Opportunities for advancing carbon cycle science in Mexico: toward a continental scale understanding

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ABSTRACT

Solutions to current global environmental problems throughout fundamental ecological understandings are only reached through international programmatic and scientific collaborations. Both scientists and policymakers recognize the importance of the role of carbon cycle science (CCS) in North America, however regional ecological studies in North America often do not include the role of Mexico. Given the sharp ecological, climatic and socio-economic differences among the three countries conforming North America it is fundamental to incorporate Mexico’s unique contributions toward regional CCS. We provide a synthesis of opportunities and challenges for advancing land and ocean research in Mexico in order to move toward a complete North American continental scale CCS. First, we provide the socio-ecological context of Mexico relevant to CCS. Second, we compare the existing relationships among scientific/governmental entities and funding agencies that contribute to CCS in the United States and Mexico. Third, we discuss Mexico’s state-of-the-art CCS, and synthesize its recent advances with emphasis on land– and ocean-atmosphere interactions. We highlight continental-scale opportunities toward a tri-national carbon research, infrastructure, and education network.

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1. Introduction

Understanding the processes that govern carbon cycle dynamics at the land, oceans and larger, continental scales is important in the role of science informing decision-makers, as well as for advancing fundamental research (Anderson and Bows, 2008). It is important to recognize that most research advancing carbon cycle science (CCS) is overwhelmingly produced in developed countries. This leaves developing countries underrepresented when building a continental- or global-scale understanding of CCS, and with a disproportional number of end users depending on other’s data. Overall, this disparity results in lost opportunities, limited advancements in knowledge, and poor information transfer among countries (Rubbelke, 2011). This is critical because environmental problems and ecological understandings are not delineated within specific sociopolitical or economic boundaries. Thus, solutions must be sought and fostered through international programmatic/scientific collaborations and will.

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With ongoing regional efforts in CCS, it is possible to measure, model, and scale carbon sources/sinks to larger spatial scales, and thereby reduce the uncertainties associated with these estimates (Peters et al., 2007). One example of a regional effort is the North American Carbon Program (NACP), which derives its capacity from a large coordinated funding/research base and political will primarily in the United States (e.g., NSF-National Ecological Observatory Network (NEON), DOE-AmeriFlux, NASA-Terrestrial Ecology) and Canada (e.g., Environment Canada-Fluxnet Canada). These multidisciplinary research programs substantially enhance our scientific understanding of North America’s carbon cycle dynamics. Furthermore, this information is needed to meet societal concerns and to provide tools for decision makers and long-term stewardship of social-ecological systems at large (Collins et al., 2011). Scientists and policymakers both recognize the importance of the role of CCS in North America (geographically and politically), but North American studies outside the United States and Canada are often left behind (but see Harmon et al., 2011; Masek et al., 2011; Peters et al., 2007). This is partially a result of the difficulty in navigating the scientific and political landscape in Mexico, which is less predictable than its northern counterparts and restrain strategic collaborations. A second restrictive issue is the competitive demand for limited research funds within Mexico, as well as, competing agency mandates for these research funds once made available.

The ecological relevance of Mexico’s carbon cycle toward a complete North American continental understanding should not be ignored or underestimated. Mexico has an active emerging economy and expanding rural and urban population; so many of the prevalent anthropogenic drivers and feedback mechanisms of carbon exchange in Mexico contrast corresponding patterns and pace in the United States and Canada. The first state of the carbon cycle report (SOCR) pointed out the role of Mexican ecosystems as principally being sources of carbon, whereas the United States and Canadian ecosystems exhibit a neutral carbon balance (King et al., 2007). This is due to rapid land use change, human population growth, human migration, a rapidly growing carbon economy, an increase in ecosystems entering the pathway to extinction (e.g., natural grasslands, mangroves), and large-scale disturbances (e.g., droughts, fires, hurricanes). These contrasting drivers among countries are important in regulating the carbon cycle and climate with repercussions at the continental and global scale.

