

This discussion paper is/has been under review for the journal Biogeosciences (BG).  
Please refer to the corresponding final paper in BG if available.

# The carbon cycle in Mexico: past, present and future of C stocks and fluxes

G. Murray-Tortarolo<sup>1</sup>, P. Friedlingstein<sup>1</sup>, S. Sitch<sup>1</sup>, V. J. Jaramillo<sup>2</sup>,  
F. Murguía-Flores<sup>3</sup>, A. Anav<sup>1</sup>, Y. Liu<sup>4</sup>, A. Arneeth<sup>5</sup>, A. Arvanitis<sup>5</sup>, A. Harper<sup>1</sup>,  
A. Jain<sup>6</sup>, E. Kato<sup>7</sup>, C. Koven<sup>8</sup>, B. Poulter<sup>9</sup>, B. D. Stocker<sup>10</sup>, A. Wiltshire<sup>11</sup>,  
S. Zaehle<sup>12</sup>, and N. Zeng<sup>13</sup>

<sup>1</sup>College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, UK

<sup>2</sup>Instituto de Investigaciones en Ecosistemas y Sustentabilidad, Universidad Nacional Autónoma de México, Morelia, México

<sup>3</sup>Department of Physical Geography, University of Bristol, Bristol, UK

<sup>4</sup>Centre of Excellence for Climate System Science & Climate Change Research Centre, University of New South Wales, Sydney, Australia

<sup>5</sup>Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, Garmisch-Partenkirchen, Germany

<sup>6</sup>Department of Atmospheric Sciences, University of Illinois, Urbana, USA

<sup>7</sup>Global Environmental Program, The Institute of Applied Energy, Tokyo, Japan

<sup>8</sup>Lawrence Berkeley National Laboratory, Berkley, USA

<sup>9</sup>Ecosystem Dynamics Lab, University of Montana, Bozeman, USA

<sup>10</sup>Department of Life Sciences, Imperial College, London, UK

<sup>11</sup>Met Office Hadley Centre, Exeter, UK

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



<sup>12</sup>Department of Biogeochemical Integration, Max Planck Institute for Biogeochemistry, Jena, Germany

<sup>13</sup>Department of Atmospheric and Oceanic Sciences, University of Maryland. College Park, USA

Received: 28 June 2015 – Accepted: 7 July 2015 – Published: 10 August 2015

Correspondence to: G. Murray-Tortarolo (gnm202@exeter.ac.uk)

Published by Copernicus Publications on behalf of the European Geosciences Union.

## BGD

12, 12501–12541, 2015

### The carbon cycle in Mexico

G. Murray-Tortarolo et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



## Abstract

We modelled the carbon (C) cycle in Mexico with a process-based approach. We used different available products (satellite data, field measurements, models and flux towers) to estimate C stocks and fluxes in the country at three different time frames: present (defined as the period 2000–2005), the past century (1901–2000) and the remainder of this century (2010–2100). Our estimate of the gross primary productivity (GPP) for the country was  $2137 \pm 1023 \text{ Tg C yr}^{-1}$  and a total C stock of  $34\,506 \pm 7483 \text{ Tg C}$ , with  $20\,347 \pm 4622 \text{ Pg C}$  in vegetation and  $14\,159 \pm 3861$  in the soil.

Contrary to other current estimates for recent decades, our results showed that Mexico was a C sink over the period 1990–2009 ( $+31 \text{ Tg C yr}^{-1}$ ) and that C accumulation over the last century amounted to  $1210 \pm 1040 \text{ Tg C}$ . We attributed this sink to the  $\text{CO}_2$  fertilization effect on GPP, which led to an increase of  $3408 \pm 1060 \text{ Tg C}$ , while both climate and land use reduced the country C stocks by  $-458 \pm 1001$  and  $-1740 \pm 878 \text{ Tg C}$ , respectively. Under different future scenarios the C sink will likely continue over 21st century, with decreasing C uptake as the climate forcing becomes more extreme. Our work provides valuable insights on relevant driving processes of the C-cycle such as the role of drought in marginal lands (e.g. grasslands and shrublands) and the impact of climate change on the mean residence time of C in tropical ecosystems.

## 1 Introduction

The global carbon (C) cycle has been altered by anthropogenic activity with the release of  $\text{CO}_2$  into the atmosphere through fossil fuel burning and land use and land cover changes since the industrial revolution (Keeling et al., 1995). As a consequence C stocks have increased in the atmosphere, land and oceans. About 50 % of the annual anthropogenic emissions are sequestered in the marine and terrestrial ecosystems (Le Quéré et al., 2015). In the latter, the atmospheric  $\text{CO}_2$  increase has led to greater gross primary productivity (GPP), as a result of the fertilization effect on the plants' photosyn-

BGD

12, 12501–12541, 2015

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



thetic machinery, hence leading to higher C storage (Norby et al., 2005). However GPP and the net biome productivity (NBP) display high interannual variability due to the effect of climate variability on vegetation processes (e.g. plant production and water use, growing season extension, fire, drought induced mortality) (Sitch et al., 2015).

5 The interaction among climatic forcing, atmospheric CO<sub>2</sub> and terrestrial C remains one of the main uncertainties in our understanding of the global C cycle and in our ability to model it, particularly concerning future projections. Different authors have documented contrasting qualitative and quantitative results regarding the future evolution of the land C cycle. These range from a strong future C sink due to a longer growing  
10 season in the Northern Hemisphere and the CO<sub>2</sub> fertilization effect, to C sources from drought-induced tropical forest dieback and temperature-induced enhancements in mid-latitude soil respiration (Friedlingstein et al., 2006, 2013; Cox et al., 2000).

These differences in the future of land C arise from two sources: the strength of the carbon cycle feedbacks (driven by the sensitivity of land C to atmospheric CO<sub>2</sub>  
15 increase and climate change) and the poor representation of smaller-scale processes (e.g. disturbance) in the models (Ciais et al., 2013). Thus, regional studies are growing in importance to close the gap in our knowledge. These use finer resolution climate information and other data sources from the field (e.g. site-level carbon stocks), from  
20 satellites, and ecosystem-level information for particular regions. An example is the Regional Carbon Cycle Assessment and Processes (RECCAP) initiative, which has promoted studies on drivers of the land C cycle in different regions worldwide (e.g. (Dolman et al., 2012; Gloor et al., 2012; King et al., 2015; Piao et al., 2012; Valentini et al., 2014), but further work is needed at finer scales (e.g. country level) (Enting et al., 2012).

25 In this context, we centred our investigation on Mexico's C cycle. Until now, studies on the C stocks or fluxes at the country level have been estimated from changes in vegetation C due to land use change (Masera et al., 1997; Cairns et al., 2003) and less frequently soil C has been incorporated in the calculations (de Jong et al., 2010). While these studies provide important insights on the processes driving the C-cycle

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



(e.g. LUC), they place Mexico as a source of C (Pacala et al., 2007), which may be a biased conclusion derived from estimating C fluxes from biomass change only (Table 1). This approach results in that important ecological processes are not taken into account, omitting soil C dynamics, the effect of CO<sub>2</sub> fertilization on GPP or the impacts of climate change. In contrast, results from global models and atmospheric CO<sub>2</sub> inversions place the country as a sink of C (Hayes et al., 2012; King et al., 2012), but they lack a representation of the driving mechanisms of change. Hence, a more comprehensive understanding of the C balance in Mexico is needed, to aid in policy formulation and to identify regions that may provide important ecosystem services like C sequestration.

In this study, we provide a country level perspective of the C cycle in Mexico and use different products and complementary approaches to estimate C stocks and fluxes over three different time frames: the present (2005–2009), the last century (1901–2000) and the remainder of this century (2010–2100). The country represents a unique opportunity to compare the different approaches, due to the high variety of climates and vegetation (Challenger, 1998), which includes a wide range of land cover types (Fig. 1, S1 in the Supplement). Thus, in addition to the country level analysis, we can compare estimates and products by land cover type. Additionally, the high environmental heterogeneity allows that multiple processes that drive the C cycle globally can be found at a smaller spatial scale (e.g. fire, drought, tropical deforestation); thus, providing insights on the global drivers of the land C.

We address the following research questions for the different time periods under consideration:

1. Present-day: what are the magnitudes of C stocks and fluxes at the country level? How do they vary geographically and by land cover type? How do the estimates with the different approaches compare?
2. Past: how have C stocks and fluxes changed over the last century? How do these relate to changes in atmospheric CO<sub>2</sub>, precipitation, temperature and land use?

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



### 3. Future: how are C stocks and fluxes projected to change over the 21st century under different climate-change scenarios?

## 2 Methods

### 2.1 Datasets

5 Climate: we used observed temperature and precipitation data from CRU v3.1 (Harris et al., 2013). We expressed the change over time as the total for the last century. These data, among other climatic drivers, were also used to force the Dynamic Global Vegetation Models (DGVMs) (Fig. 1).

10 Present-day land cover: we used the observed vegetation dataset by Ramankutty and Foley (1999). This was derived from satellite data and contains 18 different categories (Fig. 1). Ten categories were present in Mexico (Fig. S1). In order to simplify the analysis, we aggregated the vegetation into five broad categories: broadleaf evergreen forest, broadleaf deciduous forest, needleleaf evergreen forest, grassland/shrubland and croplands (Fig. 1d).

15 Past Land Use Change (LUC): we used data for the agricultural fraction from Hurtt et al. (2011). LUC emissions were obtained from the DGVMs.

DGVMs: we used vegetation C, soil C, heterotrophic respiration (Rh), GPP and the net biome productivity (NBP) from an ensemble of 9 DGVMs (Table S1 in the Supplement) from the TRENDY v2 project (Le Quéré et al., 2015; Sitch et al., 2015). All models were forced using the same input data and spin-up protocol. To attribute the relevant driver (CO<sub>2</sub> fertilization, climate or LUC) of past change a set of factorial experiments was conducted over the period 1901–2012 where the effect of individual drivers and their combinations were analysed. The runs were:

- Simulation 1 (S1): rising CO<sub>2</sub> through the century with constant climate and no LUC. Hence CO<sub>2</sub> effect only.

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Simulation 2 (S2): rising CO<sub>2</sub> through the century with real climate and no LUC. Hence CO<sub>2</sub> + climate effect.
- Simulation (S3): including all drivers (raising CO<sub>2</sub>, observed climate and land use change).

5 The attribution of the drivers was calculated as: S1: CO<sub>2</sub> effect only; S2–S1: climate effect only; S3–S2: LULCC effect only, and S3: the combined effect of all drivers and their interactions. A full description of the experiment can be found in Sitch et al., (2015).

