The Carbon Cycle in Mexico: past, present and future of C stocks and fluxes.

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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 ± 1023 TgC yr^{-1} and a total C stock of 34,506 ± 7483 TgC, with 20,347 ± 4622 PgC in vegetation and 14,159 ± 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 TgC yr^{-1}) and that C accumulation over the last century amounted to 1210 ±1040 TgC. We attributed this sink to the CO_2 fertilization effect on GPP, which led to an increase of 3408 ± 1060 TgC, while both climate and land use reduced the country C stocks by -458 ± 1001 and -1740 ± 878 TgC, respectively. Under different future scenarios the C sink will likely continue over the 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 drylands (e.g. grasslands and shrublands) and the impact of climate change on the mean residence time of soil C in tropical ecosystems.

1 Introduction

The global carbon (C) cycle has been altered by anthropogenic activity with the release of 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., 2014). In the latter, the atmospheric CO_2 increase has led to greater gross primary productivity (GPP), as a result of the fertilization effect on the plants' photosynthetic 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).

The interaction among climatic forcing, atmospheric CO_2 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 season in the Northern Hemisphere and the CO_2 fertilization effect, to C sources from drought-induced tropical forest dieback and temperature-induced enhancements in mid-latitude soil respiration (Friedlingstein et al., 2006; Cox et al., 2000; Friedlingstein et al., 2013).

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_2 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 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).

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 more recently 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 (e.g. LULCC), they place Mexico as a source of C (Pacala et al. 2007), which may be an incomplete 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, such as the effect of CO_2 fertilization on GPP and the impacts of climate change or ommiting soil C dynamics,. In contrast, results from global models and atmospheric CO_2 inversions place the country as a C sink (Hayes et al., 2012; King et al., 2012), but they lack a representation of the driving mechanisms of change. Hence, a study based on multiple sources of evidence, that takes into account the g of the C balance in multiple various driving processes of the land C in Mexico is needed is needed, particularly 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). Mexico represents a unique opportunity to compare the different approaches for several reasons. The country includes four main mountain ranges, three of them along the Gulf of Mexico and the Pacific coasts and a volcanic belt, which cuts across the middle of the country from east to west (Challenger 1998). It also comprises a large high central plateau, smaller scale depressions, large alluvial plains and two topographically contrasting peninsulas. Thus, the topography in Mexico is among the most heterogeneous in the world. The funnel shape of the country (wide in the north and narrow to the south), along with the mountain ranges, the prevailing winds and the oscillations of the high pressure subtropical belt contribute to a very high diversity of climates, with four of the five major climate types described by Koeppen represented in the country (Challenger 1998; Espinosa et al. 2008). With few exceptions, most of the country shows a summer precipitation pattern. Climate types vary from very dry in the north to sub-humid and very humid in the south, which reflect a high variety of land cover types (Figure 1, supplementary 1) and soils, as well. .The high environmental heterogeneity also allows that multiple processes that drive the C cycle globally can be identified at an intermediate 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_2, precipitation, temperature and land use?
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

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 climaic drivers, were also used to force the Dynamic Global Vegetation Models (DGVMs) (Figure 1).

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 (Figure 1). Ten categories were present in Mexico (Sup. 1). In order to simplify the analysis due to the spatial scale involved, we aggregated the vegetation into five broad categories: broadleaf evergreen forest, broadleaf deciduous forest, needleleaf evergreen forest, grassland/shrubland and croplands (Figure 1d).

Past Land Use Land Cover Change (LULCC): We used data for the agricultural fraction from Hyde et al. (2013), which was also used to force the DGVMs. LULCC emissions were obtained from the DGVMs. These datasets use a mixture of process-based and FAO country statistics to calculate the transformation of forest, agricultural areas, pastures and natural grasslands to other categories.

DGVMs: We used vegetation C, soil C, heterotrophic respiration (Rh), GPP and the net biome productivity (NBP) from an ensemble of 9 DGVMs (Sup. 2) from the TRENDY v2 project (Le Quéré et al., 2014; Sitch et al., 2015). All models were forced with the same input data and spin-up protocol. To attribute the relevant driver (CO_2 fertilization, climate or LULCC) 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:

- Simmulation 1 (S1): rising CO_2 through the century with constant climate and no LULCC; hence the CO_2 effect only.
- Simmulation 2 (S2): rising CO_2 through the century with real climate and no LULCC; hence the CO_2 + climate effect.
- Simulation (S3): all drivers included (rising CO_2, observed climate and land use change).