How these human-induced changes in large-scale ecology affect regional and continental scale carbon dynamics is largely unexplored. This has even greater implications for regional-to-global feedbacks, such as hydrological (Leduc et al., 2007) and climatological (Friedlingstein et al., 2003) patterns. Taking these issues in concert, terrestrial and aquatic carbon dynamics are changing at the regional-to-continental scale as a function of multiple and often contrasting drivers of change (Carpenter and Brock, 2006). Thus, to fully integrate CCS across North America, both for applied and basic research, there is an urgent need for more development and resources targeted toward a tri-national carbon research, infrastructure and education network.

The primary objective of this paper is to highlight emerging opportunities for the advancement of CCS in Mexico (land and ocean) to facilitate and move toward a complete continental scale (i.e., North America) CCS framework. First, we discuss the socio-ecological context of Mexico relevant for CCS. Second, we compare existing relationships among scientific/governmental entities and funding agencies, which contribute to CCS in the United States with those in Mexico. Third, we discuss the state-of-the-art of CCS in Mexico and outline opportunities and challenges within the country with emphasis on land–ocean–atmosphere interactions.

2. Biological and human dimensions for CCS in Mexico

2.1. Biological dimension

Long-term impact of land use change and anthropogenic changes in biogeography have fragmented and fundamentally transformed Mexican landscapes (CONABIO, 2008). These transformations have created a highly heterogeneous vegetation cover forming complex landscape mosaics that differ in plant cover, age, plant species, and functional group composition over a wide range of spatial scales (Mittermeier and Goettsch, 1997). The most important land use change types having caused severe ecological degradation include: deforestation (Klooster and Masera, 2000; Masek et al., 2011), high impact livestock grazing (Manzano et al., 2000), and soil tillage (Fuentes et al., 2009). The causes of land use change in Mexico are multifaceted, and have been largely influenced by government policies. For example, conversion of tropical forests to pasture resulted from an aggressive expansion of cattle ranching activities since the early 1940s. At the end of the 1970s, a political movement eliminated the concessions of large forested areas by private companies and promoted timber harvest by local communities and the ejidos (communal land), which have had a large impact on the extent of natural ecosystems (Table 1). Finally, Mexico has shown an average rate of deforestation of nearly 550,000 ha year⁻¹ for the period 1993–2007 with a slight increase in natural forest regeneration, particularly in southern Mexico (Garcia-Barrios et al., 2009; Masek et al., 2011).

<table>
<thead>
<tr>
<th>Ecosystem type</th>
<th>Area (km²)</th>
<th>Potential (km²)</th>
<th>% ecosystem lost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arid shrubland</td>
<td>508,958</td>
<td>600,095</td>
<td>15.2</td>
</tr>
<tr>
<td>Temperate and semiarid forest</td>
<td>323,305</td>
<td>439,556</td>
<td>26.5</td>
</tr>
<tr>
<td>Dry deciduous forest</td>
<td>164,357</td>
<td>258,579</td>
<td>36.4</td>
</tr>
<tr>
<td>Rain forest</td>
<td>151,511</td>
<td>254,800</td>
<td>40.5</td>
</tr>
<tr>
<td>Grassland</td>
<td>103,159</td>
<td>162,790</td>
<td>36.6</td>
</tr>
<tr>
<td>Cloud forest</td>
<td>323,305</td>
<td>439,556</td>
<td>26.5</td>
</tr>
<tr>
<td>Mangrove forest</td>
<td>7747</td>
<td>14,508</td>
<td>46.6</td>
</tr>
<tr>
<td>Water reservoirs</td>
<td>13,539</td>
<td>4675</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

Source: CONABIO
http://www.biodiversidad.gob.mx/ecosistemas/ecosistemas.html
The geographical location of Mexico between the influences of the Atlantic Ocean, west-central and central-eastern Pacific explains its large marine biodiversity (Mittermeier and Goettsch, 1997). The northwest coastal waters of Mexico are at the southernmost extension of the California Current System, and located in the northeastern Pacific Ocean with physical and biological mechanisms forced by regional (e.g., coastal upwelling, eddies, wind driven currents) and large scale processes (e.g., El Niño-La Niña cycles) (Durazo, 2009). The Gulf of California is the only evaporation basin in the Pacific Ocean, with unique oceanography which consists of upwelling on both coasts (i.e., peninsula and mainland) (Alvarez Borrego and Lara Lara, 1991). Finally, the Gulf of Mexico is a sea shared by the United States and Mexico where fishing is the primary economic force driving its environmental degradation (Kumpf et al., 1999).

