and economic modelling is underway (Eisaman et al., 2018) exploring the cost and infrastructure challenges of OCSS.

If conducted in inshore waters, OCSS would be subject to nation state regulation, customary law and wider governance dialogue. In international waters, the governance frameworks are uncertain.

N. Ocean fertilisation with iron (OFI)

Photosynthesis by plankton in the ocean removes around 40 Gt CO_2 per year from the ocean surface and transports it downward to the deep ocean (RS/RA, 2018). Iron ocean fertilisation seeks to enhance this process by introducing additional micronutrients to drive greater plankton growth. Distributing iron into the oceans is technically feasible and the industrial infrastructure required is well understood (GESAMP, 2019).

Estimates for the capacity for ocean iron fertilisation to remove and store CO_2 are extremely uncertain. For example, the IPCC estimates a range of 15.2kt for small interventions to 44Gt, (IPCC, 2018) whilst the Royal Society and the Royal Academy of Engineering, adopts an estimate of 3.7 $GtCO_2$ per annum (RS/RA, 2018). Cost estimates for this technique also vary and contain significant uncertainty. The IPCC, for example, estimate a cost range of between $2 and $457 per tonne of CO_2 removed (IPCC, 2018).

Some potential side-effects have emerged during testing, including population increases of toxic species of single-celled algae diatoms (Silver et al., 2010 and Trick et al., 2010). If iron fertilisation is carried out over large areas, there may be reductions as well as increases in productivity, affecting fisheries and potentially nutrient robbing from downstream regions, potentially with geopolitical and economic implications (GESAMP, 2019).

The technique falls under annex 4 of the London Protocol (IMO, 2013). Other interested parties could include civil society and commercial interests; however, the London Protocol has asserted authority for regulation of ocean fertilization which is widely viewed as a de facto moratorium on commercial ocean fertilization activities (IPCC, 2018).

O. Ocean fertilisation with macro-nutrients, nitrogen, and phosphorus (OFM)

The underlying principle of this technique is the same as for iron fertilisation (above), it simply uses nitrogen and/or phosphorus in place of iron. It has been suggested that nitrogen fertilisation, when additional costs including manufacture, transport, and distribution by vessels on the ocean are included, is potentially a more efficient means of sequestration than iron fertilization (Harrison, 2017; Matear and Elliot, 2004). Harrison (2017) suggests that the technique has a theoretical capacity to offset up to 15% of annual global CO_2 emissions (as at 2017).

Research is still required to understand the viability of this approach and the supply chain infrastructure and market mechanisms that would be required to underpin deployment. Because phosphorus stocks are in decline, there are concerns regarding future capacity to fertilise crops, limited supply and price volatility may also be important factors for the geo-politics of phosphorus use with this technique (GESAMP, 2019).

The technique would fall under the scope of Annex 4 of the London Protocol which restricts dumping (Hubert, 2020a). Intergovernmental and civil society organisations, and commercial interests, especially those associated with food production and mining/minerals may have a particular interest in the governance of the technique.

P. Restoring peatlands, wetlands, and coastal habitats

The restoration of peatlands, wetlands and coastal habitats requires little in the way of new technology (Zedler, 2005). It centres on rewetting or re-establishing environments, normally through practices to block excessive draining including constructing dams, managing vegetation, and restocking with plants, to colonise and hence enhance the carbon capacity (SNH, 2019). Coupled with this, measures to protect the ecosystems against further exploitation and degradation are required (Bain et al., 2011).

Current estimates of the maximum long-term carbon sequestration that can be achieved through improving wetlands, indicate a potential of between 0.4 and 18 tons of CO_2 per hectare per annum, scaling to a global potential of approximately 1 $GtCO_2$ per annum by 2030 (Bain et al., 2011). Coastal ecosystem restoration could theoretically remove 0.2 $GtCO_2$ per annum (Griscom et al., 2017). However, this may be challenging, because of the semi-permanent and on-going nature of most coastal land-use change (Li et al., 2018). Carbon sequestration costs in freshwater wetlands have been estimated to be in the range of $10 to $100 per tonne of CO_2 (Kayranli, 2010) and estimates for saltwater environment restoration range from $2,508 to $383,672 per hectare (Bayraktarov et al., 2016).

Restoring wetlands can have a range of, non-climate related benefits, including enhancing resilience to flooding and the effects of storms, improved water quality, biodiversity, and employment and recreational benefits —some of which may contribute to wider global sustainability goals (Zedler, 2005).

The release of methane and nitrous oxide from wetlands may release between 20% to 25% of global emissions (Whiting, 2001). Whilst reviews of methane mitigation technologies indicate that this may be a challenging task (Stolaroff, 2012, Lockley, 2012), it is known that such releases can be reduced significantly by planting of mosses and other plant coverage on non-coastal wetlands. The technique may then be able to both remove CO_2, but also reduce GHG emissions.

Despite the useful review of the mitigation potential of coastal wetlands prepared by the IPCC (2019), if wetland restoration is to be fully understood and any potential for CDR fully realised, more research may be beneficial to improve understandings of the technique's potential.

The key barriers to large-scale wetland restoration are largely financial. Frequently, the direct economic value of co-benefits that accompany restoration, such as water quality and availability improvements, and greater biodiversity, can be insufficient to offset the value of the loss of land (RS/RAE, 2018). Financial incentive mechanisms may then, be required, and, maintained over the long-term (Kayranli, 2009).

Challenges also remain regarding the monitoring, verification and reporting of achieved carbon sequestration, cost-effective monitoring of fluxes, and the effects, positive or negative, of land-use change (Kayranli, 2009, RS/RAE, 2018).

V. Some CDR governance agenda for global consideration

In addition to governance issues related to the techniques discussed above, several generic governance issues cut across all the techniques discussed. The following provides a snapshot of these issues:

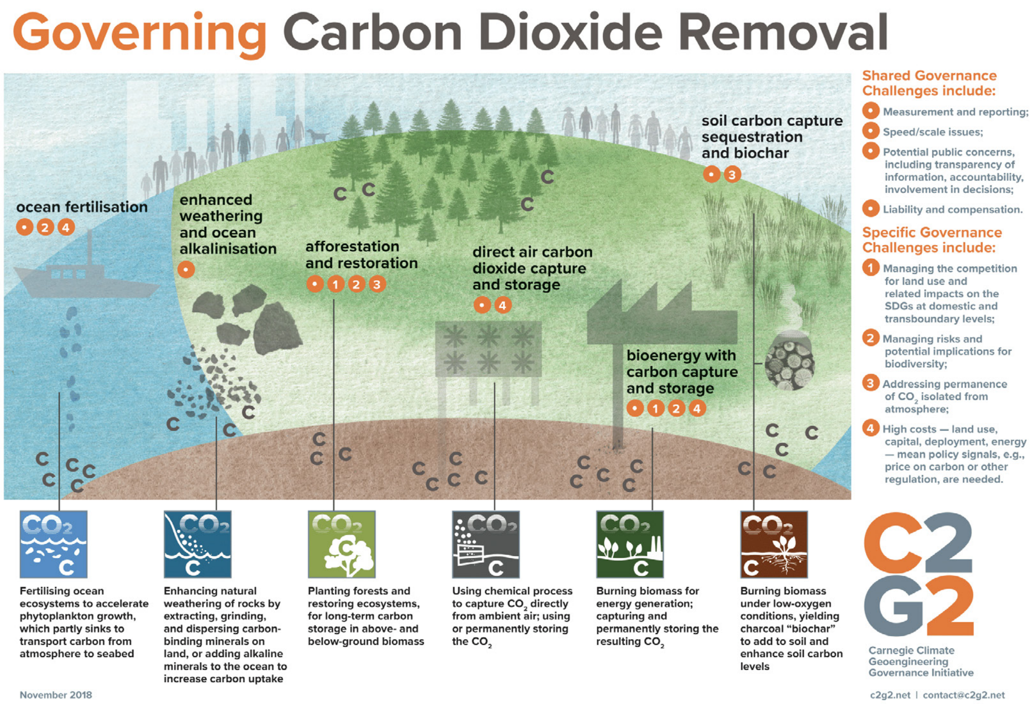
A. Research governance

CDR research may help reduce some uncertainty, easing some of the governance challenges described (Mace et al., 2018). Addressing this research need is a governance challenge in its own right, for example, it is unclear how knowledge gaps will be identified, research agenda set, and funding will be secured and provided to appropriate researchers.

It has been suggested that high-quality integrated assessments of CDR will be a key tool in addressing some of the CDR uncertainties (Fuss, 2018). However, these are lacking and whilst over 200 CDR review articles were published by 2017 (Minx et al., 2017) and a number have sought to assess a portfolio of techniques (e.g., RS/RA 2018, Fuss 2018, NAS 2015, McLaren 2012) these assessments have been fragmented with each selecting a different set of techniques and assessing them against different metrics.

CDR research may cause harms. For example, field trials may harm local biodiversity and demonstration scale DACCS infrastructure may impact on water resources availability (for a review of potential CDR harms see Dooley et al., (2020)). As such, not only does the research and science policy process require and have implications for governance, but project level governance will also require consideration. Reflecting this, several non-binding codes of conduct have been developed, such as the Oxford Principles (Rayner et al., 2013), the Asilomar Principles for Research into Climate Engineering Techniques (Asilomar, 2010), the Academic Working Group on Climate Engineering Governance (AWG, 2018) and the Code of Conduct for Responsible Geoengineering Research (Hubert, 2020b). However, although such codes encourage researchers to act in measured responsible ways, given they are voluntary and have no forfeiture available, they may not deter a committed researcher.

Image 1
Governing CDR–a summary of key governance agenda and CDR techniques



Source: C2G2 (2018).