Earth System Models (ESMs): we used NBP, precipitation and temperature for four IPCC Representative Concentration Pathways or RCPs (2.6, 4.5, 6.0 and 8.5) based on an ensemble of 9 CMIP5 models common to all RCPs (Table S1) (Taylor et al., 10 2011). A full description of the models can be found in Anav et al., (2013).

Model Tree Ensemble (MTE): this is a data-driven model of gross primary productivity (GPP) based on flux tower observations, the satellite fraction of the active photosynthetic active radiation (fAPAR) and climate fields. It uses a Model Tree Ensemble (MTE) which is a machine learning system based on the data structure (Jung et al., 15 2011, 2009).

Satellite: to estimate aboveground biomass we used annual passive microwave satellite-based vegetation optical depth (VOD). VOD is an indicator of vegetation water content of aboveground biomass and can be approximated to mean biomass (Liu et al., 20 2011, 2013). We approximated the vegetation C from VOD using a linear coefficient for each cover type, derived from the best fit to the modeled aboveground biomass. To estimate GPP we used data derived from MODIS v17 f. The MODIS GPP algorithm is described in Running et al. (2004). A simple light use efficiency model (MOD17) is at the core of the GPP algorithm and it requires daily inputs of incoming photosynthetically active radiation (PAR) and climatic variables. 25

Field data: to estimate vegetation C we used the data from the REDD-Mexico initiative, which contains extensive field measurements from the National Forestry Commission (Alianza MREDD+, 2013), for the year 2004 (Fig. S2). For soil C, we used

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



the topsoil C concentrations (0–20 cm depth) from 4000 sampling sites (SEMARNAT, 2002) covering most of the country; soil sampling was conducted between 2000 and 2006. An alternative source for soil C was the harmonized soil database from FAO v1.2 (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). We multiplied C concentrations by the reference bulk density and the soil depth from the same database to estimate soil C stocks.

Atmospheric inversions: for the analysis on the land C flux for the present-day, we used the mean annual CO<sub>2</sub> posterior flux from atmospheric CO<sub>2</sub> inversion from 10 different products from Peylin et al. (2013) for the period 1990–2005. The uncertainty was calculated as the standard deviation across products. Due to the broad scale of the product (5° × 5°) we only presented the national average and not the gridded means.

All datasets were re-gridded to a common 1° × 1° grid.

## 2.2 Data analysis

For the present-day analysis, we first we computed the gridded mean GPP (satellite, MTE and DGVMs), soil C (field data, DGVMs and FAO) and aboveground vegetation C (field data, satellite and DGVMs) for the period 2000–2005. Then, we calculated those values for each land cover type and the total for the country for same time period which was common to all datasets. We also computed the mean NBP from all DGVMs, but for an extended time period (1990–2009), as this flux is strongly affected by the interannual variability of the Earth system. Our “best estimate” for each C pool or flux was the mean across all products (i.e. the contribution of each product was equally weighted). The error was computed as the standard deviation for all years for all products pooled together. We also computed a spatially weighted correlation across products.

For the analysis on past changes, we calculated cumulative NBP from the DGVMs ensemble for the period 1901–2000 (100 years) for the three different runs. We then attributed to environmental drivers (change in NBP for the run S1: CO<sub>2</sub>, S2–S1: climate and S3–S2: LULCC). We calculated the gridded linear change for each run and each driving factor (i.e. change in stored C by climate vs. precipitation and temperature



trend). The mean residence time of C in the soil (MRT) was calculated by dividing the linear change of soil C by change in soil heterotrophic respiration (Rh).

For the analysis on future scenarios, we calculated the change in cumulative NBP for each RCP from the ensemble of ESMs for the 21st century (2010–2100). We did this by grid, by land cover type, and for the whole country. For the gridded plots we stippled the areas where at least 66 % (6) of the models agreed on the sign of change in total stored C.

### 3 Results

#### 3.1 Present

Total GPP for the country was  $2137 \pm 1023 \text{ TgCyr}^{-1}$  for the period 2000–2005 (Table 2). In terms of the distribution by land cover type, the forest areas represented 56 % of the total GPP and the croplands and grasslands/shrublands most of the rest (44 %). The highest GPP per unit area occurred in the broadleaf evergreen forests ( $2.2 \pm 0.2 \text{ kgCm}^{-2}\text{yr}^{-1}$ ) and the lowest in the grasslands and shrublands ( $0.6 \pm 0.1 \text{ kgCm}^{-2}\text{yr}^{-1}$ ; Table 2). In terms of the country's geography, we found the highest GPP in the South and Southeast with a steep decrease to the North; the lowest GPP occurred in the north-central region (Fig. 2a). The three different products (i.e. satellite, flux towers (MTE) and DGVMs) displayed similar GPP distributions (Fig. 2b–d), with DGVMs estimating higher values over the mountainous ranges in the East and the West of the country and part of the central plateau. The spatial correlations between products were very high: satellite-MTE = 0.97, satellite-DGVMs = 0.92, and MTE-DGVMs = 0.91 (see also Table S2).

Our estimate for the total C stock in Mexico was  $34\,506 \pm 7843 \text{ TgC}$  (Table 3), of which  $20\,347 \pm 4622 \text{ TgC}$  (59 %) was stored in the vegetation and  $14\,159 \pm 3861 \text{ TgC}$  (41 %) was stored in the soil (Table 3). Similar to GPP, the forested areas accounted for 60 % of the total stored C, with 40 % in grasslands/shrublands and croplands. The

**BGD**

12, 12501–12541, 2015

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



broadleaf evergreen forest showed the highest C stock per unit area in the vegetation ( $22.9 \text{ kg C m}^{-2}$ ) and soil ( $12.1 \text{ kg C m}^{-2}$ ), whereas the grassland/shrubland the smallest ( $6.0$  and  $4.7 \text{ kg C m}^{-2}$ , respectively) (Table 3, Fig. 3, Table S3).

Vegetation C estimates from the three products (DGVMs, satellite and field data) were in broad agreement at the country level and by land-cover type (Fig. 4; Table S3). The largest differences among products were evident in the grassland/shrubland, with both DGVMs and satellite-based estimates 15–24 % higher than those obtained from field measurements, which was evident in the geographical distribution of C stocks (Fig. 4a–c; Table S3). The spatial correlations between products were lower than for GPP: field-DGVMs = 0.79, field-satellite = 0.84, and DGVMs-satellite = 0.74.

The differences among products were greater for soil C. The field data estimates were on average 15 % higher than with the other two products. In particular, the DGVMs and the FAO database appeared to underestimate soil C in the grasslands and shrublands in Northern Mexico, with a value 27 % lower than the field data (Fig. 4d–f; Table S3). Nonetheless, there were similarities in the geographical patterns across products, which depicted generally higher soil C towards the South and lower towards the North, particularly in the central region. The spatial correlations between products were generally lower than for vegetation C stocks: field-DGVMs = 0.68, field-FAO = 0.69, and DGVMs-FAO = 0.92.

Our results showed that Mexico was a sink of C over recent decades (1990–2009), gaining  $31.4 \pm 18.6 \text{ Tg Cyr}^{-1}$  (Table 4). However, the sink was not equally distributed across land covers, with the broadleaf evergreen forest, the needleleaf evergreen forest and the grasslands gaining C, but the broadleaf deciduous forest and the croplands losing C. In terms of the geographical distribution of NBP, most of the country displayed positive values, except in areas of the Northwest and the central East of the country, which lost C (Fig. 5). The atmospheric inversions also displayed a positive value for the country with a value of  $21.4 \pm 12.7 \text{ Tg Cyr}^{-1}$  (Table 1).

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I ◀](#)[▶ I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

## 3.2 Past

The model results with the DGVMs showed that over the last century Mexico has been a C sink, during which time there was an overall gain of  $1210 \pm 1040 \text{ Tg C}$ . Geographically, NBP was not homogeneously distributed. The South and central regions of the country lost C, while broad regions towards the North and the Yucatan Peninsula represented a C sink (Fig. 6). Three drivers of these regional trends could be identified at this scale with the processes included in the DGVMs: (a) the rise in atmospheric  $\text{CO}_2$ , (b) long-term climate variability and change, and (c) land use change (LUC).

- a. The effect of elevated  $\text{CO}_2$  led to enhanced C storage across the whole of Mexico ( $3408 \pm 1060 \text{ Tg C}$ ), with the highest C gain occurring over the forested regions (Fig. 7).
- b. Climate impacts were highly contrasting across the country. Thus, when accounted nationwide, the positive and negative effects almost counteracted each other, although the negative effect dominated the flux with emissions of  $-458 \pm 1001 \text{ Tg C}$ . Climate led to a decrease in C storage over most areas of the country, with the exception of the Northeast and the Yucatan Peninsula (Fig. 8a). Over the last 100 years, both precipitation and temperature showed an increase in most of the country, except for decreases in precipitation especially in the Baja California Peninsula in the the Northwest (Fig. 8c). The loss of C over most of the country, in spite of generally positive climate trends was driven by a faster increase of heterotrophic respiration ( $R_h$ ) than GPP, thus leading to a decrease in the mean residence time of soil C (Fig. S5).
- c. The negative effect of LUC on total stored C ( $-1740 \pm 878 \text{ Tg C}$ ) occurred mostly over the South of the country and along the Gulf of Mexico and Pacific coasts (Fig. 9a). Carbon emissions from LUC were apparently related to the distribution of changes in the agricultural fraction over the same time period (Fig. 9b).

**BGD**

12, 12501–12541, 2015

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Thus, when the three drivers were considered simultaneously, we found that the fertilization effect of CO<sub>2</sub> on GPP during those 100 years was greater than the climate and LUC negative effects, resulting in a positive net C storage at the scale of the country.

### 3.3 Future

In three out of four RCPs scenarios, the Earth System Models predicted Mexico to remain a C sink up to 2100; only in the most extreme scenario (RCP8.5), the country would become a C source. The total amount of stored C decreased as the radiative forcing increased, from 3025 Tg C in RCP2.6, to 2150 Tg C in RCP4.5, to 1578 Tg C in RCP6.0 and -762 Tg C in RCP8.5.

Geographically, Northern Mexico was generally a C source in all RCPs and at least two thirds of the models agreed on this trend (Fig. 10). As the radiative force increased, most of the country turned into a C source and model agreement also increased. However, there was a significant uncertainty in the magnitude and even sign of the changes in other parts of the country, especially over the Yucatan Peninsula (Fig. 10).