In the coming decades and centuries, the coastal biogeochemical cycles and ecosystems within North America will become increasingly stressed by at least three independent factors: rising temperatures, ocean acidification, and ocean deoxygenation (hypoxia) causing substantial changes in the physical, chemical and biological environment (Caldeira and Wickett, 2003). However, the impact and feedback mechanisms will likely be different regionally, and have to be further explored within the major economic coastal regions surrounding North America (Caldeira and Wickett, 2003), especially along the Mexican coast where much more research is needed (Lara Lara et al., 2008).

2.2. Human dimension

The larger impacts on carbon budgets in different ecosystems are also derived from socio-economic aspects of the Mexican population. In the coastal areas human activities such as fishing/aquaculture, hydrocarbon/mineral extraction, maritime transportation/tourism, urban sprawl, and the production of pollutants exert pressure on the fragile environments (i.e., coral reefs, kelp forests). Without proper regulation and enforcement of the existing laws, the latter human activities exert pressure on fragile coastal ecosystems (Lara Lara et al., 2008).

Mexico’s land has a long human-environmental history fundamentally defined by large-scale shifts in land tenure systems including traditional small-holder farmlands in pre-Hispanic times (for over 3000 years), large privately owned hacienda holdings in colonial times (for 400 years), and communally owned land (ejidos) and private properties (for the last 90 years). This has created a landscape with a complex legacy of land use change, management practices and overall land governance. Ejido land is the one that has been most severely degraded over the last three to four decades, as a consequence of long periods of drought, overexploitation of resources, and severe soil degradation. Hence, it is this land use legacy that constitutes one of the main landscape-level controls on whether ecosystems are net sinks or sources of carbon (Kloosterman and Basra, 2000).

Recent changes in Mexican legislation (amendment of constitutional article 27; Arrendondo Moreno and Huber-Sannwald, 2011), that originally precluded ejidatarios (ejido members) from private land ownership (allowing however its free use and hereditary rights) now permit the granting of land ownership. Adoption of this new land ownership policy will most likely continue to significantly influence ecosystem carbon budgets in unpredictable ways: (a) through the redistribution of land; (b) the re-structuring of land governance and thus land use; and (c) year-to-year decisions farmers need to take (e.g., shifting agriculture, land abandonment). Historical development of ejidos and their agricultural production systems are tightly linked, unfortunately, to a history of subsistence farming and poverty. Consequently, understanding and assessing the process of human decision-making and stakeholder involvement in the context of land use and management appears key for scaling CCS in time and space (Tschakert et al., 2008), and for providing adaptation and mitigation strategies for future climate scenarios in Mexico.

Mexico has implemented two national level strategies to reduce 30% of carbon emissions by the year 2020. The first is the Programa Especial de Cambio Climático (PECC) that incorporates national objectives of mitigation and adaptation for 2008–2012, as well as establishing a long-term plan to address emission reductions for 2020–2050. This program calls for the identification of possible methodologies for emission reductions, and identification of economic sectors that are susceptible to mitigation activities. Secondly, the Programas Estatales de Acción ante el Cambio Climático (PEACCs) call for a strategic mitigation plan for contributing sectors in each State for 2020, however there exist limited national and international datasets to inform these programs (SEMARNAT-INE, 2010). The uncertainty associated with this approach is not known yet; the mitigation plan is principally considered for the forestry and agriculture sectors, and it is projected that the emission reductions for 2020 will account for 80 Mt CO2 year−1 or one third of total emissions. To date, these mitigation scenarios have not been rigorously tested or validated, and call for academic and governmental institutions to urgently support verifiable methodologies, national monitoring networks, and academic programs to train experts in CCS.

3. Institutional relationships

The role of CCS is inherently linked to numerous other biogeochemical cycles, including its abiotic controls, feedback mechanisms, and environmental management. In the United States, the list of funding agencies is large, and they often have multiple programs within an agency that can support a coordinated CCS question or focus (Dilling, 2007). In contrast, the list of funding agencies in Mexico is short with competing agency mandates and a loosely coordinated agenda for CCS research and funding (Supplementary Table 1).