B. Monitoring, Reporting and Verification (MRV)

It is suggested that the MRV of removals will require a global accounting system (Honegger, 2020) and that, given the range of approaches to CDR and the variation with which they remove and store carbon, and the challenges associated with permanency and leakage, any future MRV will have to function in the context of considerable uncertainty (Honegger, 2020). It is then, unclear how the international community may resolve the environmental, policy and research challenges that remain for MRV, and whether and how this might be done within the context of existing frameworks (Florin et al., 2020).

C. "Moral hazard" or "mitigation deterrence"

McLaren et al. (2016), Wagner (2020) and others have discussed the issue of moral hazard —the idea that the use of CDR and its potential cooling effect could provide stakeholders with an excuse to either fail to ramp up efforts to reduce emissions or to continue using fossil fuels at current, or even accelerated rates. It is suggested that this could also happen because of theoretical modelling, if the promise of any CDR techniques identified in studies deters near-term emissions reductions, by reducing the perceived future social cost of carbon (McLaren et al., 2016).

In the context of the modelled emissions scenarios that meet the Paris Agreement goals, including large scale deployment of CDR and the delivery of net-zero emissions (IPCC, 2018), it is apparent that any indications that mitigation deterrence, in the form of moral hazard, may occur could create an important governance consideration (Florin et al., 2020).

D. Risk-risk trade-offs

Risk-risk trade-offs, which apply to all CDR techniques to some extent, characterise both emergent governance and policy design choices, as well as how research is conducted and communicated. They involve risk-risk trade-offs in terms of both outcomes as well as governance choices (Honegger, 2020).

Within the policy context, risk trade-offs identified by Honegger (2020) include: effective governance versus governance efficiency, at the local, regional and global level; transboundary effects of CDR approaches as challenges to sovereignty of domestic policies; achieving the most effective mitigation verses securing and maintaining the benefits of sustainable development; and, balancing centralised and polycentric governance.

In relation to research, it is suggested that potential trade-offs include: balancing academic and innovation knowledge with lay and cultural knowledge and understandings, particularly in relation to nature-based approaches to CDR; research driven mitigation deterrence set against mitigation stalling or potentially cessation; limited international research co-operation and dialogue undermining capacity for governance cooperation; and, unbalanced research capabilities, both in terms of resources and underpinning infrastructure generating significant power differentials (Honegger, 2020).

To date how to resolve these trade-offs is uncertain, however in his comprehensive analysis of the issues, Honegger (2020) suggests, in relation to policy-design, the strengthening of capacities for international inter-agency collaboration; improving understanding of how specific governance challenges match particular international agencies' mandates; and, conducting policy assessments in the context of national mitigation policy planning. In relation to trade-offs related to research Honegger (2020) suggests enabling more diverse, transdisciplinary research; the exchange of expertise; science-policy conversations; and, conducting research on potential interlinkages in the context of the SDGs.

E. Potential implications of CDR for the sustainable development goals

The potential implications of CDR upon the delivery of the SDGs are uncertain (Mace et al, 2021) with insights about implications only available from pilot activities or by inference from other practices (Honegger et al., 2020). Climate change mitigation and co-benefits from CDR may benefit delivery of the SDGs, yet poorly designed CDR policies could also challenge their successful delivery (Honegger et al., 2020). Specific CDR options could, for example, generate conflicts over land, water, biomass, or electric power resources, and exclude communities from policy benefits with negative cascading effects for a range of SDGs (Honegger et al., 2020, Mace et al., 2021). In a detailed study of the potential interrelationships between CDR and the SDGs, Honegger et al (2021) identified four key policy insights for consideration:

(i) the stabilization of global climate is a precondition for at least partially achieving the SDGs and CDR may help deliver this;

(ii) CDR techniques can generate both positive and negative local and regional impacts on SDGs via physical, social, economic, and political channels;

(iii) the scale of CDR implementation and the implications for the SDGs are highly dependent on policy design and national planning processes; and,

(iv) more research on CDR policy design would help identification of synergies between, and prevent harm across, multiple SDGs.

F. Incentives

It is unclear how the international community might agree, set and stabilise, over the long-term, atmospheric CO_2 concentrations and other mitigation measures (Honegger, 2020). Neither is it clear how this process, and the outcomes of the decisions taken, can balance the individual interests of nation-states with the global need to reduce CO_2 concentrations in the atmosphere (Honegger, 2020). Addressing such policy challenges may warrant some incentivisation, but to date it is uncertain how that might evolve (Florin et al., 2020).

It is also unclear how the scale and speed of implementation implied by IPCC scenarios (IPCC, 2021; 2018) might be achieved and it is suggested that the substantial incentives to secure such rapid change, in terms of new financial and policy options are either very weak, or do not yet exist (Mace et al., 2021; Florin et al., 2020).

G. Sequestration and permanency

Some techniques described do not have the capability to sequester captured carbon durably or permanently. If large quantities of CO_2 were to re-enter the atmosphere, due to storage failure or leakage, this would reverse the gains from achieved CDR. This issue creates important research, engineering and governance challenges, as identified by the National Academy of Engineering (NAS, 2019), including, for example, the long-term management of sequestered carbon over century timescales, the prevention of leakage from hard to reach or challenging environments and financing or incentives (NAS, 2019).

H. Other remaining governance challenges

In addition to the technique specific and generic governance issues noted, a recent review of CDR governance challenges (Mace et al., 2021) identifies two further topics of relevance to CDR governance that require attention:

(i) the attribution of responsibility and ethical questions around implementation; and,

(ii) mechanisms to identify liability and make redress.

I. The role of international law and frameworks

A range of international frameworks are relevant to CDR, including:

- UN Framework Convention on Climate Change (UNFCCC) (UN 1992);
  - Paris Agreement 2015 (UNFCCC 2015);
  - Kyoto Protocol;
- Convention on Biodiversity (CBD) (CBD, 2008);
- London Convention 1972 and the 1996 London Protocol (IMO 2016);
- the International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978 (MARPOL, 1978); and,
- UN Convention on the Law of the Sea (UNCLOS) (UN 2009).

How these may evolve in the context of the increasing use of CDR remains uncertain. Hubert (2020a) provides an analysis of these instruments and how they may relate to CDR.

VI. Case study: impact of carbon dioxide removal measures and/or technologies on sustainable development objectives in Latin America and the Caribbean

The study titled "Impact of CDR measures and/or technologies on the Sustainable Development Goals (SDGs) in selected countries in Latin America and the Caribbean", conducted by Samaniego et al. (2021) documents the effects of the six carbon dioxide removal (CDR) measures and/or technologies on economic and environmental indicators with respect to the results of the respective BAU (Business as usual) scenarios, as well as their impact on the Sustainable Development Goals (SDGs), in selected LAC countries (Argentina and Colombia). This study includes a full version of the document, plus a summary for decision-makers (in three languages: Spanish, English and French).

The objectives of the study were focused on identifying knowledge gaps and formulating recommendations for consideration by the governments of the region in order to stimulate and organize the incorporation of CDR approaches into national climate change strategies. To respond to these objectives, the study is subdivided into three main items, which are addressed for each of the measures, technologies and/or approaches:

(i) State of the art-knowledge, plans and development.

(ii) CDR analysis, scenarios for selected technologies and countries.

(iii) Analysis of economic, social, and environmental implications.

Regarding point (a), state of the art, an intense bibliographic search was carried out to identify, in three broad outlines, the following: Policies, Plans and Programs implemented at the national level; scientific research carried out; initiatives and development of large-scale projects. Each measure was evaluated, resulting in the gap between knowledge and empirical development in LAC countries (using methodology developed by C2G). To summarize these results, see table 6.

Table 6
Current status of knowledge and development in Argentina and Colombia–scoring methodology

	Afforestation	BECCS	Biochar	EW & Ocean Alkalinization	DACCS	Ocean Fertilization
Scientific and technical knowledge	● (dark green)	● (grey)	● (light green)	● (grey)	● (orange)	● (grey)
Mainstreaming in government plans	● (dark green)	● (grey)	● (orange)	● (grey)	● (orange)	● (grey)
Implementation of initiatives and projects	● (light green)	● (grey)	● (orange)	● (orange)	● (light green)	● (orange)
	**Afforestation**	**BECCS**	**Biochar**	**EW & Ocean Alkalinization**	**DACCS**	**Ocean Fertilization**
Scientific and technical knowledge	● (dark green)	● (grey)	● (light green)	● (grey)	● (orange)	● (grey)
Mainstreaming in government plans	● (dark green)	● (grey)	● (grey)	● (grey)	● (orange)	● (grey)
Implementation of initiatives and projects	● (light green)	● (grey)	● (light green)	● (orange)	● (orange)	● (orange)

● (orange) Not Developed; ● (grey) Under development not directly/partially related to DRC; ● (light green) Less than 10 items/ programs not yet implemented/small-scale initiatives; ● (dark green) More than 10 articles/ programs under implementation or executed/completed large-scale initiatives

Source: Own elaboration based on Samaniego et al. (2021).

Based on the results reported in the table above, Afforestation and Reforestation and Enhancing soil with Biochar are the most explored CDR approaches in the scientific and academic field in LAC. The main results are summarized (table 7).

Table 7
Knowledge, planning, and implementation gaps of CDR approaches in Latin America and the Caribbean countries

Afforestation	• Supported by Laws, regulations, and national plans both in Argentina and Colombia and in most LAC countries • Several large-scale projects have been identified • Policies and plans promoting the use of wood from sustainably managed forests for industry and construction (mainly Argentina, Brazil, and Chile)	● (light green)
Enhancing soil C content Biochar and Enhanced Weathering (Land)	• Academic and research activity identified, but mainly on small lab scale tests • Enhancing soils C content and techs that include the use of biochar and soil enhancer as well as EW should be worth analyzing deeper in order to qualify its impacts and risks	● (grey)
BECCS	• There is a good basis of research on the BE side, still there is no integral research on BECCS • Incipient but rapidly increasing installed capacity of biomass and biogas power generation plants and biofuels production plants are being observed (focus on BE)	● (grey)
Other CDRs	• Indirect academic research on ocean behavior and characterization and CO_2 dynamics, but no specific examination or projects on Ocean alkalinization/fertilization • Brazil leads CCS research capabilities in Latin America and the Caribbean, mainly focused I geological storage in salt caverns in ultra-deep water • Knowledge developed on FACCS is almost null in LAC countries	● (orange)

Source: Own elaboration on the bases Samaniego et al. (2021).