The attribution of the drivers was calculated as: S1: CO_2 effect only; S2 minus S1: climate effect only; S3 minus 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 (Sup. 2) (Taylor et al., 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., 2011, 2009). We separated GPP from NEE with the methodology from Reichstein et al. (2012). Although the MTE has been widely used, it is important to note that there are only a few flux towers in Mexico and only four of those are included into the algorithm. In recent years, more data have been incorporated to FLUXNET and results may vary when these are considered.

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., 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.

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 (Sup. 3). For soil C, we used the topsoil C concentrations (0-20 cm depth) from 4000 sampling sites (Segura-Castruita et al., 2005) 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_2 posterior flux from atmospheric CO_2 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 (5x5 degrees) we only provide the national average and not the gridded means.

All datasets were re-gridded to a common 1°x1° grid.

2.2 *Data limitations*

Although we tried to use datasets that represent the state-of-the-art to our knowledge, the satellite retrievals, models (both DGVMs and ESMs), atmospheric inversions, flux tower data and field inventories contain different caveats that must be brought forward. We have summarized the advantages and limitations of each dataset in Table 2. This implies that some results could potentially change in the light of new and better constrained data in the future. In addition, we provide the link for all freely available datasets (Table S4).

2.3 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 interanual 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_2, S2 minus S1: climate and S3 minus 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 the 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 ± 1023 TgCyr^{-1} for the period 2000-2005 (Table 3). 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 ± 0.2 kgC m^{-2} yr^{-1}) and the lowest in the grasslands and shrublands (0.6 ± 0.1 kgC m^{-2} yr^{-1}; Table 3). 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 north-central region (Figure 2a). The three different products (i.e. satellite, flux towers (MTE) and DGVMs) displayed similar GPP distributions (Figure 2b, c, 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 Sup. 4).

Our estimate for the total C stock in Mexico was 34,506 ± 7843 TgC (Table 4), of which 20,347 ± 4,622 TgC (59%) was stored in the vegetation and 14,159 ± 3,861 TgC (41%) was stored in the soil (Table 4). Similar to GPP, the forested areas accounted for 60% of the total stored C, with 40% in grasslands/shrublands and croplands. The broadleaf evergreen forest showed the highest C stock per unit area in the vegetation (22.9 kgC m^{-2}) and soil (12.1 kgC m^{-2}), whereas the grassland/shrubland the smallest (6.0 and 4.7 kgC m^{-2}, respectively) (Table 4, Figure 3, Sup. 5).

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 (Figure 4; Sup. 5). 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 (Figure 4a, b, c; Sup. 5). 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 (Figure 4d, e, f; Sup. 5). 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 ± 18.6 TgC yr^{-1} (Table 5). 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 (Figure 5). The atmospheric inversions also displayed a positive value for the country with a value of 21.4 ± 12.7 TgC yr^{-1} (Table 1).

3.2 Past

The model results with the DGVMs showed that Mexico has been a C sink over the last century, during which time there was an overall gain of 1210 ± 1040 TgC. 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 (Figure 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 CO_2, b) long-term climate variability and change, and c) land use change (LULCC)

a) The effect of elevated CO_2 led to enhanced C storage across the whole of Mexico (3408 ±1060 TgC), with the highest C gain occurring over the forested regions (Figure 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 ± 1001 TgC. Climate led to a decrease in C storage over most areas of the country, with the exception of the Northeast and the Yucatan Peninsula (Figure 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 (Figure 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 (Rh) than GPP, thus leading to a decrease in the mean residence time of soil C (Suppl. 8).

c) The negative effect of LULCL on total stored C (-1740 ± 878 TgC) occurred mostly over the South of the country and along the Gulf of Mexico and Pacific coasts (Figure 9a). Carbon emissions from LULCC were apparently related to the distribution of changes in the agricultural fraction over the same time period (Figure 9b). In addition, consistent with historic-estimates and policies for LULCC the C emissions from LULCC were higher over the period 1950-1960, with a steep decline aftwerards (Figure S6).

Thus, when the three drivers were considered simultaneously, we found that the fertilization effect of CO_2 on GPP during those 100 years was greater than the climate and LULCC 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 TgC in RCP2.6, to 2150 TgC in RCP4.5, to 1578 TgC in RCP6.0 and -762 TgC 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 (Figure 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 the sign of changes in other parts of the country, especially over the Yucatan Peninsula (Figure 10).