The institutional relationships within the United States for CCS are organized by a national science plan (United States Carbon Cycle Science Plan, USCCSP) and a programmatic coordination (lead by the NACP) with a joint implementation (lead by CarbonNA). The United States Climate Change Science Program establishes the authority for interagency coordination/agreements (Supplementary Table 1) and implements the Strategic Plan for the United States Climate Change Science Program, and the USCCSP (Michalak et al., 2011; Sarmiento and Wofsy, 1998). See Dilling (2007) for a detailed
review of the United States institutional relationships that support CCS.

This programmatic coordination in the United States is led by the NACP (Wofsy and Harriss, 2002), which is designed to specifically address strategic research question 7.1 in the original USCCSP (Sarmiento and Wofsy, 1998): What are the magnitudes and distributions of North American carbon sources and sinks on seasonal to centennial time scales, and what are the processes controlling their dynamics? The 2011 USCCSP further proposes to expand the NACP to a new larger and broader Northern Hemisphere Carbon Program (Michalak et al., 2011).

To date, the NACP Scientific Steering Group (SSG) reports and assists the Carbon Cycle Interagency Working Group (CCIWG) in implementing the NACP Science Plan (in order to optimize the scientific return), and follows the NACP Implementation Strategy (Denning, 2005). The CCIWG promotes interagency cooperation and coordination, secure funding, prepare within and among agency initiatives and solicitations, and enabling the scientific community to advance our understanding in CCS. Lastly, the Ocean Carbon and Climate Change (OCCC) and Ocean Carbon and Biogeochemistry (OCB) programs also build upon the USCCP by adding the ocean component of CCS as they also have their own scientific steering committees that provide leadership to the OCB community (Donney, 2004). These organizational structures have been effective in providing both a bottom-up and top-down conduit for information and programmatic development, even amidst changing political and funding environments (Denning, 2005). This example by no means is all-inclusive of all programs and initiatives, but it does provide a model of how programs and program officers can interact to advance CCS throughout agency and governmental strata in productive ways.

North America, however, also includes Canada and Mexico. Sister to NACP, CarboNA is the international collaboration (Joint Implementation agreement) between Canada, Mexico, and the United States for CCS research, and whose working relationships are within country, governmental organizations. Members from these governmental organizations form the Government Coordination Working Group (GCWG) and a Science Steering Committee (SSC) having parallel functions of the CCIWG and the NACP SSG. In addition to the Joint Implementation agreement, the GCWG also adopted a Statement of Common Interest and Agreement to Work Together, which validates the rationale, activities, and structure of the program.

Current and past CCS programs in the United States and Canada (e.g., NCARP, NEON, Fluxnet-Canada) offer enormous opportunities in advancing regional CCS in Mexico. Yet, it is generally difficult for principal investigator/program managers in the United States or Canada to establish collaboration with Mexican counterparts, and navigate in-country logistics (Supplementary Table 1). This is due, in part because of competing Mexican mandates, and the lack of long-term sustainability in funding. Yet, we also acknowledge that the Joint Implementation with NACP is a truly unique opportunity and a new creative means of fostering and coordinating CCS related activities in Mexico, and break-down the old paradigms that limit among country collaborations. Moreover, we are encouraged by the structure of NACP, and call for similar formalized structure of agencies within Mexico to coordinate CCS. Similar such structure(s) could seek out synergies and build a robust, diverse, and long-term CCS program in Mexico; as well as establishing long-term relationships with other international agencies to foster the study of CCS at the continental scale.

3.1. **Mexican government agencies related to CCS**

Based on the goals of the Programa Especial de Cambio Climático the strongest governmental effort toward promoting CCS mainly resides in the Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT). As a federal ministry, SEMARNAT branches out into several commissions and an institute (Instituto Nacional de Ecología, INE; Supplementary Table 1). Throughout INE as a tool, SEMARNAT is entitled to coordinate Mexico’s commitment with the United Nations Framework Convention on Climate Change and supports governmental activities throughout Mexico at the State level such as the PEACCS. SEMARNAT however, does not formally fund CCS, and does not have a coordinated program to fund CCS research in Mexico. Instead, SEMARNAT together with the Consejo Nacional de Ciencia y Tecnología (CONACYT; equivalent to NSF in the United States) dictates the research needs regarding climate change mitigation and adaptation through specific calls for proposals (i.e., Fondos Sectoriales).