Under all RCPs, precipitation decreased (Fig. S4) and temperature increased over the 21st century in the whole country (Fig. S3), with the larger changes occurring with increasing radiative forcing. Under these scenarios, very likely Mexico would face drier conditions, with the North of the country drying faster than the South.

## 4 Discussion

### 4.1 Present

The GPP (2137 TgCyr<sup>-1</sup>) estimated in our study for Mexico corresponds to approximately 2% of the global values (Ciais et al., 2013), similar to the fraction of the land area the country represents. As far as we know, this is the first estimate of gross primary productivity at the country level combining different products. Although there

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



are no site-level GPP data, there are a few site estimates of net primary productivity (NPP) in Mexican ecosystems and we can compare them by assuming NPP to be 0.5 of GPP (Farquar and Sharkey, 1982). Among those, Martínez-Yrizar et al. (1996) estimated an aboveground NPP of  $0.6\text{--}0.8\text{ kg C m}^{-2}\text{ yr}^{-1}$  in the tropical dry forest of Chamela, Mexico, similar to our findings of  $0.6 \pm 0.2\text{ kg C m}^{-2}\text{ yr}^{-1}$  for broadleaf deciduous forests. García-Moya and Montanés-Castro (1992) estimated NPP in a semiarid grassland in central Mexico between  $0.3$  and  $0.6\text{ kg C m}^{-2}\text{ yr}^{-1}$ , similar to our finding of  $0.3 \pm 0.2\text{ kg C m}^{-2}\text{ yr}^{-1}$  for grasslands/shrublands. Such overall agreement provides elements to constrain C fluxes, although more field measurements are needed to provide better comparisons at the country scale.

The total C stock (vegetation and soil) for the country of  $34\,506 \pm 7483\text{ Tg C}$ , estimated with different products (field data, DGVMS and satellite), differs from the  $24\,000\text{ Tg C}$  estimated by Masera et al. (2001) with a C accounting model. More recent and comprehensive estimates put the total C stock for Mexico at around  $33\,000\text{ Tg C}$  (Pacala et al., 2007), which is similar to our value. Interestingly, the baseline estimate of  $19\,000\text{ Tg C}$  for the total C stock in forests by Masera et al. (2001) compares to our  $20\,347\text{ Tg C}$  for forest vegetation. This means that the highest source of discrepancy across estimates concerns soil C, with our estimate of  $14\,159\text{ Tg C}$  almost three times higher than Masera et al. (2001) of  $5000\text{ Tg C}$ .

Total aboveground biomass C for Mexico represents  $\sim 4\%$  of the global biomass stocks (Ciais et al., 2013). Our estimates for land cover types are difficult to compare to field-based studies because of the coarse scale of resolution used in our study, which provides large-scale averages and does not capture the heterogeneity of land cover at the local scale. Also, difficulties arise when comparing with other modelling approaches because of differences in criteria to establish land cover classes and in the methods for calculation. Nevertheless, it is interesting that our mean estimate of  $22.9 \pm 0.9\text{ kg C m}^{-2}$  in the broadleaf evergreen forest is similar to the mean value of  $20.5\text{ kg C m}^{-2}$  from Masera et al. (2001) for the same land cover, with a different modelling approach, and even to the  $19.5\text{ kg C m}^{-2}$  reported for the Los Tuxtlas region from field measure-

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

ments (Hughes et al., 1999). Also, our estimate for the needleleaf evergreen forest of  $15.1 \pm 0.9 \text{ kg C m}^{-2}$  compares to the mean temperate forest C stock of  $12.6 \text{ kg C m}^{-2}$  of Masera et al. (2001). However, it is important to note that field measurements by Jasso (2014) showed a range from 2.1 to  $20.8 \text{ kg C m}^{-2}$  for pine and fir dominated forests depending on altitude, which indicates the high degree of variability for this land cover type. Important discrepancies were found over the grasslands/shrublands for which we estimated a mean vegetation C of  $6.1 \pm 0.7 \text{ kg C m}^{-2}$ , while field studies (e.g. Búrquez et al., 2010; Navar et al., 2014) estimated  $1.6\text{--}4.4 \text{ kg C m}^{-2}$  in the deserts over the North of the country.

Total soil C storage in the country is  $\sim 0.6\%$  of the global stock (Ciais et al., 2013 IPCC Chapter 6). This represents a smaller percentage than the other stocks and fluxes, because the FAO and field data used in this study included only the top 20 cm of soil; thus, the size of the soil C stock is underestimated. Batjes (1996) showed that, on average, topsoil (20 cm) represents a third of the global soil C stock. A field study in the dry tropics of Mexico (Jaramillo et al., 2003) showed that 37–59 % of the soil C stock was in the top 20 cm of soil in land covers which comprised dry and floodplain forest and pasture. In the tropical evergreen forest of Los Tuxtlas (Hughes et al., 2000), soil C in the top 30 cm of soil represented 46 % of the soil C stock to a 1 m depth. Thus, the amount of C stored in soil at the country scale is likely to be at least twice as high as estimated here and further work is needed to better constrain this calculation.

If we compare the estimates among products and consider the high correlations, it seems that the C stocks in the vegetation and the GPP fluxes are remarkably well constrained and compare favourably against field data and findings by other authors (Pacala et al., 2007). However, model development and improvement, particularly over non-forested areas, is needed, where the DGVM estimates showed the highest differences compared to field values.

Our results also showed that Mexico was a C sink over recent decades (1990–2009), gaining  $31.4 \pm 18.6 \text{ Tg C yr}^{-1}$ . This is similar to recent calculations by Hayes et al. (2013) using inverse ( $+8.7 \text{ Tg C yr}^{-1}$ ) and forward models ( $29.0 \text{ Tg C yr}^{-1}$ ) and to the result

from atmospheric CO<sub>2</sub> inversions (21.4 TgCyr<sup>-1</sup>). However, it is in disagreement with all inventory based calculations (Masera et al., 1997; Cairns et al., 2000; de Jong et al., 2010) that place Mexico as source of C (Table 1). The discrepancy may arise because the latter estimates are only based on changes in vegetation stocks as fixed covers, which does not take into account important ecosystem processes such as the effect of CO<sub>2</sub> fertilization and the impacts of climate change. In other words, those estimates are closer to the LUC C-flux than to NBP (see Table 1). Based on our estimates and the recent literature, we argue that it is likely that Mexico is currently a sink and not a source of C, if we disregard emissions from fossil fuels.

## 4.2 Past

Similar to the present-day, our results indicated that the terrestrial ecosystems in the country were a C-sink over the last 100 years, gaining 1210 ± 1040 TgC in total. Such increment was driven by the CO<sub>2</sub> fertilization effect on vegetation (3408 ± 1060 TgCyr<sup>-1</sup>), which enhanced GPP and subsequently biomass and possibly soil C to different degrees. Both the climate (-458 ± 1001 TgCyr<sup>-1</sup>) and the land use (-1740 ± 878 TgCyr<sup>-1</sup>) drivers showed a generalized negative effect on C storage. Our estimates are highly consistent with those derived from global models for Latin America, which show these land ecosystems as C sinks (Pan et al., 2011). However, during the period 1901–2000 the country's emissions from fossil fuels amounted to about 10 600 TgC (Le Quéré et al., 2015). This suggests that only 11 % of the emissions from fossil fuels were actually captured back into the land and emphasizes the need for more efficient fossil-fuel and LUC policies.

The loss of C over NE Mexico is likely driven by climate. A long-term drought identified over the NE Mexico and SE USA (Cayan et al., 2010), has led to a reduction in grassland productivity (Grover and Musick, 1990) and the subsequent loss of stored C due to increased dry season intensity and length. However, the overall negative effect of climate on C storage in other regions is likely linked to its impact on soil C mean

**BGD**

12, 12501–12541, 2015

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



residence time (MRT; Fig. S5). The increase in temperature leads to a higher respiration rate and soil C loss. As the MRT decreases, it results in certain regions becoming a C source to the atmosphere. This source, nevertheless, is apparently overridden by the impact of higher precipitation on plant productivity in many regions of Mexico. In this sense, MRT is one of the main sources of uncertainty for the future of global soil C (Carvalho et al., 2014; Friend et al., 2014) and a more comprehensive analysis over the country, based on observed data, is lacking.

Other regions which experienced C loss are linked to the impact of LUC. LUC accounted for a loss of 1740 Tg C over this period, with most of the emissions (60 %) occurring in forested regions and 32 % in the broadleaf forests over the South. Interestingly, about a third of the emissions (34 %) were accounted for in croplands. Country-level estimates by Masera et al. (1997) calculated the flux at 61 TgCyr<sup>-1</sup> based on changes only in vegetation stocks for their baseline year in the 1980s. More comprehensive analyses including C emissions from the soil, estimated net emissions of 23.7 TgCyr<sup>-1</sup> from LUC in forests of Mexico for the period 1993–2002 (de Jong et al., 2010; Hayes et al., 2012). Despite the different methodologies, all approaches establish that the highest LUC emissions fluxes have occurred mostly over Southern Mexico.

When the effects of all drivers were considered, the models showed that changes in climatic variables had a smaller impact on stored C than LUC during the period 1901–2009. This was due to the fact that the impacts of LUC were consistently negative on all land cover types, whereas climatic variables showed a heterogeneous effect (i.e., positive and negative) on the land cover types, which are differentially distributed over the country. Notably, climate trends have promoted C capture in broadleaf evergreen forests during the past 100 years, but this was overridden by LUC. However, there is no evidence from field measurements to support or disprove this claim. While there are studies on the consequences of LUC on C pools at the site and regional levels (Hughes et al., 2000; Jaramillo et al., 2003; de Jong et al., 2010), there is very little work on the effect of climate change on NBP over Mexico (e.g. Dai et al., 2014), making this a fundamental missing piece in our understanding of C cycle at local to regional scales.

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)



This is particularly important because the DGVMs used here are poorly constrained for their drought response (Morales et al., 2007; Sitch et al., 2003), a key process for the C balance over the arid regions of Mexico (grasslands/shrublands), which cover about 40 % of the land area.

### 4.3 Future

In three out of four scenarios, Mexico represents a potential C sink in the remaining of this century. It is only in the scenario with the highest temperature and lowest precipitation (RCP8.5) that the country actually turns into a C source. While the CO<sub>2</sub> fertilization dominates the magnitude of the sink across all RCPs, the effect of climate becomes more negative and predominant as the RCP becomes more extreme (Table 5). Similar modelling results have been found at the global scale, with an increasing climate-carbon feedback as the future scenario becomes more extreme (Cox et al., 2000; Friedlingstein et al., 2006).