In general, and with rare exceptions, a significant knowledge and empirical development gap of CDR has been identified in Latin American and the Caribbean (LAC) countries:

- LAC countries efforts on climate change mitigation are primarily focused, as is appropriate, on emissions reductions and replacement of fossil fuels production and use, and only in a largely incipient manner carbon removal efforts are being considered.
- Deployment of large-scale CDR approaches would be expected to have physical side-effects and socio-economic or governance implications on the delivery of SDGs.
- The broader implications of CDR technologies in contributing to delivering or hindering sustainable development efforts are so far insufficiently explored and understood, predominantly from a planning perspective.
- LAC countries face a persistent climate finance gap, the decision on the potential development of those options would require accurate abatement costs information and careful consideration of implementation risks in order to avoid misallocation of resources.
- A comprehensive research and technical development effort for each technology should be undertaken.

Part (b) of the study on the analysis of CDR, scenarios for selected technologies and countries evaluated the BAU scenario for each measure, comparing it with environmental, social, and economic indicators. The results for Argentina are shown (table 8).

Table 8
Argentina: impact of CDR deployment on key variables

		Potential GHG emissions (sequestered)	Avg Investment requirements	Cost	Net Changes in Employment created	Contribution to GDP
		Mega t CO_2/year	MM USD/yr	USD/t CO_2	# Jobs created/ Mega t CO_2 seq	Δ MMUSD GDP/ Mega t CO_2 seq
Afforestation	Baseline	5.6 (avg) 7.7 (2050)	29 (avg)	5.1	73 direct 117 indirect	22
	Sc1	10.3 (avg) 11.3 (2050)	59 (avg)	5.6	80 direct 127 indirect	24
	Sc2	15.9 (avg) 14.4 (2050)	100 (avg)	6.1	85 direct 136 indirect	26
BECCS	Baseline	No CCS adoption in baseline scenario, only bioenergy				
	Sc1	0.1 (avg) 0.3 (2050)	35 (avg)	256.5	733 permanent 258 constr.	1 075
	Sc2	0.7 (Avg) 2.0 (2050)	163 (avg)	239.0	1 037 permanent 360 constr.	1 000
Biochar	Baseline	No biochar deployment in baseline scenario				
	Sc1	0.1 9avg) 0.2 (2050)	3 (avg)	25.4	102 industrial	110
	Sc2	1.5 (avg) 2.5 (2050)	30 (avg)	19.3	77 industrial	84

Source: Own elaboration based on Samaniego et al. (2021).
Nota: Δ MMUSD: million US dollars.

The main results for Argentina for each of the indicators evaluated are listed below:

- Afforestation and reforestation present the lowest cost per ton sequestered (~6 USD/tonCO_2e) and the largest emissions removal for Argentina and should be prioritized in the near term. In spite of its abatement low cost, the scenarios estimate investments of around 60-100 million

USD/yr. and provide a significant source of direct employment. Larger investments, effects in employment and Gross Domestic Product (GDP) than estimated might be possible if the wood industrial value chain is significantly developed.

- Changes in livestock production practices, in particular those increasing soil carbon stocks can provide further means to rising mitigation ambition in the short to medium term.
- Similarly, changes in current but evolving agricultural practices (and thus technically and culturally feasible) can contribute to incremental emission reductions.
- The application of biochar on soils could sequester up to 2.5 Megatons of CO_2e/yr. by 2050, considering only fruit trees. Further expansion to other intensive crops and later to extensive crops might be an upside to explore with further research and pilot projects. Moreover, biochar deployment exhibits the second lowest abatement cost.
- There is uncertainty about the feasibility of timely upscaling of BECCS. CCS is largely absent from the Argentinean NDC and lowly ranked in investment priorities. It is estimated that BECCS could sequester up to 2.0 Megatons of CO_2e/yr. by 2050 with over 1,300 MegaWatts (MW) of additional installed capacity.
- BECCS deployment in the mid-term implies large investments in capital intensive industrial facilities, and therefore exhibits high GDP and employment multipliers. However, BECCS is still an immature technology in Argentina with the largest abatement cost (240 to 260 USD/tonCO_2e), among CDR approaches analyzed.

Table 9 below shows the results for Colombia:

Table 9
Colombia: impact of CDR deployment on key variables

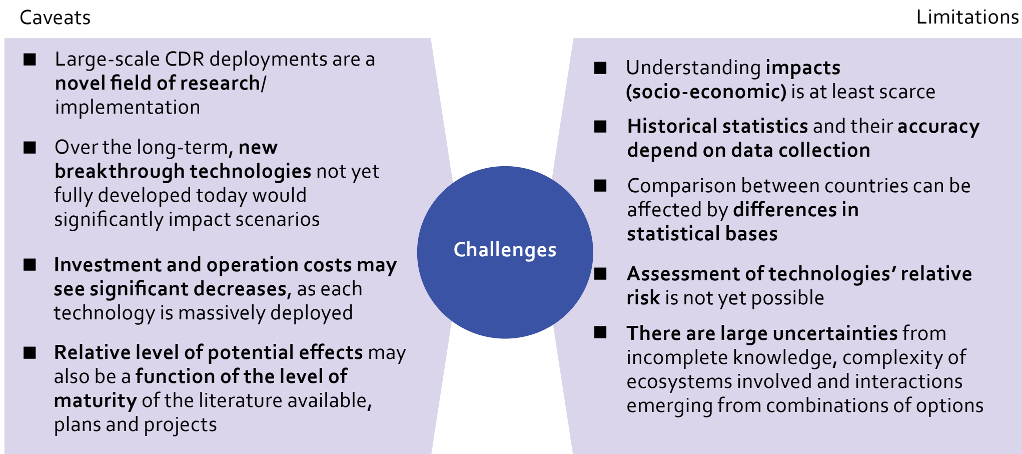
		Potential GHG emissions (sequestered)	Avg Investment requirements	Cost	Net Changes in Employment created	Contribution to GDP
		Mega t CO_2/year	MM USD/yr	USD/t CO_2	# Jobs created/ Mega t CO_2 seq	Δ MMUSD GDP/ Mega t CO_2 seq
Afforestation	Baseline	4.7 (avg) 6.3 (2050)	48 (avg)	9.7	76 direct 122 indirect	62
	Sc1	7.5 (avg) 8.1 (2050)	78 (avg)	10.1	74 direct 118 indirect	65
	Sc2	13.4 (avg) 12.0 (2050)	144 (avg)	10.5	66 direct 106 indirect	67
Mangrove restauration	Baseline	Null or marginal mangrove restoration in Colombia				
	Sc1	0.4 (avg) 0.8 (avg)	5 (avg)	11.1	65 direct	69
	Sc2	1.4 (avg) 2.9 (2050)	15 (avg)	10.9	69 direct	68
BECCS	Baseline	No CCS adoption in baseline scenario, only bioenergy				
	Sc1	0.1 (avg) 0.4 (2050)	12 (avg)	72.9	271 permanent 104 construction	453
	Sc2	2.1 (avg) 4.7 (2050)	146 (avg)	69.2	259 permanent 101 construction	429
Biochar	Baseline	No biochar deployment in baseline scenario				
	Sc1	0.3 (avg) 0.4 (2050)	7 (avg)	25.0	100 industrial	161
	Sc2	3.1 (avg) 4.8 (2050)	58 (avg)	18.0	72 industrial	116

Source: Own elaboration based on Samaniego et al. (2021).

- Controlling deforestation is key for lowering national emissions. Further, given the need to produce additional food and biomass by intensifying agriculture and cattle production, halting deforestation emerges as an imperative to facilitate the adoption of a deep decarbonization and long-term sustainable food production.
- Afforestation also presents the largest Greenhouse Gases (GHG) emissions potential in Colombia, with an average of over 13 Megaton of CO_2e/yr. in the 2020-2050 period.
- Colombia is one of the world's top 20 countries in terms of mangrove coverage, with nearly 300,000 ha of mangrove trees in the Pacific and Caribbean Coasts. Mangroves are well known for their high capacity to capture carbon stock per unit of land compared with terrestrial forests. It is expected that mangrove restoration at a 0.7% annual rate (58 thousand ha restored in the next 30 years) could sequester up to 3 Megaton of CO_2e/yr., with relatively low investments and costs per ton of CO_2.
- Effects in employment and GDP contribution of afforestation and mangrove restoration interventions might be underestimated if other indirect economic activities derived from its value chain and ecosystem respectively were also considered (not included in the figures below) beyond primary plantations activities.
- Only considering deployment in fruit tree plantations, Biochar application on Colombian soil could sequester up to 5 Megatons of CO_2e/yr by 2050. As mentioned in Argentina, further expansion to other intensive crops and later to extensive crops might be an upside to explore with further research and pilots in Colombia. Although higher than Afforestation and Mangrove restoration, Biochar application cost per ton is expected to remain below 25 USD/ton CO_2e.
- Over 1,100 MW of BECCS installed capacity are forecasted for Colombia by 2050 in a high adoption scenario, potentially sequestering nearly 5 Megatons of CO_2e/yr. BECCS is constrained by sustainable bioenergy potential and availability of safe storage for CO_2. Similar to Argentina, in Colombia there is also uncertainty about the feasibility of timely upscaling of BECCS. CCS is largely absent from the Colombian NDC and lowly ranked in investment priorities. BECCS competes with other land-based CDR approaches and mitigation measures for resources.
- Larger investments requirements like capital intensive BECCS deployment and Biochar production plants generate larger effects in employment creation and GDP contribution. Although significantly lower than in Argentina, BECCS present the highest CDR abatement cost in Colombia at an estimate of about 70 USD/ ton CO_2e.