Under all RCPs, precipitation decreased (Sup 7) and temperature increased over the 21st century in the whole country (Sup 6), 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 TgC yr^{-1}) 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. There are quite recent estimates of GPP at the site and regional levels determined from flux tower measurements of tropical dry forest in the northern range of its distribution (Verduzco et al. 2015; see Fig. S1) and from fPAR as a proxy of GPP for the Baja California Peninsula (Reimer et al. 2015). Tropical dry forest GPP was estimated at 831-1099 gC m^2 yr^{-1} (Verduzco et al. 2015), which is comparable to our mean estimate of 1200 gC m^2 yr^{-1} for broadleaf deciduous forest and to the range of GPP values estimated for that NW region of the country. Also, GPP estimates for the Baja California Peninsula (700-960 gC m^2 yr^{-1}; Reimer et al. 2015) are comparable to the range of GPP values estimated in the peninsula from our study, especially to the satellite derived estimates.

There are a few site estimates of net primary productivity (NPP) in Mexican ecosystems, since most studies use litterfall as a proxy for NPP (see for example the literature revision by Escobar et al., 2008). We can compare them by assuming NPP to be 0.5 of GPP (Farquhar and Sharkey, 1982). Among those, Martínez-Yrízar et al. (1996) estimated an aboveground NPP of 0.6-0.8 kgC m^{-2} yr^{-1} in the tropical dry forest of Chamela, Mexico, similar to our findings of 0.6 ± 0.2 kgC m^{-2} yr^{-1} for broadleaf deciduous forest. García-Moya and Montanés-Castro (1992) estimated NPP in a semiarid grassland in central Mexico between 0.3 and 0.6 kgC m^{-2} yr^{-1}, similar to our finding of 0.3 ± 0.2 kgC$m^{-2}yr^{-1}$ for grasslands/shrublands. Such overall agreement of GPP and NPP 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 ± 7483 TgC, estimated with different products (field data, DGVMS and satellite), differs from the 24000 TgC 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 33000 TgC (Pacala et al., 2007), which is similar to our value. Interestingly, the baseline estimate of 19,000 TgC for the total C stock in forests by Masera et al. (2001) compares to our 20,347 TgC for forest vegetation. This means that the highest source of discrepancy across estimates concerns soil C, with our estimate of 14,159 TgC almost three times higher than Masera et al. (2001) of 5,000 TgC.

Total aboveground biomass C for Mexico represents ~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 ± 0.9 kgC m^{-2} in the broadleaf evergreen forest is similar to the mean value of 20.5 kgC m^{-2} from Masera et al. (2001) for the same land cover, with a different modelling approach, and even to the 19.5 kgC m^{-2} reported for the Los Tuxtlas region from field measurements (Hughes et al., 1999). Also, our estimate for the needleaf evergreen forest of 15.1 ± 0.9 kgC m^{-2} compares to the mean temperate forest C stock of 12.6 kgCm^{-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 kgC 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 ± 0.7 kgC m^{-2}, while field studies (e.g. Búrquez et al., 2010; Navar et al., 2014) estimated 1.6-4.4 $kgCm^{-2}$ in the deserts over the North of the country. Broadleaf deciduous forest C is more difficult to compare to field-based estimates, since for the purposes of our study this land cover type combined oak and tropical dry forest.

Total soil C storage in the country is ~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. Nevertheless, our estimate for the 20 cm soil depth of 14.2 Pg C for the country compares to the 15.3 PgC calculated by de Jong et al. (2010) in a study of the impact of LULCC on C stocks in Mexico. A more recent estimate based on extensive field measurements of soil organic C for the top 30 cm of soil (Cruz-Gaistardo and Paz-Pellat 2014) provides 9.2 Pg C for the country. This implies, that if soil inorganic C is accounted for, soil C stocks would be higher and likely similar to the estimates above. In fact, maximum soil C stocks occur in the Yucatan Peninsula, with soils rich in calcium carbonate, and in the southern edge of the eastern Sierra (Etchevers et al. 2014), which is consistent with the geographical distribution of soil C depicted in our study, especially as estimated from the field data set.

If we compare the estimates among products and consider the high correlations among them, 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. This is particularly important, because in spite of the fact that drylands only represent 25% of the GPP and C stocks, they account for nearly half the area of the country. This means that error propagation in this particular land cover may lead to changes in the estimations of the C cycle.

Our results showed that Mexico was a C sink over recent decades (1990-2009), gaining 31.4 ± 18.6 TgC yr^{-1}. This is similar to recent calculations by Hayes et al. (2012) using inverse (+8.7 TgC yr^{-1}) and forward models (29.0 TgC yr^{-1}) and to the result from atmospheric CO_2 inversions (21.4 TgC yr^{-1}). Also, recent flux tower estimates of net ecosystem production (NEP) in tropical dry forest at the site scale (Verduzco et al. 2015) have shown a predominant local C sink. Our results are in disagreement with 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 based on changes in vegetation stocks as fixed covers, which do not take into account other C fluxes and important ecosystem processes such as the effect of CO_2 fertilization and the impact of climatic variables. In other words, those estimates are closer to the LULCC 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. The definition of Mexico as a C sink is consistent with the overall role of North America (USA and Canada; Hayes et al. 2012) and would place the North American C sink at approximately 377 TgC yr^{-1}.