Important considerations should be taken into account. The CO<sub>2</sub> fertilization effect is likely counterbalanced not only by climate, but also by the effect of limiting nutrients on C uptake – a process that is not considered in many Earth-System-Models (ESMs) (Reich et al., 2014, 2006; Zaehle et al., 2015) or by more severe fires as a result of more intense and recurrent ENSO (Yocom et al., 2010). Additionally, as shown by the past trends, a decrease in the MRT of soil C can change an ecosystem from a C-sink into a source. There is a lack of field information to estimate MRT and its response to temperature and soil moisture to fully understand the implications for the future of stored C, especially in tropical and sub-tropical ecosystems.

## 5 Final considerations

We quantify different aspects of the C cycle for Mexico (GPP and the total land C flux, as well as vegetation and soil C stocks) using different products over three time

**BGD**

12, 12501–12541, 2015

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



periods. As far as we know, this is the first time these pools and fluxes have been quantified for the whole country with a process-based approach. It takes into account different drivers (e.g. CO<sub>2</sub>, climate and LUC) and provides a more realistic estimate of the C cycle for the country. Additionally, we quantify fluxes (e.g. GPP and NBP), not previously estimated at the country scale.

Contrary to other inventory-based estimates (de Jong et al., 2010; Pacala et al., 2007; Hayes et al., 2012), our analysis shows that over the last 100 years and recent decades the country was a C sink. Our results suggest this is mainly due to the positive effect of CO<sub>2</sub> fertilization and to precipitation and temperature changes in some regions. This pattern is likely to persist, although with a diminishing trend, over the remaining part of the century. Such a sink however only accounts for 11 % of C emissions from fossil fuels during the period, which clearly points towards the need of more fuel-efficient policies and emissions controls.

Our work also identifies the need to study the role of drought in marginal lands (e.g. grasslands and shrublands) and to determine soil carbon MRT in tropical ecosystems. Finally, as we used data from global sources (e.g. DGVMs, ESMs, satellite), the methodology proposed here can be used to analyse the full-C cycle of regions elsewhere.

**The Supplement related to this article is available online at doi:10.5194/bgd-12-12501-2015-supplement.**

*Author contributions.* G. Murray-Tortarolo, P. Friedlingstein, S. Sitch and V. J. Jaramillo designed, executed and wrote the paper. F. Murguía-Flores, A. Anav and Y. Liu provided and analyzed data. The rest of the authors provided the DGVMs data and helped writing the paper.

*Acknowledgements.* The lead author (G. Murray-Tortarolo) thanks CONACYT-CECTI, the and Secretaria de Educacion Publica (SEP), Mexico and University of Exeter, UK for their funding for this project. The authors extend their thanks to Carlos Ortiz Solorio and to the Colegio de

**BGD**

12, 12501–12541, 2015

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Posgraduados for the field soil data and to the Alianza Redd + Mexico for the field biomass data. This project would not have been possible without the valuable data from the CMIP5 models. A. Arneeth and S. Sitch acknowledge the support of the European Commission-funded project LUC4C (grant no. 603 542). This work was also funded by the European Commission's 7th Framework Programme under Grant Agreements 282672 (EMBRACE project).

## References

- Alianza MREDD+: Mapa y base de datos sobre la distribución de la biomasa aérea de la vegetación leñosa en México, Woods Hole Research Center, USAID, CONAFOR, CONABIO, Proyecto México Noruega, México, 2013.
- Anav, A., Friedlingstein, P., Kidston, M., Bopp, L., Ciais, P., Cox, P., Jones, C., Jung, M., Myrneni, R., and Zhu, Z.: Evaluating the land and ocean components of the global carbon cycle in the CMIP5 earth system models, *J. Climate*, 26, 6801–6843, doi:10.1175/JCLI-D-12-00417.1, 2013.
- Batjes, N. H.: Total carbon and nitrogen in the soils of the world, *Eur. J. Soil Sci.*, 47, 151–163, doi:10.1111/j.1365-2389.1996.tb01386.x, 1996.
- Búrquez, A., Martínez-Yrizar, A., Núñez, S., Quintero, T., and Aparicio, A.: Aboveground biomass in three Sonoran Desert communities: variability within and among sites using replicated plot harvesting, *J. Arid Environ.*, 74, 1240–1247, doi:10.1016/j.jaridenv.2010.04.004, 2010.
- Cairns, M. A., Olmsted, I., Granados, J., and Argaez, J.: Composition and aboveground tree biomass of a dry semi-evergreen forest on Mexico's Yucatan Peninsula, *Forest Ecol. Manag.*, 186, 125–132, doi:10.1016/S0378-1127(03)00229-9, 2003.
- Carvalho, N., Forkel, M., Khomik, M., Bellarby, J., Jung, M., Migliavacca, M., Mu, M., Saatchi, S., Santoro, M., Thurner, M., Weber, U., Ahrens, B., Beer, C., Cescatti, A., Randerson, J. T., and Reichstein, M.: Global covariation of carbon turnover times with climate in terrestrial ecosystems, *Nature*, 514, 213–217, doi:10.1038/nature13731, 2014.
- Cayan, D. R., Das, T., Pierce, D. W., Barnett, T. P., Tyree, M., and Gershunov, A.: Future dryness in the southwest US and the hydrology of the early 21st century drought, *P. Natl. Acad. Sci. USA*, 107, 21271–21276, doi:10.1073/pnas.0912391107, 2010.

**BGD**

12, 12501–12541, 2015

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



- Challenger, A.: Utilización y conservación de los ecosistemas terrestres de México, Pasado, presente y futuro, Conabio, IBUNAM y Agrupación Sierra Madre, México, 1998.
- Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Le Queirei, C., Myneni, R. B., Piao, S., and Thorn-ton, P.: Carbon and other biogeochemical cycles, in: *Climate Change: The Physical Science Basis*, Contribution of Working Group I to the Fifth Assessment Report of the Intergovern-mental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge Univer-sity Press, Cambridge, UK, New York, NY, USA, 465–544, 2013.
- Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A., and Totterdell, I. J.: Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model, *Nature*, 408, 184–187, doi:10.1038/35041539, 2000.
- Dai, Z., Birdsey, R. A., Johnson, K. D., Dupuy, J. M., Hernandez-Stefanoni, J. L., and Richard-son, K.: Modeling carbon stocks in a secondary tropical dry forest in the Yucatan Peninsula, Mexico, *Water Air Soil Poll.*, 225, 1–15, doi:10.1007/s11270-014-1925-x, 2014.
- De Jong, B., Anaya, C., Maser, O., Olguín, M., Paz, F., Etchevers, J., Martínez, R. D., Guerrero, G., and Balbontín, C.: Greenhouse gas emissions between 1993 and 2002 from land-use change and forestry in Mexico, *Forest Ecol. Manag.*, 260, 1689–1701, doi:10.1016/j.foreco.2010.08.011, 2010.
- Dolman, A. J., Shvidenko, A., Schepaschenko, D., Ciais, P., Tchebakova, N., Chen, T., van der Molen, M. K., Belelli Marchesini, L., Maximov, T. C., Maksyutov, S., and Schulze, E.-D.: An estimate of the terrestrial carbon budget of Russia using inventory-based, eddy covari-ance and inversion methods, *Biogeosciences*, 9, 5323–5340, doi:10.5194/bg-9-5323-2012, 2012.
- Enting, I. G., Rayner, P. J., and Ciais, P.: Carbon Cycle Uncertainty in REgional Carbon Cycle Assessment and Processes (RECCAP), *Biogeosciences*, 9, 2889–2904, doi:10.5194/bg-9-2889-2012, 2012.
- FAO/IIASA/ISRIC/ISSCAS/JRC: Harmonized World Soil Database (version 1.2), FAO, Rome, Italy and IIASA, Laxenburg, Austria, 2012.
- Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H. D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K.-G., Schnur, R., Strassmann, K., Weaver, A. J., Yoshikawa, C., and Zeng, N.: Climate–carbon

---

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



cycle feedback analysis: results from the C4MIP model intercomparison, *J. Climate*, 19, 3337–3353, doi:10.1175/JCLI3800.1, 2006.

Friedlingstein, P., Meinshausen, M., Arora, V. K., Jones, C. D., Anav, A., Liddicoat, S. K., and Knutti, R.: Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks, *J. Climate*, 27, 511–526, doi:10.1175/JCLI-D-12-00579.1, 2013.

Friend, A. D., Lucht, W., Rademacher, T. T., Keribin, R., Betts, R., Cadule, P., Ciais, P., Clark, D. B., Dankers, R., Falloon, P. D., Ito, A., Kahana, R., Kleidon, A., Lomas, M. R., Nishina, K., Ostberg, S., Pavlick, R., Peylin, P., Schaphoff, S., Vuichard, N., Warszawski, L., Wiltshire, A., and Woodward, F. I.: Carbon residence time dominates uncertainty in terrestrial vegetation responses to future climate and atmospheric CO<sub>2</sub>, *P. Natl. Acad. Sci. USA*, 111, 3280–3285, doi:10.1073/pnas.1222477110, 2014.

Garcia-Moya, E. and Montanes-Castro, P. M.: Saline grassland near Mexico City, in: *Primary Productivity of Grass Ecosystems of the Tropics and Sub-Tropics*, Chapman and Hall, London, 70–99, 1992.

Gloor, M., Gatti, L., Brienen, R., Feldpausch, T. R., Phillips, O. L., Miller, J., Ometto, J. P., Rocha, H., Baker, T., de Jong, B., Houghton, R. A., Malhi, Y., Aragão, L. E. O. C., Guyot, J.-L., Zhao, K., Jackson, R., Peylin, P., Sitch, S., Poulter, B., Lomas, M., Zaehle, S., Huntingford, C., Levy, P., and Lloyd, J.: The carbon balance of South America: a review of the status, decadal trends and main determinants, *Biogeosciences*, 9, 5407–5430, doi:10.5194/bg-9-5407-2012, 2012.

Grover, H. D. and Musick, H. B.: Shrubland encroachment in southern New Mexico, USA: an analysis of desertification processes in the American southwest, *Climatic Change*, 17, 305–330, doi:10.1007/BF00138373, 1990.

Harris, I., Jones, P. D., Osborn, T. J., and Lister, D. H.: Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 dataset, *Int. J. Climatol.*, 34, 623–642, doi:10.1002/joc.3711, 2013.