To develop point (c) on the analysis of the economic, social, and environmental implications, the limitations of the analysis carried out in the study are developed. To this end, the considerations and/ or caveats and limitations to be considered in addressing CDR measures in the region are generated (diagram 2).

Diagram 2
Limitations of the analysis



Source: Own elaboration based in Samaniego et al. (2021).

The following recommendations aim to enable better informed decision-making on the potential deployment of applicable large-scale CDR approaches in LAC.

- Given the complexities and remaining uncertainties associated with some of the CDR approaches analyzed, progress is required at least in:
  - Elaboration of integrated assessment models at the national and sectoral level
  - Cost-benefit analysis
  - Risk analysis
  - Intensification of ongoing scientific and technical research
  - Multiple pilot projects
- LAC countries might face a persistent finance gap 9accentuated by the pandemic). The decision on the potential CDR development would require accurate abatement costs information and careful consideration and assessment of implementation risks.
- Overall assessment of the technical and economic feasibility of the CFR approaches should be embedded in the framework to be provided by long-term strategies elaborated by LAC countries, including next generation of NDCs.
- Collaborative platforms and programs of work and a common requirement for additional international climate finance to address the need for additional resources.
- The potential for coalescing robust finance flows in the context of Article 6 might contribute to finance the required long-term transitions in LAC countries.
- More transdisciplinary and geographically diverse research is required on the linkages of large-scale CDR deployment and the delivery of the Sustainable Development Goals, which may include development of common assessment principles or metrics.
- Integrated policy impact assessments are needed to understand potential policy designs to mobilize CDR and what implications they would have for delivery of the SDGs.

VII. Conclusion

If global warming is to be limited sufficiently to achieve the Paris Agreement targets, the IPCC scenarios (IPCC, 2021; 2018) clearly imply that, in addition to transformational emission reductions, CDR techniques would need to be adopted as part of the response. In this paper, the global climate targets and national commitments derived from the Paris Agreement have been described inserting, in turn, the regional context of mitigation and adaptation and the current NDCs ambition levels. In this development, we have delved into how CDRs are inserted in NDCs and their importance for the region which, based on recent studies for LAC, opportunities in more nature-based sectors will predominantly be implemented and considered in national NDCs.

In the case study that addresses the problem of soil desertification at the regional level, the need to consider the interrelationships between productive systems and their natural resource bases in the different geographic areas becomes evident, where degradation affects productivity and jobs and, therefore, the regional economy. The exploration of a number of CDR measures and technologies commonly discussed in the literature has provided insight into the possibility of available options for these measures, but at the same time on the knowledge gaps that still exist for their implementation. Based on this, guidelines are provided on a number of governance programs that should be considered to inform future decisions on the development, implementation, or long-term management of CDR measures and technologies. Finally, a summary of the study done on the impact that the deployment of these measures would have gives an overview of the co-benefits that these measures would bring.

Regardless of one's concept of how to combat climate change, the challenges of mitigation and adaptation require consideration of all options. Because of their complexity, CDRs need to deepen their technical knowledge of policies and instruments in order to be in a position to participate in the international debates that are already taking place and to take the necessary measures in as informed a manner as possible. In this context, Latin America and the Caribbean need to deepen their knowledge and debates on CDRs.

Bibliography

Amann, T., Hartmann, J., Struyf, E., de Oliveira Garcia, W., Fischer, E. K., Janssens, I., Meire, P., & Schoelynck, J. (2020), Enhanced Weathering and related element fluxes – a cropland mesocosm approach. *Biogeosciences*, *17*(1), 103–119. https://doi.org/10.5194/bg-17-103-2020.

Anderson, P. (2020), Climate Intervention with Biochar: A White Paper about Biochar and Energy (BC&E) for Carbon Dioxide Removal (CDR) and Emission Reduction (ER). *Woodgas Pyrolytics, Inc*. https://woodgas.energy/wp-content/uploads/2020/12/Climate-Intervention-With-Biochar.pdf.

Arévalos, F., Ortiz, E., Báez, M., Benítez, C., Allegretti, L., & Duré, A. (2018), *Monitoreo Mensual del Cambio de Uso y Cobertura de la Tierra, Incendios y Variación de la Cubierta de Aguas en el Gran Chaco Americano*.

Asilomar Scientific Organizing Committee (2010), *The Asilomar conference report. Principles for Research into Climate Engineering Techniques. Conference Report* . http://www.climateresponsefund.org/images/Conference/finalfinalreport.pdf.

Aure, J., Strand, Ø., Erga, S., & Strohmeier, T. (2007), Primary production enhancement by artificial upwelling in a western Norwegian fjord. *Marine Ecology Progress Series*, *352*, 39–52. https://doi.org/10.3354/meps07139.

Bakkegaard, R. et al. (2015), *Developing INDCs: A Guidance Note, Asociación PNUMA-DTU.* https://orbit.dtu.dk/en/publications/developing-indcs-a-guidance-note.

Banco Centroamericano de Integración Económica, & FAO (2019), *Reunión técnica: Corredor Seco Centroamericano y soluciones de desarrollo*. https://www.fao.org/americas/eventos/ver/es/?uid=1196866.

Banco Mundial (2010), *The Cost to Developing Countries of Adapting to Climate Change. New Methods and Estimates*.

Barbier, E. B., & Hochard, J. P. (2016), Does Land Degradation Increase Poverty in Developing Countries? *PLOS ONE*, *11*(5), e0152973. https://doi.org/10.1371/journal.pone.0152973.

Bárcena, A., Samaniego, J., Galindo, L. M., Ferrer Carbonell, J., Alatorre, J. E., Stockins, P., Reyes, O., Sánchez, L., & Mostacedo, J. (2018), *LA ECONOMÍA DEL CAMBIO CLIMÁTICO EN AMÉRICA LATINA Y EL CARIBE. UNA VISIÓN GRÁFICA*.

Bárcena, A., Samaniego, J., Peres, W., & Alatorre, J. E. (2020), *La emergencia del cambio climático en América Latina y el Caribe:¿ seguimos esperando la catástrofe o pasamos a la acción?.* Comisión Económica para América Latina y el Caribe (CEPAL). https://repositorio.cepal.org/bitstream/handle/11362/45677/S1900711_es.mobi.

Bayraktarov, E., Saunders, M. I., Abdullah, S., Mills, M., Beher, J., Possingham, H. P., Mumby, P. J., & Lovelock, C. E. (2016), The cost and feasibility of marine coastal restoration. *Ecological Applications*, *26*(4), 1055–1074. https://doi.org/10.1890/15-1077.

Beerling, D. J., Kantzas, E. P., Lomas, M. R., Wade, P., Eufrasio, R. M., Renforth, P., Sarkar, B., Andrews, M. G., James, R. H., Pearce, C. R., Mercure, J.-F., Pollitt, H., Holden, P. B., Edwards, N. R., Khanna, M., Koh, L., Quegan, S., Pidgeon, N. F., Janssens, I. A., … Banwart, S. A. (2020), Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. *Nature*, *583*(7815), 242–248. https://doi.org/10.1038/s41586-020-2448-9.

Bhave, A., Taylor, R. H. S., Fennell, P., Livingston, W. R., Shah, N., Dowell, N. mac, Dennis, J., Kraft, M., Pourkashanian, M., Insa, M., Jones, J., Burdett, N., Bauen, A., Beal, C., Smallbone, A., & Akroyd, J. (2017), Screening and techno-economic assessment of biomass-based power generation with CCS technologies to meet 2050 CO_2 targets. *Applied Energy*, *190*, 481–489. https://doi.org/10.1016/j.apenergy.2016.12.120.

BID (2018), *Proceso Regional de las Américas: Foro Mundial del Agua 2018: Informe regional América Latina y el Caribe: Resumen ejecutivo*. https://doi.org/10.18235/0001028.

BID, & DDPLAC (2019), *Cómo Llegar a Cero Emisiones Netas: Lecciones de América Latina y el Caribe*.

BMRS (2019), *Programa de investigación sobre la conversión de algas en bioproductos*. https://www.bmrs.ie/bmrs-projects#seaweed-conversion-to-bio-products.

C2G (2021), *Remoción del dióxido de carbono Carnegie Climate Governance Initiative - informes y recursos educativos para la gobernanza de RDC*. https://www.c2g2.net/carbon-dioxide-removal/.

______(2018), *Governing Carbon Dioxide Removal*. https://www.c2g2.net/wp-content/uploads/Carbon-Dioxide-Removal-Nov-2018.pdf.

Cardozo, R., Caballero, J., Arévalos, F., Bazán, D., & Palacios, F. (2013), *INFORME TÉCNICO. Resultados del Monitoreo Mensual de los Cambios de Uso de la Tierra, Incendios e Inundaciones en el* . https://www.academia.edu/11429083/INFORME_T%C3%89CNICO_Resultados_del_Monitoreo_Mensual_de_los_Cambios_de_Uso_de_la_Tierra_Incendios_e_Inundaciones_en_el.

Comisión Económica para América Latina y el Caribe (CEPAL) (n.d.), *NDC LAC*. Retrieved March 15, 2022, from https://ndclac.cepal.org/es/acerca-de.

______(2020), Construir un nuevo futuro: una recuperación transformadora con igualdad y sostenibilidad. In *(LC/SES.38/3-P/Rev.1)*.