In addition, the Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (SAGARPA) is as a multi-tasked agency mainly occupied on food production and regulation. Through its rural development branch this agency is endeavored at promoting sensitivity to climate change issues in rural Mexico by coordinating community programs that aim at reducing greenhouse gas emissions. Similar to SEMARNAT, SAGARPA partners with CONACYT to coordinate research needs through specific calls for proposals (Supplementary Table 1). See Cavazos (in press) for a review of the Mexican institutional relationships that support climate change activities.

Despite the fact that the above-mentioned government organizations reside mainly under the umbrella of SEMARNAT, a cross-agency coordination entity is difficult to envision (Supplementary Table 1). Recently, two non-governmental organizations coordinated by scientists have led bottom-up CCS related activities: Programa Mexicano de Carbono and the Mexican Long-term Ecological Research Network. These non-governmental organizations consider carbon cycle research questions one of the central cross-cutting themes in their agendas (Huber-Sannwald et al., 2008). We propose that there is a need for a novel government agency to coordinate and integrate the network of Mexican governmental organizations and programs related to CCS for development and implementation of a tri-national carbon research, infrastructure and education network.

4. **State-of-the-art of CCS in Mexico: land–ocean–atmosphere interactions**

Carbon cycle science in Mexico is still a nascent research field that has been principally developed by terrestrial ecologists
Early CCS in Mexico was focused on primary productivity studies in both terrestrial (Martinez-Yrizar et al., 1992) and marine ecosystems (Lara Lara et al., 2003). Land–ocean–atmosphere interactions have not been explored until recently with few examples for terrestrial ecosystems (Davidson et al., 1993; Hastings et al., 2005; Perez-Ruiz et al., 2010; Vargas and Allen, 2008) and in the ocean (Alvarez-Borrego, 2007). This is due in part because of the scarce scientific expertise in Mexico working with limited support for infrastructure and long-term monitoring and programs. However, recent scientific efforts have initiated the establishment of multiple research sites to continuously measure land–ocean–atmosphere interactions, particularly CO2 exchange (Fig. 1). Here, we discuss two ongoing monitoring programs relevant for CCS: MexFlux for land–atmosphere, and FLUCAR for ocean–atmosphere interactions.

MexFlux is a consortium of scientists using the eddy covariance method to measure mass and energy exchange between vegetation and the free atmosphere (Loescher et al., 2006) in Mexican ecosystems (Vargas and Yepez, 2011). MexFlux represents a regional network within the global network of eddy covariance sites (i.e., FLUXNET), which is represented by over 500 study sites around the world (Baldocchi, 2008). FLUXNET has provided unprecedented information for synthesis and modeling, but is mostly represented by study sites located in the United States and Europe. To enhance our understanding on the large regional diversity of ecosystems and biomes, and to enhance our capability to scale carbon fluxes to regions and continents there is a strong need to expand these networks to underrepresented ecosystems/regions. MexFlux has eleven active eddy covariance sites that represent a variety of ecosystem types, including shrublands, forests and grasslands from arid to tropical climates (Fig. 1). The longest ongoing operational site was established in 2002 (Hastings et al., 2005), and MexFlux has >35 site-years of information of mass and energy exchange (Vargas and Yepez, 2011).

MexFlux fills a knowledge gap within FLUXNET and has potential to improve our understanding of land–atmosphere interactions across North America as the United States (i.e., AmeriFlux) and Canada (i.e., Fluxnet-Canada) regional networks have demonstrated. For example, the North American Monsoon System (NAMS) is an important regional phenomenon that provides the majority of annual rainfall over large parts of western Mexico and the southwestern United States. Tropical dry forests in the northwest of Mexico influenced by NAMS showed that net ecosystem exchange of carbon (NEE) was significantly different between wet and dry seasons with an overall carbon uptake of 374 gCO2 m−2 during the monsoon season (Perez-Ruiz et al., 2010; Fig. 2). Studies that identify sources/sinks and controls of carbon dynamics could be used to better parameterize land surface models over a larger regional area (e.g., southwest of the United States and northern Mexico), and show the importance of establishing a baseline understanding of CCS in Mexico. As MexFlux grows, there will be new opportunities for data exchange to test models and hypotheses under distinct conditions (e.g., from drought to hurricane prone areas), highly productive ecosystems (e.g., mangroves and tropical forests), and to incorporate the effects of land use change across North America.