Hayes, D. J., Turner, D. P., Stinson, G., McGuire, A. D., Wei, Y., West, T. O., Heath, L. S., de Jong, B., McConkey, B. G., Birdsey, R. A., Kurz, W. A., Jacobson, A. R., Huntzinger, D. N., Pan, Y., Post, W. M., and Cook, R. B.: Reconciling estimates of the contemporary North American carbon balance among terrestrial biosphere models, atmospheric inversions, and a new approach for estimating net ecosystem exchange from inventory-based data, *Glob. Change Biol.*, 18, 1282–1299, doi:10.1111/j.1365-2486.2011.02627.x, 2012.

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Hughes, R. F., Kauffman, J. B., and Jaramillo, V. J.: Biomass, carbon, and nutrient dynamics of secondary forests in a humid tropical region of México, *Ecology*, 80, 1892–1907, doi:10.1890/0012-9658(1999)080[1892:BCANDO]2.0.CO;2, 1999.

Hurt, G., Chini, L., Frolking, S., Betts, R., Feddema, J., Fischer, G., Fisk, J., Hibbard, K., Houghton, R., Janetos, A., Jones, C., Kindermann, G., Kinoshita, T., Klein Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., van Vuuren, D., and Wang, Y.: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands, *Climatic Change*, 109, 117–161, doi:10.1007/s10584-011-0153-2, 2011.

Jasso, R.: Crecimiento, biomasa y carbono arbóreo en un gradiente altitudinal en bosques templados, Tesis de Maestría, Posgrado en Ciencias Biológicas, UNAM, Mexico, 2014.

Jung, M., Reichstein, M., and Bondeau, A.: Towards global empirical upscaling of FLUXNET eddy covariance observations: validation of a model tree ensemble approach using a biosphere model, *Biogeosciences*, 6, 2001–2013, doi:10.5194/bg-6-2001-2009, 2009.

Jung, M., Reichstein, M., Margolis, H. A., Cescatti, A., Richardson, A. D., Arain, M. A., Arneth, A., Bernhofer, C., Bonal, D., Chen, J., Gianelle, D., Gobron, N., Kiely, G., Kutsch, W., Lasslop, G., Law, B. E., Lindroth, A., Merbold, L., Montagnani, L., Moors, E. J., Papale, D., Sottocornola, M., Vaccari, F., and Williams, C.: Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations, *J. Geophys. Res.-Biogeo.*, 116, G00J07, doi:10.1029/2010JG001566, 2011.

Keeling, C. D., Whorf, T. P., Wahlen, M., and Van Der Plicht, J.: Interannual extremes in the rate of rise of atmospheric carbon dioxide since, 1980, *Nature*, 375, 666–670, 1995.

King, A. W., Hayes, D. J., Huntzinger, D. N., West, T. O., and Post, W. M.: North American carbon dioxide sources and sinks: magnitude, attribution, and uncertainty, *Front. Ecol. Environ.*, 10, 512–519, doi:10.1890/120066, 2012.

King, A. W., Andres, R. J., Davis, K. J., Hafer, M., Hayes, D. J., Huntzinger, D. N., de Jong, B., Kurz, W. A., McGuire, A. D., Vargas, R., Wei, Y., West, T. O., and Woodall, C. W.: North America's net terrestrial CO<sub>2</sub> exchange with the atmosphere 1990–2009, *Biogeosciences*, 12, 399–414, doi:10.5194/bg-12-399-2015, 2015.

Le Quéré, C. L., Raupach, M. R., Canadell, J. G., Al, G. M. et, Al, C. L. Q. et, Al, C. L. Q. et, Raupach, M. R., Canadell, J. G., Marland, G., Bopp, L., Ciais, P., Conway, T. J., Doney, S. C., Feely, R. A., Foster, P., Friedlingstein, P., Gurney, K., Houghton, R. A., House, J. I., Hunt-

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



ingford, C., Levy, P. E., Lomas, M. R., Majkut, J., Metzl, N., Ometto, J. P., Peters, G. P., Prentice, I. C., Randerson, J. T., Running, S. W., Sarmiento, J. L., Schuster, U., Sitch, S., Takahashi, T., Viovy, N., Werf, G. R. van der, Woodward, F. I., Al, C. L. Q. et, Al, C. L. Q. et, Raupach, M. R., Canadell, J. G., Marland, G., Bopp, L., Ciais, P., Conway, T. J., Doney, S. C., Feely, R. A., Foster, P., Friedlingstein, P., Gurney, K., Houghton, R. A., House, J. I., Huntingford, C., Levy, P. E., Lomas, M. R., Majkut, J., Metzl, N., Ometto, J. P., Peters, G. P., Prentice, I. C., Randerson, J. T., Running, S. W., Sarmiento, J. L., Schuster, U., Sitch, S., Takahashi, T., Viovy, N., Werf, G. R. van der, and Woodward, F. I.: Trends in the sources and sinks of carbon dioxide, *Nat. Geosci.*, 2, 831–836, doi:10.1038/ngeo689, 2009.

Le Quéré, C., Moriarty, R., Andrew, R. M., Peters, G. P., Ciais, P., Friedlingstein, P., Jones, S. D., Sitch, S., Tans, P., Arneeth, A., Boden, T. A., Bopp, L., Bozec, Y., Canadell, J. G., Chini, L. P., Chevallier, F., Cosca, C. E., Harris, I., Hoppema, M., Houghton, R. A., House, J. I., Jain, A. K., Johannessen, T., Kato, E., Keeling, R. F., Kitidis, V., Klein Goldewijk, K., Koven, C., Landa, C. S., Landschützer, P., Lenton, A., Lima, I. D., Marland, G., Mathis, J. T., Metzl, N., Nojiri, Y., Olsen, A., Ono, T., Peng, S., Peters, W., Pfeil, B., Poulter, B., Raupach, M. R., Regnier, P., Rödenbeck, C., Saito, S., Salisbury, J. E., Schuster, U., Schwinger, J., Séférian, R., Segschneider, J., Steinhoff, T., Stocker, B. D., Sutton, A. J., Takahashi, T., Tilbrook, B., van der Werf, G. R., Viovy, N., Wang, Y.-P., Wanninkhof, R., Wiltshire, A., and Zeng, N.: Global carbon budget 2014, *Earth Syst. Sci. Data*, 7, 47–85, doi:10.5194/essd-7-47-2015, 2015.

Liu, Y. Y., Parinussa, R. M., Dorigo, W. A., De Jeu, R. A. M., Wagner, W., van Dijk, A. I. J. M., McCabe, M. F., and Evans, J. P.: Developing an improved soil moisture dataset by blending passive and active microwave satellite-based retrievals, *Hydrol. Earth Syst. Sci.*, 15, 425–436, doi:10.5194/hess-15-425-2011, 2011.

Liu, Y. Y., Evans, J. P., McCabe, M. F., de Jeu, R. A. M., van Dijk, A. I. J. M., Dolman, A. J., and Saizen, I.: Changing climate and overgrazing are decimating Mongolian steppes, *PLoS ONE*, 8, e57599, doi:10.1371/journal.pone.0057599, 2013.

Martinez-Yrizar, A., Maass, J. M., Perez-Jimenez, L. A., and Sarukhan, J.: Net primary productivity of a tropical deciduous forest ecosystem in western Mexico, *J. Trop. Ecol.*, 12, 169–175, doi:10.1017/S026646740000938X, 1996.

Masera, O. R., Ordóñez, M. J., and Dirzo, R.: Carbon emissions from Mexican forests: Current situation and long-term scenarios, *Climatic Change*, 35, 265–295, 1997.

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Masera, O. R., Cerón, A. D., and Ordóñez, A.: Forestry mitigation options for Mexico: finding synergies between national sustainable development priorities and global concerns, *Mitig. Adapt. Strateg. Glob. Change*, 6, 291–312, doi:10.1023/A:1013327019175, 2001.

Morales, P., Hickler, T., Rowell, D. P., Smith, B., and Sykes, M. T.: Changes in European ecosystem productivity and carbon balance driven by regional climate model output, *Glob. Change Biol.*, 13, 108–122, doi:10.1111/j.1365-2486.2006.01289.x, 2007.

Navar, J., Rodriguez-Flores, F. J., Dominguez-Calleros, P. A., and Perez-Verdin, G.: Diversity-productivity relationship in the northeastern Tamaulipan thornscrub forest of Mexico, *Int. J. Ecol.*, 2014, e196073, doi:10.1155/2014/196073, 2014.

Norby, R. J., DeLucia, E. H., Gielen, B., Calfapietra, C., Giardina, C. P., King, J. S., Ledford, J., McCarthy, H. R., Moore, D. J. P., Ceulemans, R., De Angelis, P., Finzi, A. C., Karnosky, D. F., Kubiske, M. E., Lukac, M., Pregitzer, K. S., Scarascia-Mugnozza, G. E., Schlesinger, W. H., and Oren, R.: Forest response to elevated CO<sub>2</sub> is conserved across a broad range of productivity, *P. Natl. Acad. Sci. USA*, 102, 18052–18056, doi:10.1073/pnas.0509478102, 2005.

Pacala, S., Birdsey, R., Bridgman, S., Conant, R., Davis, K., Houghton, R., Jenkins, J., Johnston, M., Marland, G., and Paustian, K.: The North American carbon budget past and present, in: *The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle*, A Report by the U. S. Climate Change Science Program and the Subcommittee on Global Change Research, National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, USA, 29–36, 2007.

Pappas, C., Fatichi, S., Leuzinger, S., Wolf, A., and Burlando, P.: Sensitivity analysis of a process-based ecosystem model: pinpointing parameterization and structural issues, *J. Geophys. Res.-Biogeophys.*, 118, 505–528, doi:10.1002/jgrg.20035, 2013.

Piao, S. L., Ito, A., Li, S. G., Huang, Y., Ciais, P., Wang, X. H., Peng, S. S., Nan, H. J., Zhao, C., Ahlström, A., Andres, R. J., Chevallier, F., Fang, J. Y., Hartmann, J., Huntingford, C., Jeong, S., Levis, S., Levy, P. E., Li, J. S., Lomas, M. R., Mao, J. F., Mayorga, E., Mohammat, A., Muraoka, H., Peng, C. H., Peylin, P., Poulter, B., Shen, Z. H., Shi, X., Sitch, S., Tao, S., Tian, H. Q., Wu, X. P., Xu, M., Yu, G. R., Viovy, N., Zaehle, S., Zeng, N., and Zhu, B.: The carbon budget of terrestrial ecosystems in East Asia over the last two decades, *Biogeosciences*, 9, 3571–3586, doi:10.5194/bg-9-3571-2012, 2012.