______(2019), *CEPALSTAT | Bases de Datos y Publicaciones Estadísticas*. CEPAL. https://estadisticas.cepal.org/cepalstat/portada.html.

______(2015), La economía del cambio climático en América Latina y el Caribe: paradojas y desafíos del desarrollo sostenible. In *Comisión Económica para América Latina y el Caribe (CEPAL)*, LC/G.2624.

CEPAL, & C2G. (2022), *Herramienta interactiva sobre el impacto de las medidas y tecnologías de remoción de dióxido de carbono sobre los Objetivos de Desarrollo Sostenible en América Latina y el Caribe*.

CEPAL, & OIT (2018), *Environmental sustainability and employment in Latin America and the Caribbean*. https://repositorio.cepal.org/bitstream/handle/11362/44186/1/S1800885_en.pdf.

CG, B., Bonn, A., Stoneman, R., Chapman, S., Coupar, A., Evans, M., Geary, B., Howat, M., Joosten, H., Keenleyside, C., Lindsay, R., Labadz, J., Littlewood, N., Lunt, P., CJ, M., Moxey, A., Orr, H., Reed, M., Smith, P., & Worrall, F. (2011), *IUCN UK Commission of inquiry on peatlands*.

Chará, J., Ernesto, R., Otte, J., Peri, P., Arce, E., & Schneider, F. (2019), *Silvopastoral Systems and their Contribution to Improved Resource Use and Sustainable Development Goals: Evidence from Latin America*.

Cherlet, M., Hutchinson, C., Reynolds, J., Hill, J., Sommer, S., & von Maltitz, G. (2018), *World Atlas of Desertification* (Issue KJ-07-17-008-EN-C (print),KJ-07-17-008-EN-N (online)). Publications Office of the European Union. https://doi.org/10.2760/06292 (online),10.2760/9205 (print).

CLIMEWORKS (2019), *Clime Works* . https://climeworks.com/.

Comisión Económica para América Latina y el Caribe (CEPAL), & Organización Internacional del Trabajo (OIT) (2018), *"Sostenibilidad medioambiental con empleo en América Latina y el Caribe", Coyuntura Laboral en América Latina y el Caribe, No 19 (LC/TS.2018/85)*.

Cox, E., Spence, E., & Pidgeon, N. (2020), Incumbency, Trust and the Monsanto Effect: Stakeholder Discourses on Greenhouse Gas Removal. *Environmental Values*, *29*(2), 197–220. https://doi.org/10.3197/096327119X15678473650947.

Daggash, H., Fajardy, M., Heptonstall, P., Dowell, N., & Gross, R. (2019), Bioenergy with carbon capture and storage, and direct air carbon capture and storage: Examining the evidence on deployment potential and costs in the UK. *UK Energy Research Centre Technology and Policy Assessment Imperial College Centre for Energy Policy and Technology*. https://ukerc.ac.uk/project/bioenergy-with-ccas/.

De Oliveira Garcia, W., Amann, T., Hartmann, J., Karstens, K., Popp, A., Boysen, L. R., Smith, P., & Goll, D. (2020), Impacts of enhanced weathering on biomass production for negative emission technologies and soil hydrology. *Biogeosciences*, *17*(7), 2107–2133. https://doi.org/10.5194/bg-17-2107-2020.

Doelman, J. C., Stehfest, E., Vuuren, D. P., Tabeau, A., Hof, A. F., Braakhekke, M. C., Gernaat, D. E. H. J., Berg, M., Zeist, W., Daioglou, V., Meijl, H., & Lucas, P. L. (2020), Afforestation for climate change mitigation: Potentials, risks and trade-offs. *Global Change Biology*, *26*(3), 1576–1591. https://doi.org/10.1111/gcb.14887.

Donato Nobre, A. (2014), *The Future Climate of Amazonia. Scientific Assessment Report*. https://d20uvy59podg6k.cloudfront.net/downloads/the_future_climate_of_amazonia_report.pdf.

Dooley, K., Harrould-Kolieb, E., & Talberg, A. (2021), Carbon-dioxide Removal and Biodiversity: A Threat Identification Framework. *Global Policy*, *12*(S1), 34–44. https://doi.org/10.1111/1758-5899.12828.

Edwards, D. P., Lim, F., James, R. H., Pearce, C. R., Scholes, J., Freckleton, R. P., & Beerling, D. J. (2017), Climate change mitigation: potential benefits and pitfalls of enhanced rock weathering in tropical agriculture. *Biology Letters*, *13*(4), 20160715. https://doi.org/10.1098/rsbl.2016.0715.

Eisaman, M. D., Rivest, J. L. B., Karnitz, S. D., de Lannoy, C.-F., Jose, A., DeVaul, R. W., & Hannun, K. (2018), Indirect ocean capture of atmospheric CO_2: Part II. Understanding the cost of negative emissions. *International Journal of Greenhouse Gas Control*, *70*, 254–261. https://doi.org/10.1016/j.ijggc.2018.02.020.

ELD Initiative (2015), *The value of land: Prosperous lands and positive rewards through sustainable land management*. https://reliefweb.int/sites/reliefweb.int/files/resources/ELD-main-report_05_web_72dpi.pdf.

Ellison, D., Morris, C. E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., Noordwijk, M. van, Creed, I. F., Pokorny, J., Gaveau, D., Spracklen, D. v., Tobella, A. B., Ilstedt, U., Teuling, A. J., Gebrehiwot, S. G., Sands, D. C., Muys, B., Verbist, B., … Sullivan, C. A. (2017), Trees, forests and water: Cool insights for a hot world. *Global Environmental Change*, *43*, 51–61. https://doi.org/10.1016/j.gloenvcha.2017.01.002.

Fan, W., Zhang, Z., Yao, Z., Xiao, C., Zhang, Y., Zhang, Y., Liu, J., Di, Y., Chen, Y., & Pan, Y. (2020), A sea trial of enhancing carbon removal from Chinese coastal waters by stimulating seaweed cultivation through artificial upwelling. *Applied Ocean Research*, *101*, 102260. https://doi.org/10.1016/j.apor.2020.102260.

FAO (2019), *FAOSTAT | Food and Agriculture Organization of the United Nations* . https://www.fao.org/faostat/en/#home.

______(2018), *El estado de los bosques del mundo. Las vías forestales hacia el desarrollo sostenible*. https://www.fao.org/3/i9535es/i9535es.pdf.

______(2017), *Sustainable woodfuel for food security. A smart choice: green, renewable and affordable*. https://www.fao.org/3/I7917EN/i7917en.pdf.

______(2014), *The State of World Fisheries and Aquaculture. Opportunities and challenges*. www.fao.org/documents/card/en/c/097d8007-49a4-4d65-88cd-fcaf6a969776/.

Fasihi, M., Efimova, O., & Breyer, C. (2019), Techno-economic assessment of CO_2 direct air capture plants. *Journal of Cleaner Production*, *224*, 957–980. https://doi.org/10.1016/j.jclepro.2019.03.086.

Fearnside, P. M. (2005), *Desmatamento na Amazônia brasileira: História, índices e conseqüências. Megadiversidade 1(4): 113-123.* http://philip.inpa.gov.br/publ_livres/2005/Desmatamento%20historia-Megadiversidade.pdf.

Florin, M.-V., Rouse, P., Hubert, A.-M., Honegger, M., & Reynolds, J. (2020), *International governance issues on climate engineering Information for policymakers*. https://infoscience.epfl.ch/record/277726.

Fujikawa, S., Selyanchyn, R., & Kunitake, T. (2021), A new strategy for membrane-based direct air capture. *Polymer Journal*, *53*(1), 111–119. https://doi.org/10.1038/s41428-020-00429-z.

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. L. V., Wilcox, J., del Mar Zamora Dominguez, M., & Minx, J. C. (2018), Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*(6), 063002. https://doi.org/10.1088/1748-9326/aabf9f.

Gambhir, A., & Tavoni, M. (2019), Direct Air Carbon Capture and Sequestration: How It Works and How It Could Contribute to Climate-Change Mitigation. *One Earth*, *1*(4), 405–409. https://doi.org/10.1016/j.oneear.2019.11.006.

GESAMP (2019), *GESAMP Working Group 41: high level review of a wide range of proposed marine geoengineering techniques*. https://doi.org/10.13140/RG.2.2.29818.03528.

GGREW (2020), *The Greenhouse Gas Removal by Enhanced Weathering project*. https://www.earth.ox.ac.uk/research-groups/ggrew-greenhouse-gas-removal-by-enhanced-weathering/.

Goeppert, A., Czaun, M., Surya Prakash, G. K., & Olah, G. A. (2012), Air as the renewable carbon source of the future: an overview of CO_2 capture from the atmosphere. *Energy & Environmental Science*, *5*(7), 7833. https://doi.org/10.1039/c2ee21586a.

González, M. F., & Ilyina, T. (2016), Impacts of artificial ocean alkalinization on the carbon cycle and climate in Earth system simulations. *Geophysical Research Letters*, *43*(12), 6493–6502. https://doi.org/10.1002/2016GL068576.

Grassi, G. et al. (2017), *The key role of forests in meeting climate targets requires science for credible mitigation. Nature Climate Change, 7: 220 - 226*.

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. v., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R., … Fargione, J. (2017), Natural climate solutions. *Proceedings of the National Academy of Sciences*, *114*(44), 11645–11650. https://doi.org/10.1073/pnas.1710465114.

Hammad, H. M., Fasihuddin Nauman, H. M., Abbas, F., Ahmad, A., Bakhat, H. F., Saeed, S., Shah, G. M., Ahmad, A., & Cerdà, A. (2020), Carbon sequestration potential and soil characteristics of various land use systems in arid region. *Journal of Environmental Management*, *264*, 110254. https://doi.org/10.1016/j.jenvman.2020.110254.