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 1,210 ± 1040 TgC in total. Such increment was driven by the CO_2 fertilization effect on vegetation (3408 ± 1060 $TgCyr^{-1}$), which enhanced GPP and subsequently biomass and possibly soil C to different degrees. Both the climate (-458 ± 1001 $TgCyr^{-1}$) and the land use (-1740 ± 878 $TgCyr^{-1}$) 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., 2014). 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 LULCC policies.

The loss of C over NE Mexico is likely driven by climate. A long-term drought identified over this region 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 (Murray-Tortarolo et al., submitted). However, the overall negative effect of climate on C storage in other regions is likely linked to its impact on soil C mean residence time (MRT; Sup. 8). 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 (Carvalhais 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 LULCC. LULCC accounted for a loss of 1740 TgC 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 TgC yr^{-1} based on changes only in vegetation stocks for their baseline year in the 1980s. More comprehensive analyses including C emissions from the soil C, estimated net emissions of 23.7 TgC yr^{-1} from LULCC 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 LULCC 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 LULCC during the period 1901-2009. This was due to the fact that the impacts of LULCC 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 LULCC. However, there is no evidence from field measurements to support or disprove this claim. While there are studies on the consequences of LULCC 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 it a fundamental missing piece in our understanding of the C cycle at local to regional scales. This is particularly important because the DGVMs we used 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.

4.2 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_2 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 6). 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_2 fertilization effect is likely counterbalanced not only by climate, but also by the effect of limiting nutrients on C uptake –a process 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.

4.3 Limitations and considerations

Although all our calculations are based on state-of-the-art datasets and models, several limitations must be taken into account. Firstly, our study only comprises data that was either freely available (or will be soon) or published. Several government agencies in Mexico (e.g. CONABIO, CONAFOR and INEGI) have concentrated in producing new, more comprehensive and updated datasets than those used in this study. This means that our results should be revised in the light of newer data, in particular with the inclusion of additional time-slices in the field data which can facilitate the comparison of modelled and observed changes in the C stocks.

Secondly, most of the datasets we used are improved constantly (e.g. models include additional processes and flux tower data is steadily increasing), therefore, our evaluation of the C cycle in Mexico should improve as as these products evolve. Also, and particularly important, models will include additional processes such as fire (although some of the models used already included a fire module), nutrient limitations, a more complex representation of agriculture and finer-scale processes (such as landslides or floods), to mention a few.

Finally, while we tried to tackle the large heterogeneity of the country, it is quite clear that the spatial resolution used cannot provide a detailed analysis. Thus, our results should be used with caution when comparing them with site-level data and are better fit for country-level comparisons. In this sense, additional local/regional modeling studies with appropriate forcing data are a fundamental missing link to compare the different approaches to evaluate the C cycle over complex and dynamic terrains.

5 Final remarks

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 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_2, climate and LULCC) 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 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 has been a C sink. Our results suggest this has resulted mainly from the positive effect of CO_2 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 drylands (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.

Authors Contributions

GMT, PF, SS and VJJ designed, executed and wrote the paper. FMF, AA and YL provided and analyzed data. The rest of the authors provided the DGVMs data and provided critical comments on the manuscript. ? ~~helped writting the paper.~~

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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 a sink.

Land C Flux estimates			
Author(s)	**Years**	**Method**	**Estimate (total) TgC yr^{-1}**
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 Atmospheric Inversions LULCC-only	31.4 21.4 -19.5
This work	1901-2009	DGVMs	12.1

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

Table 2: Advantages and limitations of the different datasets used.

Dataset	Advantages	Limitations
Satellite (biomass and GPP)	• High-resolution • Includes all driving mechanisms	• Not measu FPAR or V • Saturation • Need for present.
Flux towers (MTE) GPP and NBP	• In-situ measurements • Includes all driving mechanisms	• Few sites i rapidly. • Uses clim (added un • Small inter
DGVMs (GPP, biomass, soil C, NBP	• Longer time period of all datasets (full century) • Allow testing of individual driving factors to attribute the change in NBP over time.	• Do not ac (e.g. some only few ir • Broad unc to drought
Biomass field data (National inventory)	• In-situ measurements • “Land-truth” data	• Limited to • Different country • Point-data
Soil field data (road data)	• In-situ measurements • “Land-truth” data	• Limited to • Different country. • Only accou soil. • Point-data
Harmonized Soil Dataset (FAO)	• Standardized global product used in different fields. •	• Broad app type. • Only accou soil.
Earth-System-Models	• Only approach for future changes in land C. • Commonly used in policy making (IPCC).	• High unce agreement most of the • Do not ac changes in
Atmospheric CO_2 inversions	• Includes all driving mechanisms • Top-down Approach	• Broad-Scal analysis.