Prentice, I. C., Farquhar, G. D., Fasham, M. J., Heimann, M., Jaramillo, V., Kheshi, H. S., Le Quéré, C. L., Scholes, R. J., and Wallace, D. W.: *The Carbon Cycle and Atmospheric Carbon*



## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Dioxide In: Climate Change 2001: the Scientific Basis, Contributions of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A., Cambridge University Press, Cambridge, UK, 185–237, 2001.

5 Ramankutty, N. and Foley, J. A.: Estimating historical changes in global land cover: croplands from 1700 to 1992, *Global Biogeochem. Cy.*, 13, 997–1027, doi:10.1029/1999GB900046, 1999.

Reich, P. B., Hobbie, S. E., Lee, T., Ellsworth, D. S., West, J. B., Tilman, D., Knops, J. M. H., Naeem, S., and Trost, J.: Nitrogen limitation constrains sustainability of ecosystem response to CO<sub>2</sub>, *Nature*, 440, 922–925, doi:10.1038/nature04486, 2006.

10 Reich, P. B., Hobbie, S. E., and Lee, T. D.: Plant growth enhancement by elevated CO<sub>2</sub> eliminated by joint water and nitrogen limitation, *Nat. Geosci.*, 7, 920–924, doi:10.1038/ngeo2284, 2014.

Running, S. W., Nemani, R. R., Heinsch, F. A., Zhao, M., Reeves, M., and Hashimoto, H.: A continuous satellite-derived measure of global terrestrial primary production, *BioScience*, 54, 547–560, doi:10.1641/0006-3568(2004)054[0547:ACSMOG]2.0.CO;2, 2004.

SEMARNAT: Evaluacion de la degradacion de suelo causada por el hombre en la Republica Mexicana, escala 1:250000, Memoria Nacional 2001–2002, Mexico, 2002.

15 Sitch, S., Smith, B., Prentice, I. C., Arneeth, A., Bondeau, A., Cramer, W., Kaplan, J. O., Levis, S., Lucht, W., Sykes, M. T., Thonicke, K., and Venevsky, S.: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model, *Glob. Change Biol.*, 9, 161–185, doi:10.1046/j.1365-2486.2003.00569.x, 2003.

Sitch, S., Friedlingstein, P., Gruber, N., Jones, S. D., Murray-Tortarolo, G., Ahlström, A., Doney, S. C., Graven, H., Heinze, C., Huntingford, C., Levis, S., Levy, P. E., Lomas, M., Poulter, B., Viovy, N., Zaehle, S., Zeng, N., Arneeth, A., Bonan, G., Bopp, L., Canadell, J. G., Chevallier, F., Ciais, P., Ellis, R., Gloor, M., Peylin, P., Piao, S. L., Le Quéré, C., Smith, B., Zhu, Z., and Myneni, R.: Recent trends and drivers of regional sources and sinks of carbon dioxide, *Biogeosciences*, 12, 653–679, doi:10.5194/bg-12-653-2015, 2015.

20 Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An overview of CMIP5 and the experiment design, *B. Am. Meteorol. Soc.*, 93, 485–498, doi:10.1175/BAMS-D-11-00094.1, 2011.

30 Valentini, R., Arneeth, A., Bombelli, A., Castaldi, S., Cazzolla Gatti, R., Chevallier, F., Ciais, P., Grieco, E., Hartmann, J., Henry, M., Houghton, R. A., Jung, M., Kutsch, W. L., Malhi, Y., Mayorga, E., Merbold, L., Murray-Tortarolo, G., Papale, D., Peylin, P., Poulter, B., Ray-

- mond, P. A., Santini, M., Sitch, S., Vaglio Laurin, G., van der Werf, G. R., Williams, C. A., and Scholes, R. J.: A full greenhouse gases budget of Africa: synthesis, uncertainties, and vulnerabilities, *Biogeosciences*, 11, 381–407, doi:10.5194/bg-11-381-2014, 2014.
- 5 Yocom, L. L., Fulé, P. Z., Brown, P. M., Cerano, J., Villanueva-Díaz, J., Falk, D. A., and Cornejo-Oviedo, E.: El Niño–Southern Oscillation effect on a fire regime in northeastern Mexico has changed over time, *Ecology*, 91, 1660–1671, doi:10.1890/09-0845.1, 2010.

**BGD**

12, 12501–12541, 2015

**The carbon cycle in Mexico**

G. Murray-Tortarolo et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

**Table 1.** Different estimates for the land C-flux of the country. A negative sign indicates a source to the atmosphere and a positive sign indicates a sink.

| Land C Flux estimates |           |                              |   |
|-----------------------|-----------|------------------------------|---|
| Author(s)             | Years     | Method                       | Estimate (total)<br>TgCyr <sup>-1</sup> |
| Masera et al. (1997)  | 1985–1987 | Changes in vegetation cover  | –52.6                                   |
| Cairns et al. (2000)  | 1977–1992 | Changes in vegetation cover* | –18.6                                   |
| De Jong et al. (2010) | 1993–2002 | Inventory-based              | –18.4                                   |
| Haynes et al. (2011)  | 1993–2002 | Inventory-based              | –18.4                                   |
| Haynes et al. (2011)  | 2000–2006 | Forward models               | 29.0                                    |
| Haynes et al. (2011)  | 2000–2006 | Inverse models               | 8.7                                     |
| This work             | 1990–2009 | DGVMs                        | 31.4                                    |
|                       |           | Atmospheric Inversions       | 21.4                                    |
|                       |           | LUC-only                     | –19.5                                   |
| This work             | 1901–2009 | DGVMs                        | 12.1                                    |

\* This estimate only accounts for part of the South of Mexico.

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

**Table 2.** Mean GPP, total area and total GPP by land cover type for the period 2000–2005.

| Gross Primary Productivity for Mexico (2000–2005) |   |  |                              |
|---|---|--|------------------------------|
| Land Cover type                                   | Mean<br>kgCm <sup>-2</sup> yr <sup>-1</sup> | Area<br>10 <sup>9</sup> m <sup>2</sup> | Total<br>TgCyr <sup>-1</sup> |
| Broadleaf evergreen forest                        | 2.2 ± 0.23                                  | 257                                    | 553 ± 264                    |
| Broadleaf deciduous forest                        | 1.2 ± 0.16                                  | 438                                    | 519 ± 356                    |
| Needleleaf evergreen forest                       | 1.4 ± 0.31                                  | 92                                     | 134 ± 34                     |
| Grassland/Shrubland                               | 0.6 ± 0.12                                  | 747                                    | 420 ± 260                    |
| Croplands   | 1.2 ± 0.09                                  | 423                                    | 508 ± 210                    |
| <b>TOTAL</b>                                      |   | <b>1957</b>                            | <b>2137 ± 1023</b>           |

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[I ◀](#)
[▶ I](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[I ◀](#)

[▶ I](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



**Table 3.** Mean ( $\text{kg C m}^{-2}$ ) and total (Tg C) carbon stored in the vegetation and soil in each land cover type for the period 2000–2005.

| TOTAL STORED C<br>Land Cover Type | Vegetation C                 |                      | Soil C                       |                      | Total                        |                      |
|-----------------------------------|------------------------------|----------------------|------------------------------|----------------------|------------------------------|----------------------|
|                                   | Mean<br>$\text{kg C m}^{-2}$ | Sum<br>Tg C          | Mean<br>$\text{kg C m}^{-2}$ | Sum<br>Tg C          | Mean<br>$\text{kg C m}^{-2}$ | Sum<br>Tg C          |
| Broadleaf evergreen forest        | 22.9 ± 0.9                   | 5884 ± 1220          | 12.1 ± 0.4                   | 3100 ± 1167          | 35.0 ± 1.3                   | 8984 ± 2387          |
| Broadleaf deciduous forest        | 12.4 ± 0.5                   | 5431 ± 1319          | 8.9 ± 0.6                    | 3880 ± 1235          | 21.3 ± 1.1                   | 9311 ± 2554          |
| Needleleaf evergreen forest       | 15.1 ± 0.9                   | 1385 ± 575           | 10.9 ± 0.4                   | 1336 ± 586           | 26.0 ± 1.3                   | 2721 ± 1161          |
| Grassland/Shrubland               | 6.0 ± 0.7                    | 4482 ± 1556          | 4.7 ± 0.7                    | 3535 ± 1208          | 10.7 ± 1.4                   | 8017 ± 2764          |
| Cropland                          | 7.5 ± 0.3                    | 3158 ± 1190          | 6.2 ± 0.5                    | 2635 ± 790           | 13.7 ± 0.8                   | 5793 ± 1980          |
| <b>TOTAL</b>                      |                              | <b>20 347 ± 4622</b> |                              | <b>14 159 ± 3861</b> |                              | <b>34 506 ± 7483</b> |

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

⏪

⏩

◀

▶

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



**Table 4.** Land C-flux to the atmosphere (NBP) for the period 1990–2009 by land cover type. For all cases, a positive value indicates a sink and vice versa.

| Land-C Flux for Mexico (1990–2009) |   |                                   |
|------------------------------------|---|-----------------------------------|
| Land Cover type                    | Mean<br>$\text{gC m}^{-2} \text{yr}^{-1}$ | Total<br>$\text{TgC yr}^{-1}$     |
| Broadleaf evergreen forest         | 100.8                                     | 20.6                              |
| Broadleaf deciduous forest         | −42.1                                     | −8.9                              |
| Needleleaf evergreen forest        | 22.2                                      | 1.5                               |
| Grassland/Shrubland                | 55.2                                      | 21.3                              |
| Croplands                          | −52.2                                     | −3.1                              |
| <b>TOTAL</b>                       |   | <b><math>31.4 \pm 18.6</math></b> |

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

**Table 5.** Sensitivity of carbon to climate in four RCPs for the whole country.  $dC$ : change in total stored C,  $dT$ : change in mean land surface temperature,  $\gamma$ : change in the Land-C flux relative to the change in temperature,  $\gamma_0$  land carbon sensitivity to climate in the past. A negative  $\gamma - \gamma_0$  implicates a detrimental effect of climate in the land-C-flux in the future compared to the present.