FLUCAR is a consortium of scientists interested in quantifying and understanding the controls of carbon fluxes in the Pacific Ocean within Mexican territory. Most of the studies have focused on phytoplankton primary productivity however a large part of ocean–atmosphere interactions is understudied and still unknown (Hernández de la Torre and Gaxiola Castro, 2007). FLUCAR combines the use of buoys and ships to monitor biophysical variables associated to ocean dynamics as well as characterizing the effects of teleconnection events such as El Niño and La Niña. Buoys account for continuous measurements in time but limited spatial coverage, in the case of the FLUCAR studies; however, studies are complemented by ship board measurements that cover a grid increasing estimates of spatial variation. There are three FLUCAR sites functioning along the Baja California Peninsula, the Mexican Occidental Pacific, and three more are planned at the Gulf of California, Veracruz, and the Yucatan Peninsula (Fig. 1). The oldest site has been operational since 2008.
FLUCAR works informally with several international programs such as: NACP, Land-Ocean Interactions in the Coastal Zone, and the Integrated Marine Biogeochemistry and Ecosystem Research. The potential of data derived from this program to enhance our understanding of ocean carbon dynamics occurs through several forms. For example, California’s nearshore waters provide habitat for a diversity of marine life that is characterized by high productivity rates. This high productivity is maintained by the divergence of currents that bring deeper, colder, nutrient-rich waters to the surface (i.e., upwelling), further enhancing CO₂ exchanges between the ocean and the atmosphere (de La Cruz Orozco et al., 2007). Results from continuous measurements of partial pressure of CO₂ (pCO₂) in the upwelling region of Baja California suggest that the ocean becomes a carbon source during upwelling events in the summer for nearly five months (Fig. 3).

MexFlux and FLUCAR are bottom-up consortia of individual principal investigators (PI) with no long-term funding or consistent programmatic support from government funding agencies, but with the joint goal to advance fundamental understanding of the regional carbon cycle. Therefore, collaboration between these consortia could create for the first time in Mexico a coordinated and integrated long-term monitoring program for land–ocean CCS. Because of the current lack of a government-supported coordination of CCS, this self-organized PI-driven approach has emerged as a need to foster the advancement of CCS in Mexico. However, there is a need for a more concerted effort linking bottom-up with top-down (government organized programmatic support) initiatives with the following two goals: strengthen adaptive coordination among government agency and academic activities, and foster strong political will and commitment and a long-term vision for the organization of broader applied and basic CCS issues.

5. Advancing Mexican CCS

Even though CCS in Mexico is a nascent research field there is a strong, bottom-up commitment within the scientific research community to establish effective collaborative research networks. Currently Mexican CCS could be viewed mainly as a PI driven effort, especially for land–ocean–atmosphere interactions. The bottom-up PI driven approach was the basis for the creation of other networks (e.g., AmeriFlux) in which PIs initially self-organized, collectively discussed scientific issues, and have been recognized by numerous agencies as a unique opportunity for both basic and applied research. As these PI-driven networks matured, the data, analyses and results pointed toward the use of very robust techniques (e.g., eddy covariance, ecosystem functions and services, inverse modeling) that enhanced our capability to scale our understanding of the carbon cycle through time and space (Peters et al., 2007). The development of these networks is now one of the rationales for building even larger continental scale observatories (e.g., NEON [United States], Integrated Carbon Observation System [European Union]). Agencies and funding mechanisms then had to act fast and be committed to accommodate these rapid advancements, and had the vision to encourage (and support) oversight structures like NACP working groups.

The tasks of funding agencies are not easy, and we fully recognize that programs constantly have to justify and argue for funds, and then often face different funding scenarios than originally planned (Table 2). However, Mexico could benefit from a coordinated and innovative vision that can optimize resources (economic, human, institutional) to advance CCS at the continental scale. For example, MexFlux, FLUCAR and the National Meteorological System (Sistema Meteorológico Nacional) are complementary in that they have a large overlap in data product needs, however with different objectives. Thus, we encourage government agencies to seek new ways for collaboration and to identify synergistic activities in supporting CCS in hope to optimize these resources and advance with stronger bottom-up and top-down actions.