Table 3: 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 kgC m^{-2} yr^{-1}	Area 10^9 m^2	Total TgC yr^{-1}
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
TOTAL		1957	**2137 ± 1023**

Table 4: Mean (kgC m^{-2}) and total (TgC) carbon stored in the vegetation and soil in each land cover type for the period 2000-2005.

TOTAL STORED C	**Vegetation C**		**Soil C**		**Total**	
Land Cover Type	Mean kgC m^{-2}	Sum TgC	Mean kgC m^{-2}	Sum TgC	Mean kgC m^{-2}	Sum TgC
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 ± 0l8	5793 ± 1980
TOTAL		20,347 ± 4622		14,159 ± 3861		34,506 ± 7483

Table 5: 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 gC m^{-2} yr^{-1}	Total 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
TOTAL		**31.4 ± 18.6**

Table 6: 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, **γ:** Change in the Land-C flux relative to the change in temperature, γo land carbon sensitivity to climate in the past. A negative **γ-γo** implicates a detrimental effect of climate in the land-C-flux in the future compared to the present.

Period/RCP	**dC**	**dT**	**γ**	**γo-γ**
	PgC	ºK	PgC/ºK	PgC/ºK
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

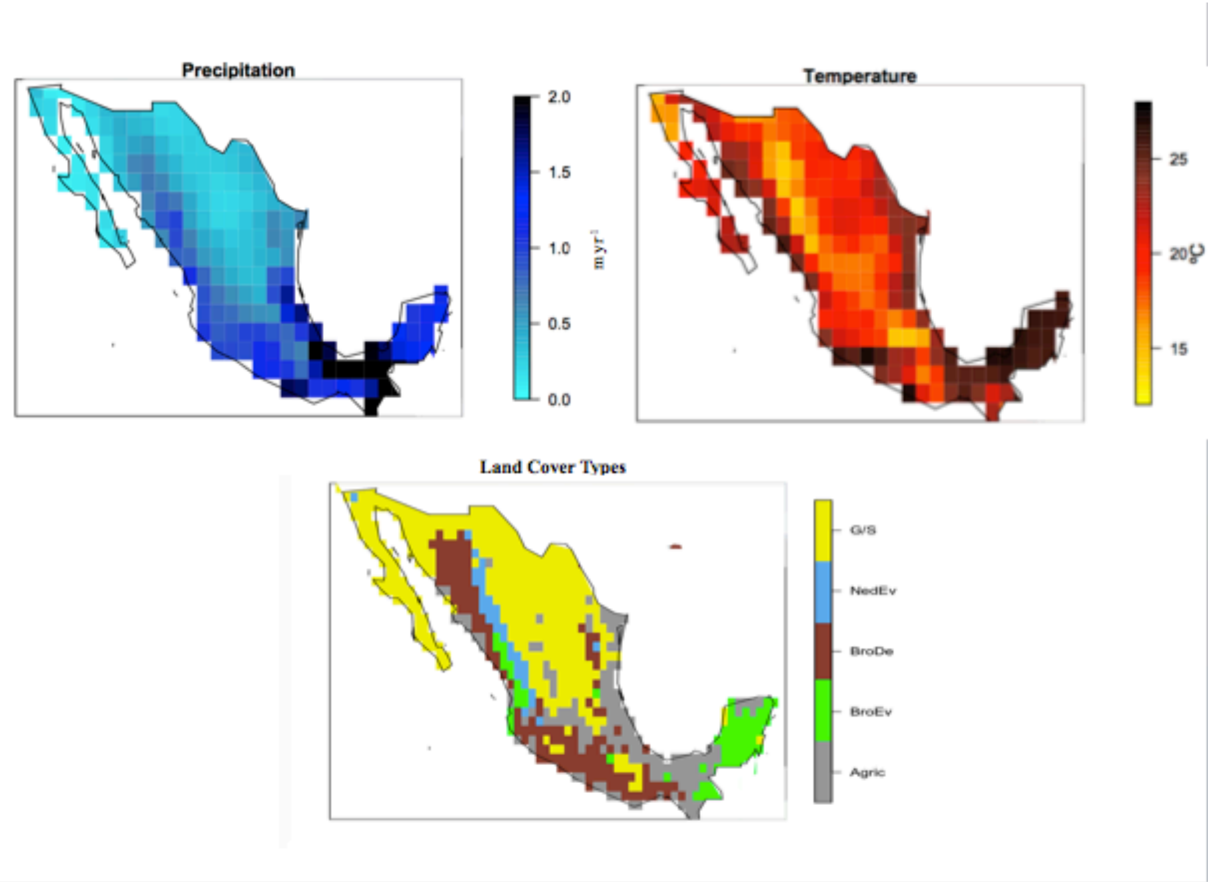

Figure 1. Observed precipitation (m yr^{-1}), temperature (ºC), and land cover types for Mexico (mean of 2000-2005). Agric: Croplands, BroEv: Broadleaf Evergreen Forest, BroDe: Broadleaf Deciduous Forest, NedEv: Needleleaf Evergreen Forest, G/S: Grassland/Shrubland.

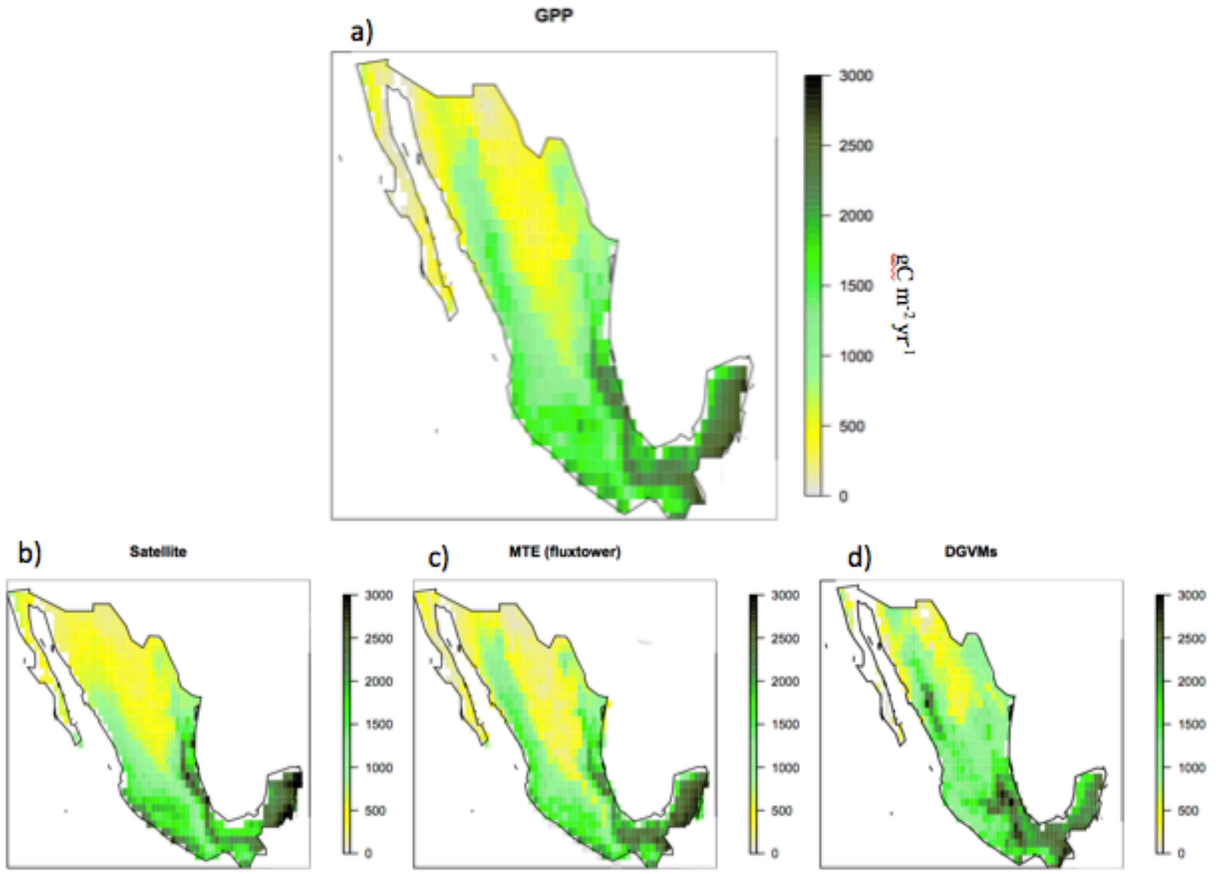

Figure 2: Mean GPP (gC m^{-2} yr^{-1}) for a) ensemble of the three products, b-d) individual products (Satellite, MTE and DGVMs). All maps correspond to the period 2000-2005.