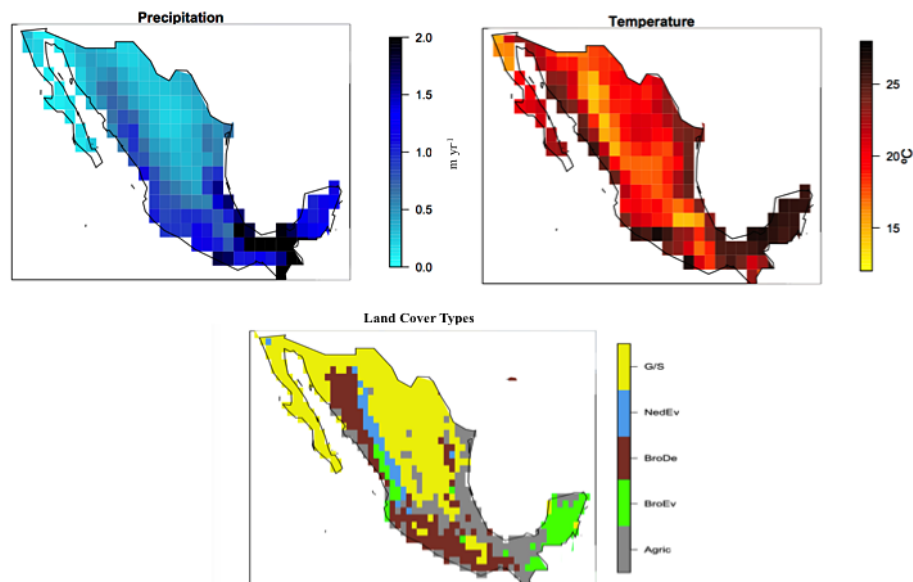
| Period/RCP | $dC$<br>PgC | $dT$<br>° K | $\gamma$<br>PgC°K <sup>-1</sup> | $\gamma_0 - \gamma$<br>PgC°K <sup>-1</sup> |
|------------|-------------|-------------|---------------------------------|--|
| 1901–2000  | 1.2         | 0.88        | 1.36*                           |  |
| RCP2.6     | 3.0         | 2.4         | 1.25                            | −0.11                                      |
| RCP4.5     | 2.1         | 3.6         | 0.58                            | −0.78                                      |
| RCP6.0     | 1.5         | 4.5         | 0.33                            | −1.03                                      |
| RCP8.5     | −0.7        | 6.1         | −0.21                           | −1.57                                      |

\*  $\gamma_0$  Land carbon sensitivity to climate in the past (1901–2005).

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


## The carbon cycle in Mexico

G. Murray-Tortarolo et al.



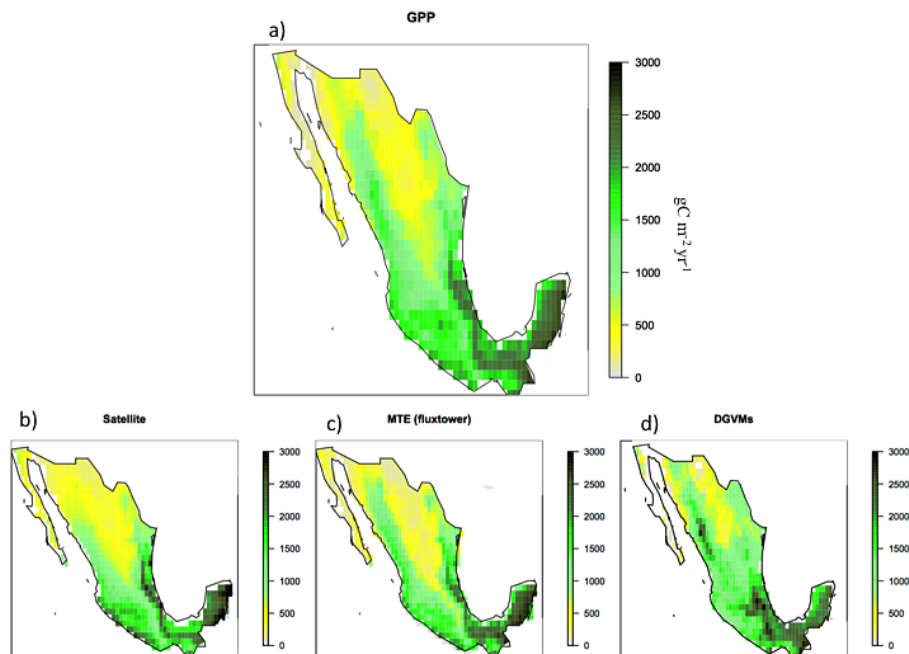
**Figure 1.** Observed precipitation ( $\text{m yr}^{-1}$ ), Temperature ( $^{\circ}\text{C}$ ), and Land Cover Types for Mexico (mean of 2000–2005). Agric: croplands, BroEv: Broadleaf Evergreen Forest, BroDe: Broadleaf Deciduous Forest, NedEv: needleleaf Evergreen Forest, G/S: Grassland/Shrubland.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I ◀](#)[▶ I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)



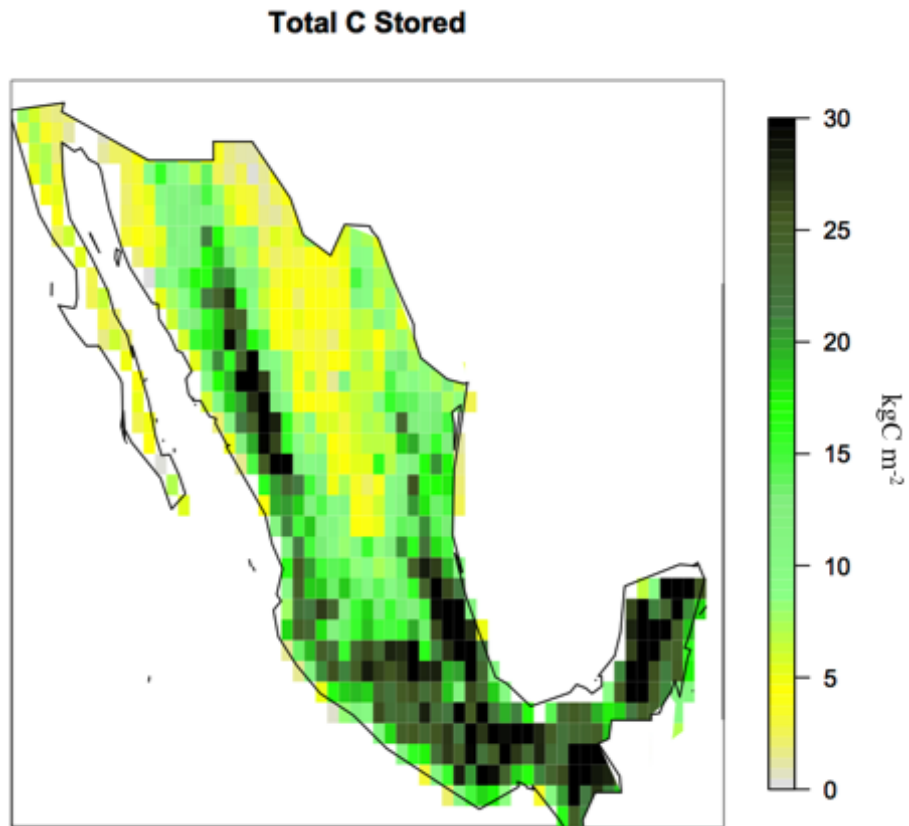
## The carbon cycle in Mexico

G. Murray-Tortarolo et al.



**Figure 2.** Mean GPP ( $\text{gC m}^{-2} \text{yr}^{-1}$ ) for **(a)** ensemble of the three products, **(b–d)** individual products (Satellite, MTE and DGVMs). All maps correspond to the period 2000–2005.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I ◀](#)[▶ I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)



**Figure 3.** Total stored C in soil and vegetation ( $\text{kgC m}^{-2}$ ), ensemble from all products (6) for the period 2000–2005.

## BGD

12, 12501–12541, 2015

### The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

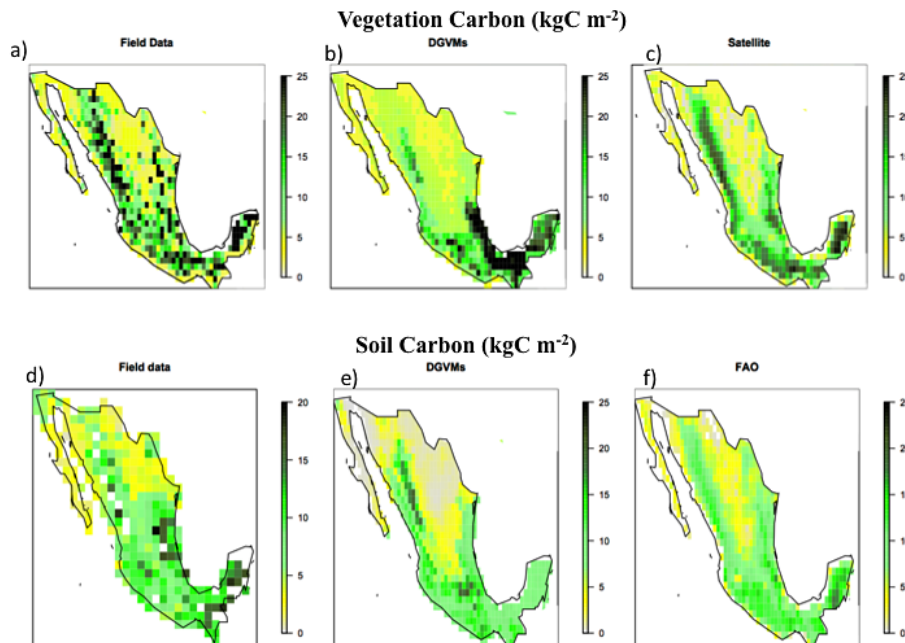
Printer-friendly Version

Interactive Discussion



## The carbon cycle in Mexico

G. Murray-Tortarolo et al.



**Figure 4.** (Top) Vegetation stored carbon for three products: field data, DGVMs and satellite ( $\text{kgC m}^{-2}$ ). (Bottom) Soil stored carbon for three products: field data, DGVMs and FAO estimates based on multiple datasets ( $\text{kgC m}^{-2}$ ). Mean for the time-period 2000–2005.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I ◀](#)[▶ I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