Hansen, M. C., Potapov, P., Moore, R., Hancher, M., Turubanova, S., Tyukavina, A., Thau, D., Stehman, S., Goetz, S., Loveland, T., Kommareddy, A., Egorov, A., Chini, L., Justice, C. O., & Townshend, J. (2013), High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science (New York, N.Y.)*, *342*, 850–853. https://doi.org/10.1126/science.1244693.

Harrison, D. P. (2017), Global negative emissions capacity of ocean macronutrient fertilization. *Environmental Research Letters*, *12*(3), 035001. https://doi.org/10.1088/1748-9326/aa5ef5.

Hasegawa, T., Fujimori, S., Havlík, P., Valin, H., Bodirsky, B. L., Doelman, J. C., Fellmann, T., Kyle, P., Koopman, J. F. L., Lotze-Campen, H., Mason-D'Croz, D., Ochi, Y., Pérez Domínguez, I., Stehfest, E., Sulser, T. B., Tabeau, A., Takahashi, K., Takakura, J., van Meijl, H., Witzke, P. (2018), Risk of increased food insecurity under stringent global climate change mitigation policy. *Nature Climate Change*, *8*(8), 699–703. https://doi.org/10.1038/s41558-018-0230-x.

Hickey, V., & Wellenstein, A. (2020, April 22), La naturaleza como motor de la recuperación en el mundo después del coronavirus. *Banco Mundial Blogs*. https://blogs.worldbank.org/es/latinamerica/la-naturaleza-como-motor-de-la-recuperacion-en-el-mundo-despues-del-coronavirus.

Honegger, M. (2020), *Chapter 3: Addressing risks and trade-offs in governance' in Florin, M.-V. (Ed.), International governance issues on climate engineering. Information for policymakers; IRGC (2020).* (pp. 72–91). https://doi.org/10.5075/epfl-irgc-277726.

Honegger, M., Michaelowa, A., & Roy, J. (2021), Potential implications of carbon dioxide removal for the sustainable development goals. *Climate Policy*, *21*(5), 678–698. https://doi.org/10.1080/14693062.2020.1843388.

Hosonuma, N., Herold, M., de Sy, V., de Fries, R. S., Brockhaus, M., Verchot, L., Angelsen, A., & Romijn, E. (2012), An assessment of deforestation and forest degradation drivers in developing countries. *Environmental Research Letters*, *7*(4), 044009. https://doi.org/10.1088/1748-9326/7/4/044009.

Hubert, A. (2020), A Code of Conduct for Responsible Geoengineering Research. *Global Policy*, *12*(S1), 82–96. https://doi.org/10.1111/1758-5899.12845.

Hubert, A.-M. (2020), Chapter 2: International Legal and Institutional Arrangements relevant to the Governance of Climate Engineering Technologies. *Lnternational Governance Issues on Climate Engineering - Information for Policymakers. International Risk Governance Centre (IRGC). Lausanne, Switzerland: EPFL Scientific Publications*. https://infoscience.epfl.ch/record/277726.

IEA (2017), *Energy Technology Perspectives 2017, IEA, Paris*. https://www.iea.org/reports/energy-technology-perspectives-2017.

INPE (2020), *Nota Ténica. Estimativa deo Prodes. Estimativa de desmatamento por corte raso na Amazônia Legal para 2020 é de 11.088 km2*. http://www.obt.inpe.br/OBT/noticias-obt-inpe/estimativa-de-desmatamento-por-corte-raso-na-amazonia-legal-para-2020-e-de-11-088-km2/NotaTecnica_Estimativa_PRODES_2020.pdf.

International Maritime Organization (2016), *The London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972*. https://www.imo.org/en/OurWork/Environment/Pages/London-Convention-Protocol.aspx.

IPBES (2020), *Workshop Report on Biodiversity and Pandemics of the Intergovernmental Platform on Biodiversity and Ecosystem Services. Daszak, P., Amuasi, J., das Neves, C. G., Hayman, D., Kuiken, T., Roche, B., Zambrana-Torrelio, C., Buss, P., Dundarova, H., Feferholtz, Y., Földvári, G., Igbinosa, E., Junglen, S., Liu, Q., Suzan, G., Uhart, M., Wannous, C., Woolaston, K., Mosig Reidl, P., O'Brien, K., Pascual, U., Stoett, P., Li, H., Ngo, H. T., IPBES secretariat, Bonn, Germany, DOI:10.5281/zenodo.4147317.* https://ipbes.net/sites/default/files/2020-12/IPBES%20Workshop%20on%20Biodiversity%20and%20Pandemics%20Report_0.pdf.

IPCC (2021), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (V. , P. Masson-Delmotte, A. Zhai, S. L. Pirani, C. P. S. Connors, N. Berger, Y. Caud, L. G. M. I. Chen, M. Gomis, K. Huang, E. Leitzell, J. B. R. Lonnoy, T. K. Matthews, T. Maycock, O. Waterfield, R. Y. Yelekçi, & B. Zhou, Eds.). Cambridge University Press.

______(2019), *The Ocean and Cryosphere in a Changing Climate* (D. C. Pörtner, V. Roberts, Masson-Delmotte P, M. T. E. Zhai, K. Poloczanska, A. Mintenbeck, M. Alegría, Nicolai A, J. Okem, B. Petzold, N. M. Rama, & Weyer, Eds.). Cambridge University Press. https://doi.org/10.1017/9781009157964.

______(2018), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways*. https://www.ipcc.ch/sr15/.

______(2013), *"Summary for policymakers", Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, T. Stocker y otros (eds.), Cambridge, Cambridge University Press*.

______(2005), *IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf.

IPCC, Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, R., Chen, Y., Zhou, X., Gomis, M., Lonnoy, E., Maycock, T., Tignor, M., & Tabatabaei, M. (2018), *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. https://doi.org/10.1017/9781009157940.

IUCN (2011), *The Bonn Challenge*. https://www.bonnchallenge.org/.

Kayranli, B., Scholz, M., Mustafa, A., & Hedmark, Å. (2010), Carbon Storage and Fluxes within Freshwater Wetlands: a Critical Review. *Wetlands*, *30*(1), 111–124. https://doi.org/10.1007/s13157-009-0003-4.

Keith, D. W. (2001), Sinks, Energy Crops and Land Use: Coherent Climate Policy Demands an Integrated Analysis of Biomass. *Climatic Change*, *49*(1/2), 1–10. https://doi.org/10.1023/A:1010617015484.

Kelemen, P. B., McQueen, N., Wilcox, J., Renforth, P., Dipple, G., & Vankeuren, A. P. (2020), Engineered carbon mineralization in ultramafic rocks for CO_2 removal from air: Review and new insights. *Chemical Geology*, *550*, 119628. https://doi.org/10.1016/j.chemgeo.2020.119628.

Lal, R. (2013), Soil carbon management and climate change. *Carbon Management*, 4(4), 439–462. https://doi.org/10.4155/cmt.13.31.

______(2011), Sequestering carbon in soils of agro-ecosystems. *Food Policy*, *36*, S33–S39. https://doi.org/10.1016/j.foodpol.2010.12.001.

Lehmann, J., & Joseph, S. (2015), *Biochar for Environmental Management* (J. Lehmann & S. Joseph, Eds.). Routledge. https://doi.org/10.4324/9780203762264.

Lenton, T. M., & Vaughan, N. E. (2009), The radiative forcing potential of different climate geoengineering options. *Atmospheric Chemistry and Physics*, *9*(15), 5539–5561. https://doi.org/10.5194/acp-9-5539-2009.

Li, X., Bellerby, R., Craft, C., & Widney, S. E. (2018), Coastal wetland loss, consequences, and challenges for restoration. *Anthropocene Coasts*, 1–15. https://doi.org/10.1139/anc-2017-0001.

Lockley, A. (2012), Comment on "Review of Methane Mitigation Technologies with Application to Rapid Release of Methane from the Arctic." *Environmental Science & Technology*, *46*(24), 13552–13553. https://doi.org/10.1021/es303074j.

Mace, M. J., Fyson, C. L., Schaeffer, M., & Hare, W. L. (2021), Large-Scale Carbon Dioxide Removal to Meet the 1.5°C Limit: Key Governance Gaps, Challenges and Priority Responses. *Global Policy*, *12*(S1), 67–81. https://doi.org/10.1111/1758-5899.12921.

Magrin, G. et al. (2014), *"Central and South America", Climate Change 2014: Impacts, Adaptation, and Vulnerability. Volume II: Regional Aspects, V. Barros y otros (eds.), Cambridge, Cambridge University Press. (2007), "Latin America", Climate Change 2007: Impacts, Adaptation, and Vulnerability, Cambridge, Cambridge University Press*.

MARPOL. (1978), *Convenio internacional para prevenir la contaminación por los buques, 1973, modificado por el Protocolo de 1978.* https://www.imo.org/es/About/Conventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx.

Matear, R. J. (2004), Enhancement of oceanic uptake of anthropogenic CO 2 by macronutrient fertilization. *Journal of Geophysical Research*, *109*(C4), C04001. https://doi.org/10.1029/2000JC000321.

Maza, M., Lara, J. L., & Losada, I. J. (2021), Predicting the evolution of coastal protection service with mangrove forest age. *Coastal Engineering*, *168*, 103922. https://doi.org/10.1016/j.coastaleng.2021.103922.

McQueen, N., Psarras, P., Pilorgé, H., Liguori, S., He, J., Yuan, M., Woodall, C. M., Kian, K., Pierpoint, L., Jurewicz, J., Lucas, J. M., Jacobson, R., Deich, N., & Wilcox, J. (2020), Cost Analysis of Direct Air Capture and Sequestration Coupled to Low-Carbon Thermal Energy in the United States. *Environmental Science & Technology*, *54*(12), 7542–7551. https://doi.org/10.1021/acs.est.0c00476.