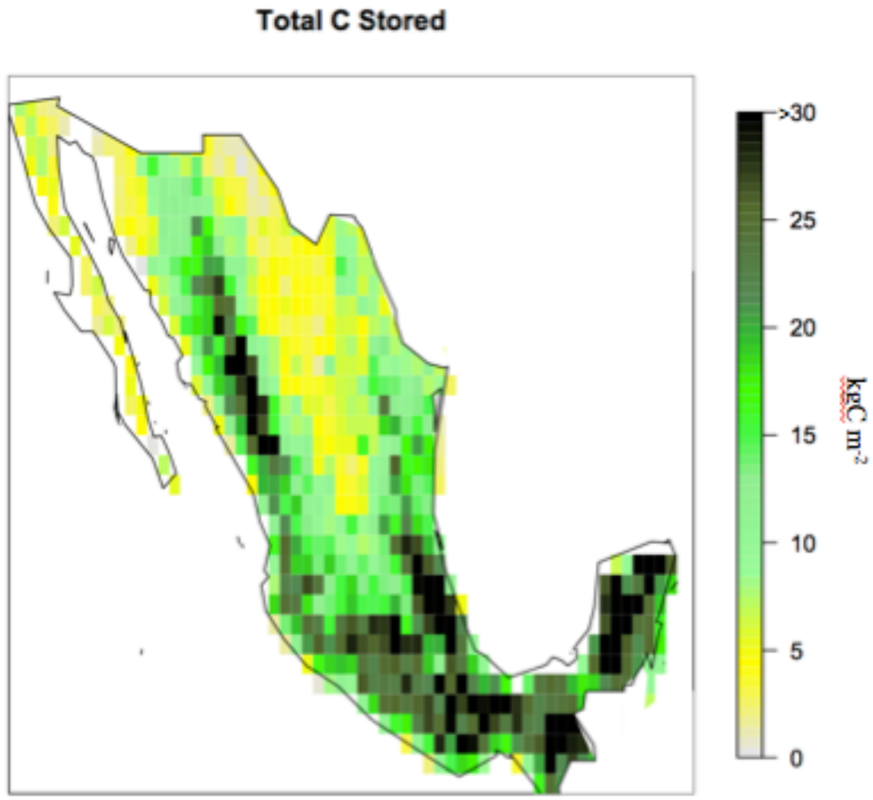

Figure 3: Total stored C in soil and vegetation (kgC m^{-2}), ensemble from all products (6) for the period 2000-2005. OJO: favor de quitarle “stored” al título de la figura.