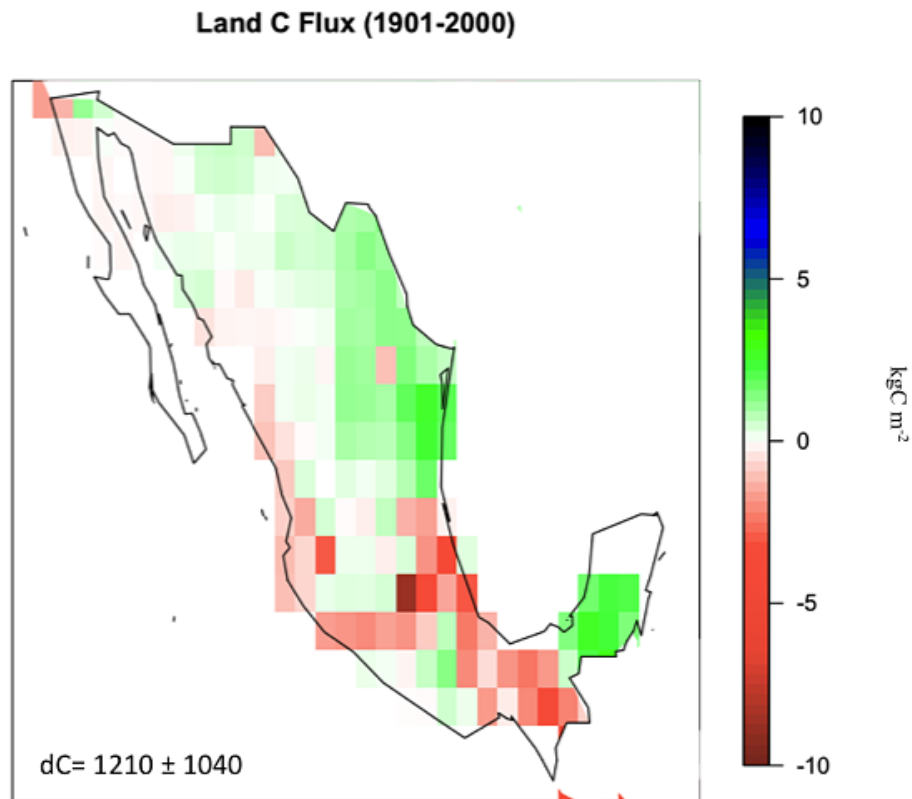


# BGD

12, 12501–12541, 2015

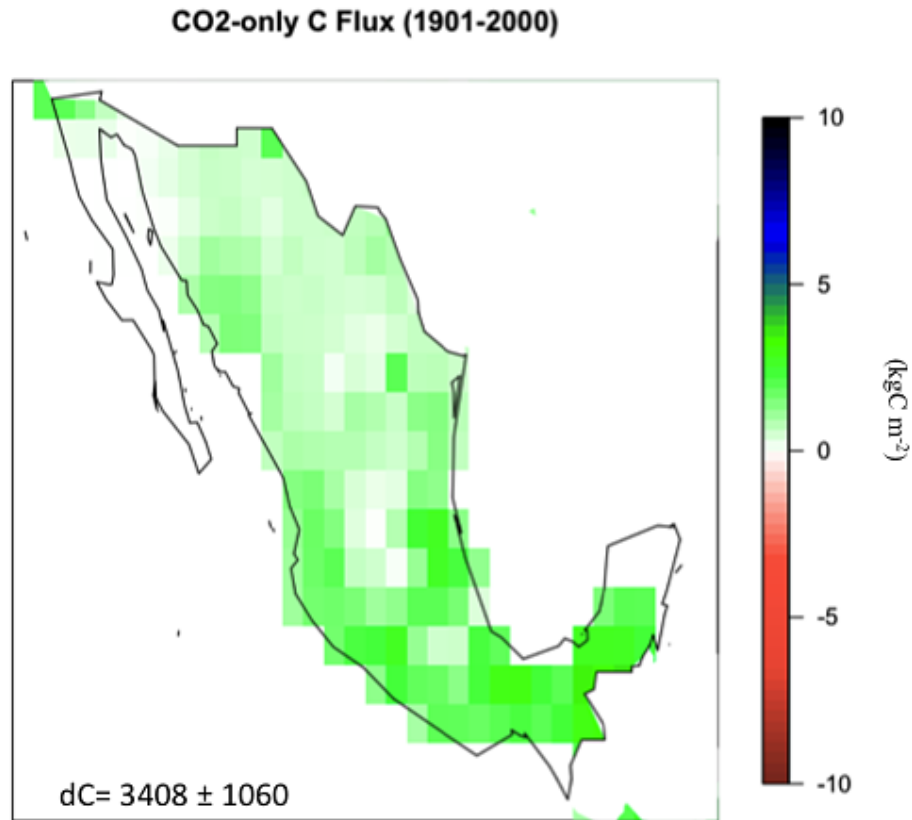
## The carbon cycle in Mexico

G. Murray-Tortarolo et al.



**Figure 6.** Total change in land C during 1901–2000 ( $\text{kgC m}^{-2}$ ). A positive sign indicates C gain.  $dC$  = total change in stored C ( $\text{TgC}$ ).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)



**Figure 7.** Change in total stored C by the effect of CO<sub>2</sub>-only over the period 1901–2000 (kgC m<sup>-2</sup>). A positive sign indicates C gain. dC = total change in stored C (TgC).

## BGD

12, 12501–12541, 2015

### The carbon cycle in Mexico

G. Murray-Tortarolo et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

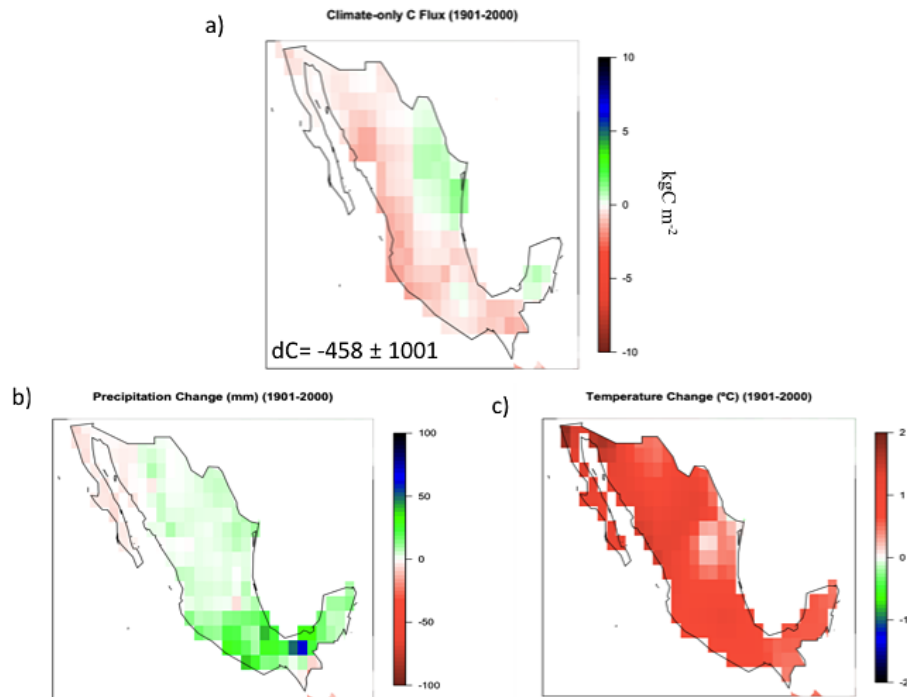
Printer-friendly Version

Interactive Discussion



## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

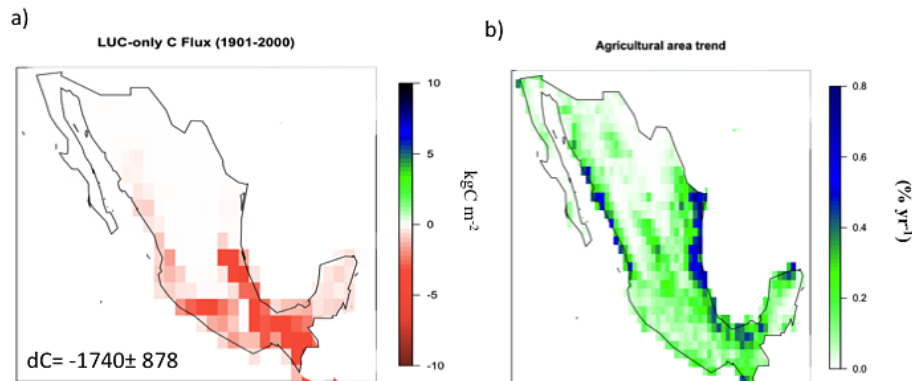


**Figure 8.** (top) Change in stored C by the effect of climate-only for the period 1901–2000 ( $\text{kgC m}^{-2}$ ). A positive sign indicates C gain.  $dC$  = total change in stored C ( $\text{TgC}$ ). (Bottom) change in climate (precipitation and temperature) for the same time-period.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

## The carbon cycle in Mexico

G. Murray-Tortarolo et al.

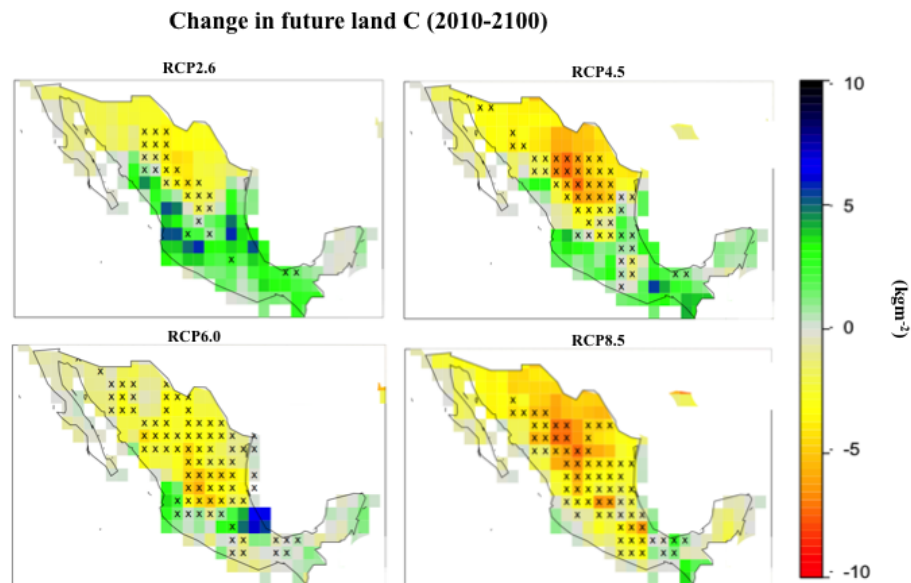


**Figure 9.** (a) Change in stored C by the effect of LUC-only for the period 1901–2000 ( $\text{kg C m}^{-2}$ ). A positive sign indicates C gain.  $dC$  = total change in stored C (Tg C). (b) Agricultural area change for the same time period.



## The carbon cycle in Mexico

G. Murray-Tortarolo et al.



**Figure 10.** Gridded future change in total stored C for four RCPs for the period 2010–2100 ( $\text{kg C m}^{-2}$ ). The stippling represents areas where  $> 66\%$  of the ESMS models agree on the sign of the flux.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I ◀](#)[▶ I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)