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., Das, B. S., Field, D. J., Gimona, A., Hedley, C. B., Hong, S. Y., Mandal, B., Marchant, B. P., Martin, M., McConkey, B. G., Mulder, V. L., … Winowiecki, L. (2017), Soil carbon 4 per mille. *Geoderma*, *292*, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002.

Minx, J. C., Lamb, W. F., Callaghan, M. W., Bornmann, L., & Fuss, S. (2017), Fast growing research on negative emissions. *Environmental Research Letters*, *12*(3), 035007. https://doi.org/10.1088/1748-9326/aa5ee5.

Moore, C. M., Mills, M. M., Arrigo, K. R., Berman-Frank, I., Bopp, L., Boyd, P. W., Galbraith, E. D., Geider, R. J., Guieu, C., Jaccard, S. L., Jickells, T. D., la Roche, J., Lenton, T. M., Mahowald, N. M., Marañón, E., Marinov, I., Moore, J. K., Nakatsuka, T., Oschlies, A., … Ulloa, O. (2013), Processes and patterns of oceanic nutrient limitation. *Nature Geoscience*, *6*(9), 701–710. https://doi.org/10.1038/ngeo1765.

Muñoz Ávila, L. (2016), *"Derechos de acceso en asuntos ambientales en Colombia: hacia el desarrollo de una actividad minera respetuosa del entorno y las comunidades", serie Medio Ambiente y Desarrollo, N° 164 (LC/L.4280), Santiago, Comisión Económica para América Latina y el Caribe (CEPAL), diciembre*.

National Academies of Sciences, E. and M. (2019), *Negative Emissions Technologies and Reliable Sequestration*. National Academies Press. https://doi.org/10.17226/25259.

National Research Council. (2015), *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. National Academies Press. https://doi.org/10.17226/18805.

N'Yeurt, A. de R., Chynoweth, D. P., Capron, M. E., Stewart, J. R., & Hasan, M. A. (2012), Negative carbon via Ocean Afforestation. *Process Safety and Environmental Protection*, *90*(6), 467–474. https://doi.org/10.1016/j.psep.2012.10.008.

Observatório ABC. (2017), *Impactos econômicos e ambientais do Plano ABC. RELATÓRIO COMPLETO*. http://observatorioabc.com.br/wp-content/uploads/2017/09/Relatorio5-Completo.pdf.

Oliveira, P. P. A., Pezzopane, J. R. M., Pedroso, A. de F., Nicodemo, M. L. F., & Berndt, A. (2018), *Produção de carne carbono neutro: um novo conceito para carne sustentável produzida nos trópicos*. https://www.alice.cnptia.embrapa.br/handle/doc/1095333.

ONU. (2014), United Nations New York Declaration On Forests - Declaration and Action Agenda. *Climate Summit 2014*. https://www.undp.org/content/dam/undp/library/Environment%20and%20Energy/Forests/New%20York%20Declaration%20on%20Forests_DAA.pdf.

Oschlies, A., Pahlow, M., Yool, A., & Matear, R. J. (2010), Climate engineering by artificial ocean upwelling: Channelling the sorcerer's apprentice. *Geophysical Research Letters*, *37*(4). https://doi.org/10.1029/2009GL041961.

Pan, Y., Fan, W., Zhang, D., Chen, J., Huang, H., Liu, S., Jiang, Z., Di, Y., Tong, M., & Chen, Y. (2016), Research progress in artificial upwelling and its potential environmental effects. *Science China Earth Sciences*, *59*(2), 236–248. https://doi.org/10.1007/s11430-015-5195-2.

Pereira, R., Yarish, C., & Critchley, A. T. (2013), Seaweed seaweed Aquaculture seaweed aquaculture for Human Foods in Land-Based and IMTA Systems. In *Sustainable Food Production* (pp. 1405–1424). Springer New York. https://doi.org/10.1007/978-1-4614-5797-8_189.

Peri, P., Dube, F., & Varella, A. C. (2016), *Silvopastoral Systems in the Subtropical and Temperate Zones of South America: An Overview* (pp. 1–8). https://doi.org/10.1007/978-3-319-24109-8_1.

Pidgeon, N. F., & Spence, E. (2017), Perceptions of enhanced weathering as a biological negative emissions option. *Biology Letters*, *13*(4), 20170024. https://doi.org/10.1098/rsbl.2017.0024.

Pidgeon, N., Parkhill, K., Corner, A., & Vaughan, N. (2013), Deliberating stratospheric aerosols for climate geoengineering and the SPICE project. *Nature Climate Change*, *3*(5), 451–457. https://doi.org/10.1038/nclimate1807.

Rayner, S., Heyward, C., Kruger, T., Pidgeon, N., Redgwell, C., & Savulescu, J. (2013), The Oxford Principles. *Climatic Change*, *121*(3), 499–512. https://doi.org/10.1007/s10584-012-0675-2.

Renforth, P., Washbourne, C.-L., Taylder, J., & Manning, D. A. C. (2011), Silicate Production and Availability for Mineral Carbonation. *Environmental Science & Technology*, *45*(6), 2035–2041. https://doi.org/10.1021/es103241w.

Rodríguez, A., Clemente, S., Brito, A., & Hernández, J. C. (2018), Effects of ocean acidification on algae growth and feeding rates of juvenile sea urchins. *Marine Environmental Research*, *140*, 382–389. https://doi.org/10.1016/j.marenvres.2018.07.004.

Rouse, P. (2020), Chapter 1. A review of climate-altering technologies - in Florin, M.-V. (Ed.), International Governance of Climate Engineering. Information for policymakers. *Lausanne: EPFL International Risk Governance Center (IRGC)*. https://infoscience.epfl.ch/record/277726?ln=en.

RS, & RAE. (2018), *Greenhouse gas removal*.

Saget, C., Vogt-Schilb, A., & Luu, T. (2020), *El empleo en un futuro de cero emisiones netas en América Latina y el Caribe*. ZBW - Leibniz Information Centre for Economics. https://EconPapers.repec.org/RePEc:zbw:esmono:224490.

Samaniego, J., Alatorre, J. E., Reyes, O., Ferrer, J., Muñoz, L., & Arpaia, L. (2019), *Panorama de las contribuciones determinadas a nivel nacional en América Latina y el Caribe, 2019: avances para el cumplimiento del Acuerdo de París*. CEPAL. https://repositorio.cepal.org/handle/11362/44974.

Samaniego, J., Alatorre, J. E., van der Borght, R., & Ferrer, J. (2022), Panorama de las actualizaciones de las contribuciones determinadas a nivel nacional de cara a la COP 26. In *Documentos de Proyectos (LC/TS.2021/190)*. Comisión Económica para América Latina y el Caribe (CEPAL).

Samaniego, J., Schmidt, K.-U., Carlino, H., Caratori, L., Carlino, M., Gogorza, A., & Rodríguez-Vagaría, A. (2021), *Current understanding of the potential impacts of Carbon Dioxide Removal approaches on the SDGs in selected countries in Latin America and the Caribbean. Final Report*. https://www.cepal.org/es/node/54322.

Samari, M., Ridha, F., Manovic, V., Macchi, A., & Anthony, E. J. (2020), Direct capture of carbon dioxide from air via lime-based sorbents. *Mitigation and Adaptation Strategies for Global Change*, *25*(1), 25–41. https://doi.org/10.1007/s11027-019-9845-0.

Sandalow, D., Friedmann, J., McCormick, C., & McCoy, S. (2018), *Direct Air Capture of Carbon Dioxide*. Innovation for Cool Earth Forum.

Sanz-Pérez, E. S., Murdock, C. R., Didas, S. A., & Jones, C. W. (2016), Direct Capture of CO_2 from Ambient Air. *Chemical Reviews*, *116*(19), 11840–11876. https://doi.org/10.1021/acs.chemrev.6b00173.

Seddon, N. et al. (2020), *"Understanding the value and limits of nature-based solutions to climate change and other global challenges", Philosophical Transactions of the Royal Society B: Biological Sciences, vol. 375, No 1794*.

Sigman, D. M., & Haug, G. H. (2003), The Biological Pump in the Past. In *Treatise on Geochemistry* (pp. 491–528). Elsevier. https://doi.org/10.1016/B0-08-043751-6/06118-1.

Silver, M. W., Bargu, S., Coale, S. L., Benitez-Nelson, C. R., Garcia, A. C., Roberts, K. J., Sekula-Wood, E., Bruland, K. W., & Coale, K. H. (2010), Toxic diatoms and domoic acid in natural and iron enriched waters of the oceanic Pacific. *Proceedings of the National Academy of Sciences*, *107*(48), 20762–20767. https://doi.org/10.1073/pnas.1006968107.

Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R. B., Cowie, A., Kriegler, E., van Vuuren, D. P., Rogelj, J., Ciais, P., Milne, J., Canadell, J. G., McCollum, D., Peters, G., Andrew, R., Krey, V., … Yongsung, C. (2016), Biophysical and economic limits to negative CO_2 emissions. *Nature Climate Change*, *6*(1), 42–50. https://doi.org/10.1038/nclimate2870.

Smith, P., Lanigan, G., Kutsch, W. L., Buchmann, N., Eugster, W., Aubinet, M., Ceschia, E., Béziat, P., Yeluripati, J. B., Osborne, B., Moors, E. J., Brut, A., Wattenbach, M., Saunders, M., & Jones, M. (2010), Measurements necessary for assessing the net ecosystem carbon budget of croplands. *Agriculture, Ecosystems & Environment*, *139*(3), 302–315. https://doi.org/10.1016/j.agee.2010.04.004.

SNH. (2019), *Peatland Action Scottish Natural Heritage*. https://www.nature.scot/climate-change/taking-action/peatland-action.