5.1. Challenges and opportunities for continental-scale CCS integration in Mexico

Mexico has shown strong political will by hosting the United Nations Climate Change Conference (COP16) in 2010. However, there is no clear mechanism to orchestrate an effective CCS program with a long-term commitment and a continental approach. Thus, there is a strong need to create a strong interactive political and scientific environment that permits a linking bottom-up with top-down coordination of CCS across Mexico in order to work together toward an education and research network for climate change research and mitigation.

Although there is no simple solution to consolidate a CCS program at the regional and continental scale, there are several key recommendations that can be highlighted (Table 2). Furthermore, as future climate and economies change it becomes increasingly important to tie basic ecosystem services, ecosystem stewardship, and human well-being to CCS and to broader scientific and policy-making communities (Collins et al., 2011; Dilling, 2007). To enable Mexico to engage in meaningful national and international planning activities we encourage the accomplishment of two targets: (1) establish a baseline understanding of the processes and controls governing the carbon dynamics in terrestrial and oceanic

![Image](https://example.com/image.png)

**Fig. 3** - Example of delta partial pressure of CO₂ (ΔpCO₂) in Baja California’s coastal waters showing the effect of upwelling on ocean–atmosphere interactions. Positive ΔpCO₂ values represent CO₂ losses from the ocean. DOY = day of the year. The time series is between DOY 11/8/2008 and 12/6/2009; DOY 1 is 11/8/2008. The shaded area represents the upwelling months when the ocean becomes a carbon source (Lara-Lara, unpublished data).
systems and (2) provide a prognostic capability to inform likely trajectories of these processes given a decision made today.

In the view of the scarce funding and the short history of CCS in Mexico an important step is to increase the small pool of trained scientists. This can be done by promoting CCS within Mexico and by establishing a Mexico–United States–Canada research and education network that without doubt will result in benefits for CCS across North America. Support for CCS in Mexico should be a transparent process with a fair and equitable distribution of resources to maximize the advancement of science and to avoid monopoly of information by government participants or specific research groups. Thus, in order to generate useful and comparable information a close relationship between national and international activities should be promoted. Furthermore, there is a need for data repositories with clear data sharing policies, which could be coordinated by an autonomous decentralized agency to reduce transaction costs and bureaucracy locks. Currently the environmental science community is deeply engaged in maturing the various platforms for environmental observation systems (Benson et al., 2010) that should be modified for specific socio-political and scientific needs. We believe that Mexico could benefit by developing a synergetic interplay with these various platforms into a sustainable integrated observation system. This will only be successful if the system is designed to respond to well-addressed and new emerging scientific questions at the national and continental scales that will bring opportunities and advancement for CCS across North America (Table 2).

### Conclusion

Over the next decade, progress on CCS will be essential for improving estimates of land–ocean–atmosphere interactions and estimates of carbon balance across North America. Both in short- and long-term scenarios, the biases and uncertainties of the estimates must be characterized to the extent possible to facilitate policy decisions and carbon management strategies. Therefore, the future of CCS in Mexico and across North America along with the implementation of observation systems and monitoring networks relies on the choice of the scientific questions that are being asked. These questions should ultimately have forecasting applicability at seasonal, annual and interannual time scales. However, the techniques applied by the observation systems and monitoring networks will evolve along with technological improvements and economic investments. An ultimate challenge could be data sharing and data management across North American scientists where different agencies an data sharing policies may apply (e.g., ISO 2005). Thus, it requires an extraordinary