Sondak, C. F. A., Ang, P. O., Beardall, J., Bellgrove, A., Boo, S. M., Gerung, G. S., Hepburn, C. D., Hong, D. D., Hu, Z., Kawai, H., Largo, D., Lee, J. A., Lim, P.-E., Mayakun, J., Nelson, W. A., Oak, J. H., Phang, S.-M., Sahoo, D., Peerapornpis, Y., … Chung, I. K. (2017), Carbon dioxide mitigation potential of seaweed aquaculture beds (SABs). *Journal of Applied Phycology*, *29*(5), 2363–2373. https://doi.org/10.1007/s10811-016-1022-1.

Soussana, J.-F., Lutfalla, S., Ehrhardt, F., Rosenstock, T., Lamanna, C., Havlík, P., Richards, M., Wollenberg, E. (Lini), Chotte, J.-L., Torquebiau, E., Ciais, P., Smith, P., & Lal, R. (2019), Matching policy and science: Rationale for the '4 per 1000 - soils for food security and climate' initiative. *Soil and Tillage Research*, *188*, 3–15. https://doi.org/10.1016/j.still.2017.12.002.

Stolaroff, J. K., Bhattacharyya, S., Smith, C. A., Bourcier, W. L., Cameron-Smith, P. J., & Aines, R. D. (2012), Review of Methane Mitigation Technologies with Application to Rapid Release of Methane from the Arctic. *Environmental Science & Technology*, *46*(12), 6455–6469. https://doi.org/10.1021/es204686w.

Strassburg, B. B. N., Latawiec, A. E., Barioni, L. G., Nobre, C. A., da Silva, V. P., Valentim, J. F., Vianna, M., & Assad, E. D. (2014), When enough should be enough: Improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. *Global Environmental Change*, *28*, 84–97. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2014.06.001.

The Institute For Carbon Removal Law and Policy. (2018), *Carbon Removal Fact Sheet*.

Torvanger, A. (2019), Governance of bioenergy with carbon capture and storage (BECCS): accounting, rewarding, and the Paris agreement. *Climate Policy*, *19*(3), 329–341. https://doi.org/10.1080/14693062.2018.1509044.

Trick, C. G., Bill, B. D., Cochlan, W. P., Wells, M. L., Trainer, V. L., & Pickell, L. D. (2010), Iron enrichment stimulates toxic diatom production in high-nitrate, low-chlorophyll areas. *Proceedings of the National Academy of Sciences*, *107*(13), 5887–5892. https://doi.org/10.1073/pnas.0910579107.

UNCCD (2019), *The Global Land Outlook, Latin America and the Caribbean Thematic*.

______(2017), *PERSPECTIVA GLOBAL DE LA TIERRA*. https://www.unccd.int/sites/default/files/documents/2017-09/GLO_Full_Report_low_res_Spanish.pdf.

UNEP (2022, June 1), *Nueva reserva marina trae esperanza en América Latina, pero permanecen desafíos de conservación*. https://www.unep.org/es/noticias-y-reportajes/reportajes/nueva-reserva-marina-trae-esperanza-en-america-latina-pero.

______(2021), *The State of Climate Ambition. Nationally Determined Contributions (NDC) Global Outlook Report 2021*. https://www.undp.org/sites/g/files/zskgke326/files/2021-11/UNDP-NDC-Global-Outlook-Report-2021-The-State-of-Climate-Ambition.pdf.

UNFCCC (2021), *Nationally determined contributions under the Paris Agreement. Synthesis report by the secretariat*. https://unfccc.int/sites/default/files/resource/cma2021_08S.pdf.

______(2015), *El Acuerdo de París*. UNFCCC. https://unfccc.int/es/process-and-meetings/the-paris-agreement/el-acuerdo-de-paris.

______(2007), *Investment and Financial Flows to Address Climate Change [en línea]*. http://unfccc.int/resource/docs/publications/ financial_flows.pdf.

Van der Ent, R. J., Savenije, H. H. G., Schaefli, B., & Steele-Dunne, S. C. (2010), Origin and fate of atmospheric moisture over continents. *Water Resources Research*, *46*(9). https://doi.org/10.1029/2010WR009127.

Viebahn, P., Scholz, A., & Zelt, O. (2019), The Potential Role of Direct Air Capture in the German Energy Research Program—Results of a Multi-Dimensional Analysis. *Energies*, *12*(18), 3443. https://doi.org/10.3390/en12183443.

Voskian, S., & Hatton, T. A. (2019), Faradaic electro-swing reactive adsorption for CO 2 capture. *Energy & Environmental Science*, *12*(12), 3530–3547. https://doi.org/10.1039/C9EE02412C.

Welch, B., Gauci, V., & Sayer, E. J. (2019), Tree stem bases are sources of CH 4 and N 2 O in a tropical forest on upland soil during the dry to wet season transition. *Global Change Biology*, *25*(1), 361–372. https://doi.org/10.1111/gcb.14498.

Whiting, G. J., & Chanton, J. P. (2001), Greenhouse carbon balance of wetlands: methane emission versus carbon sequestration. *Tellus B: Chemical and Physical Meteorology*, *53*(5), 521–528. https://doi.org/10.3402/tellusb.v53i5.16628.

WILLAUER, H. D. , F., & HARDY, D. (2017), *Extraction of Carbon Dioxide and Hydrogen from Seawater by an Electrolytic Cation Exchange Module (E-CEM) Part V: E-CEM Effluent Discharge Composition as a Function of Electrode Water Composition*. https://apps.dtic.mil/sti/pdfs/AD1038769.pdf.

WMO (2021), *State of the Global Climate 2020 - Unpacking the Indicators*. https://public.wmo.int/en/our-mandate/climate/wmo-statement-state-of-global-climate.

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010), Sustainable biochar to mitigate global climate change. *Nature Communications*, *1*(1), 56. https://doi.org/10.1038/ncomms1053.

World Resources Institute. (n.d.), *Global Forest Watch*. Retrieved March 20, 2022, from https://www.globalforestwatch.org/dashboards/lobal/?category=summary&dashboardPrompts=eyJzaG93UHJvbXB0cyI6dHJ1ZSwicHJvbXB0c1ZpZXdlZCI6W10sInNldHRpbmdzIjp7Im9wZW4iOmZhbHNlLCJzdGVwSW5kZXgiOjAsInN0ZXBzS2V5IjoiIn0sIm9wZW4iOnRydWUsInN0ZXBzS2V5IjoiZG93bmxvYWREYXNoYm9hcmRTdGF0cyJ9&location=WyJnbG9iYWwiXQ%3D%3D&map=eyJkYXRhc2V0cyI6W3sib3BhY2l0eSI6MC43LCJ2aXNpYmlsaXR5Ijp0cnVlLCJkYXRhc2V0IjoicHJpbWFyeS1mb3Jlc3RzIiwibGF5ZXJzIjpbInByaW1hcnktZm9yZXN0cy0yMDAxIl19LHsiZGF0YXNldCI6InBvbGl0aWNhbC1ib3VuZGFyaWVzIiwibGF5ZXJzIjpbImRpc3B1dGVkLXBvbGl0aWNhbC1ib3VuZGFyaWVzIiwicG9saXRpY2FsLWJvdW5kYXJpZXMiXSwiYm91bmRhcnkiOnRydWUsIm9wYWNpdHkiOjEsInZpc2liaWxpdHkiOnRydWV9LHsiZGF0YXNldCI6InRyZWUtY292ZXItbG9zcyIsImxheWVycyI6WyJ0cmVlLWNvdmVyLWxvc3MiXSwib3BhY2l0eSI6MSwidmlzaWJpbGl0eSI6dHJ1ZSwidGltZWxpbmVQYXJhbXMiOnsic3RhcnREYXRlIjoiMjAwMi0wMS0wMSIsImVuZERhdGUiOiIyMDIwLTEyLTMxIiwidHJpbUVuZERhdGUiOiIyMDIwLTEyLTMxIn0sInBhcmFtcyI6eyJ0aHJlc2hvbGQiOjMwLCJ2aXNpYmlsaXR5Ijp0cnVlfX1dfQ%3D%3D&showMap=true.

Wright, M. J., Teagle, D. A. H., & Feetham, P. M. (2014). A quantitative evaluation of the public response to climate engineering. Nature Climate Change, 4(2), 106–110. https://doi.org/10.1038/nclimate2087.

WWF (2020). Living Planet Report 2020 - Bending the curve of biodiversity loss (R. E. A. Almond, Grooten M., & T. Petersen, Eds.).

Zedler, J. B., & Kercher, S. (2005). WETLAND RESOURCES: Status, Trends, Ecosystem Services, and Restorability. Annual Review of Environment and Resources, 30(1), 39–74. https://doi.org/10.1146/annurev.energy.30.050504.144248.

Zomer, R. J., Bossio, D. A., Sommer, R., & Verchot, L. v. (2017). Global Sequestration Potential of Increased Organic Carbon in Cropland Soils. Scientific Reports, 7(1), 15554. https://doi.org/10.1038/s41598-017-15794-8.

The negative impacts of climate change call for an urgent global response, to mitigate emissions and strengthen the adaptive capacity of social, economic, and environmental structures. In Latin America and the Caribbean, in a context of high vulnerability and three simultaneous crises affecting the region, development models need to be transformed, to bring about a sustainable transition. During this process, national and local policies must harness the full potential of climate action, through adoption of new technologies, innovation, productive reorganization, and identification of synergies. This is why nature-based solutions and carbon dioxide removal measures and technologies are critical to achieving climate goals. Against this backdrop, this paper examines the opportunities and challenges of large-scale implementation of such measures in the region, emphasizing the need to accelerate ongoing efforts, expand the research frontier and manage risks. The results outline the existing limitations and links between goals, policies and tools, as well as the joint benefits of their implementation, which can contribute to a big push for sustainability.

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