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Recommendations</th>
<th>Scientific opportunities</th>
</tr>
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<tbody>
<tr>
<td>Limited economic and human resources.</td>
<td>Identify synergies, optimize resources, and design a new collaborative framework among agencies as part of a long-term national CCS plan.</td>
<td>Mexico has a high beta diversity which opens the opportunity to establish experimental transects to study land/ocean-atmosphere interactions.</td>
</tr>
<tr>
<td>The impediment of how carbon is dealt with within countries is not allowing for development of a fructiferous cross-country carbon initiative.</td>
<td>Support for training and education network/workshops on theory, applications and techniques of field measurements, data analyses, data handling and archiving.</td>
<td>Test models under distinct conditions (e.g., from drought to hurricane prone areas) and ecosystems such as mangroves, tropical forests, aridlands.</td>
</tr>
<tr>
<td>Lack of coordination of national and international CCS activities.</td>
<td>Clearly defined government goals and scientific questions for CCS research.</td>
<td>Perform complete synthesis and regional studies across all North America (Canada–USA–Mexico).</td>
</tr>
<tr>
<td>Lack of a consolidated CCS research platform.</td>
<td>Support bottom-up strategic planning activities of coordinated research scientists.</td>
<td>Reduction of uncertainties in carbon fluxes by using new data and model outputs.</td>
</tr>
<tr>
<td>Lack of long-term funding strategies that prevent long-term monitoring commitment for CCS.</td>
<td>Provide a scaling a modeling framework to inform policymakers, educators, and research scientists alike.</td>
<td>Close the knowledge gap on the carbon which is exchanged between the land and ocean remains an unknown in the global carbon budget.</td>
</tr>
<tr>
<td>Bureaucracy locks for accessing information relevant for CCS (e.g., national inventories) and monopoly of information.</td>
<td>Establish a clear and transparent open data sharing policy with a robust data archiving scheme.</td>
<td>Understanding the biophysical factors that generate and maintain the mega diversity found in Mexico.</td>
</tr>
<tr>
<td>Lack of baseline data to establish thresholds and model parameters.</td>
<td>Development of baseline understanding of the processes and controls on carbon dynamics in Mexican terrestrial and oceanic systems at multiple temporal scales.</td>
<td>New environmental management approaches may result from exploring the interactions among humans and the ecosystems across the different social and ecological gradients in North America.</td>
</tr>
<tr>
<td>Lack of timely processed information available for the CCS community.</td>
<td>Standardization of measurements, QA/QC procedures, and data formats and content traceable to known nationally or internationally recognized standards.</td>
<td>Mitigation strategies in Mexico: Joint implementation programs and payments for environmental services.</td>
</tr>
</tbody>
</table>

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*Table 2 – Description of challenges, recommendations and opportunities for a continental scale carbon cycle science (CCS) program in Mexico.*
coordinated continental effort to standardize protocols and quality assurance and quality control to make data available and useful to the broader scientific community.

Research networks across North America are confronting the paradox about establishing multiple small research study sites or a few highly instrumented “super sites” to generate the baseline information for up-scaling (Schimel et al., 2009). Mexico (and other developing nations) has limited human resources and unfortunately is going through a delicate socio-political moment where safety issues complicate the establishment of study sites. The possibility of establishing a few “super sites” where multiple PIs apply for funding and share scientific questions and information across countries may be an alternative option (e.g., NSF Partnerships for Enhanced Engagement in Research (PEER) program). However, the implementation of a sparse network within a highly heterogeneous landscape may never close the gap in reducing and understanding spatial and temporal uncertainties across North America. Consequently, this brings up the question as to how much investment is needed to achieve the necessary (not necessarily the maximum) gain in knowledge. Although there is not a simple answer it should be analyzed and discussed among the scientific and political communities in each country across North America based on a cost–benefit approach, where increases in funding would equate to a much higher return of investment in knowledge (Fig. 4).

Finally, Mexico could increase its role in global carbon governance through participation in the development of global regulations and regulation-making systems to coordinate national responses to climate changes. However, this is a challenge for politicians and political scientists that need to be addressed with the relevant information about carbon dynamics and climate change in Mexico. Today global carbon governance is characterized by an increasing participation of actors that have so far been largely active at the sub-national level (e.g., scientific organizations, non-governmental organizations). This is particularly true for Mexico where the knowledge base on CCS is rather low within the political community. Thus, the emergence of a new cohort of scientists knowledgeable in CCS and land–ocean–atmosphere interactions (both modeling and measurements) may open the urgently needed science-policy dialog. These new scientists may have the ability to assist in political decision-making and participate in advancement of CCS with Mexico and across North America.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2012.04.003.

REFERENCES


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