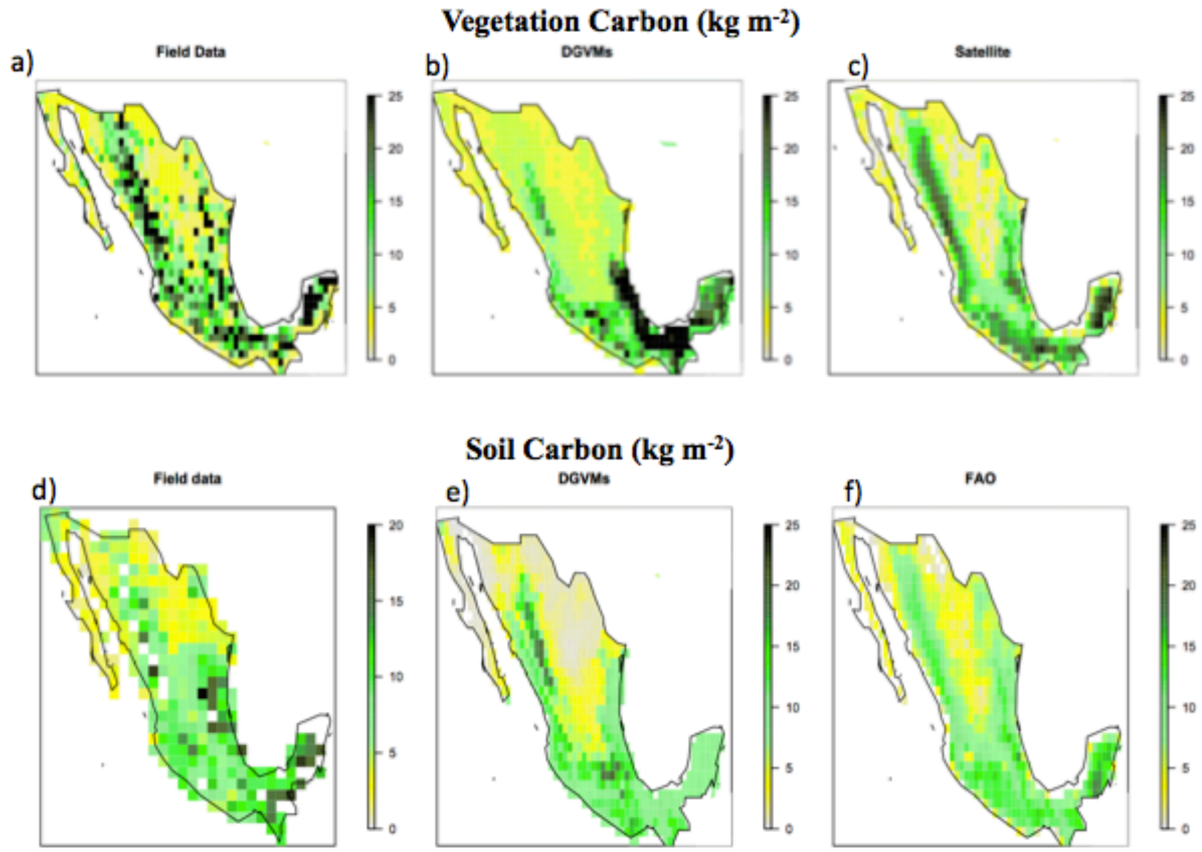

Figure 4: Top) Vegetation stored carbon for three products: field data, DGVMs and satellite (kgC m^{-2}). Bottom) Soil stored carbon for three products: field data, DGVMs and FAO estimates based on multiple datasets (kgC m^{-2}). Mean for the time-period 2000-2005.

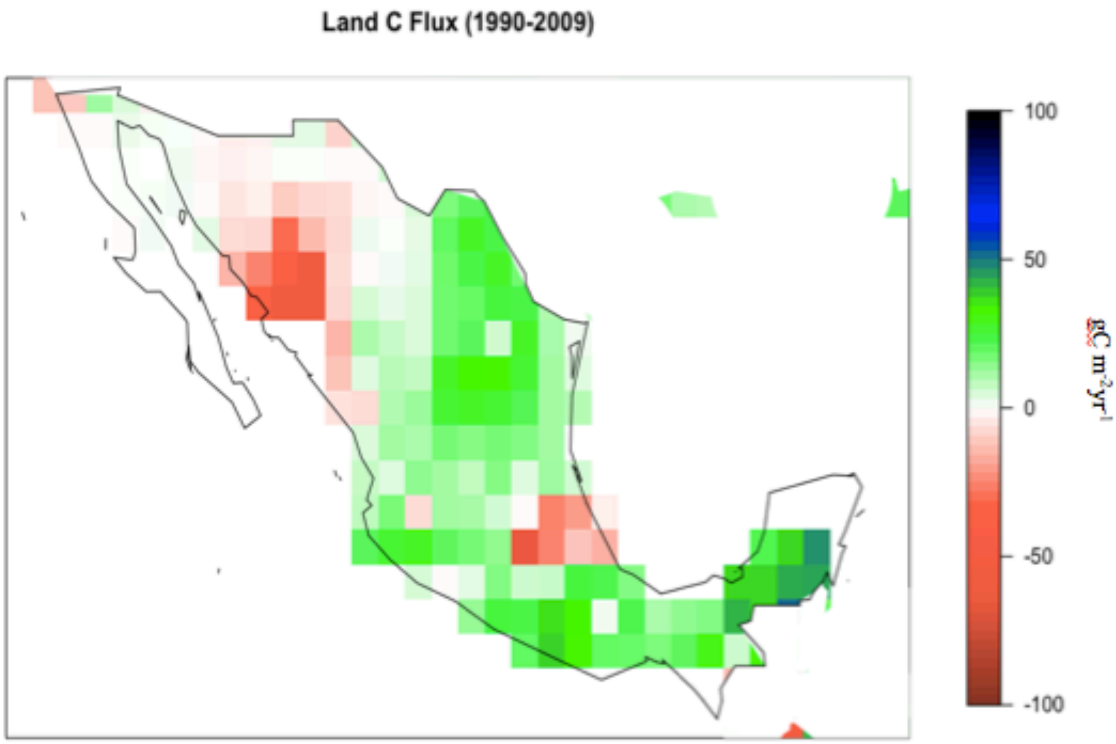

Figure 5: Land-C flux (NBP) for the period 1990-2009 (gC m^{-2} yr^{-1}). A positive value indicates a C sink and vice versa.

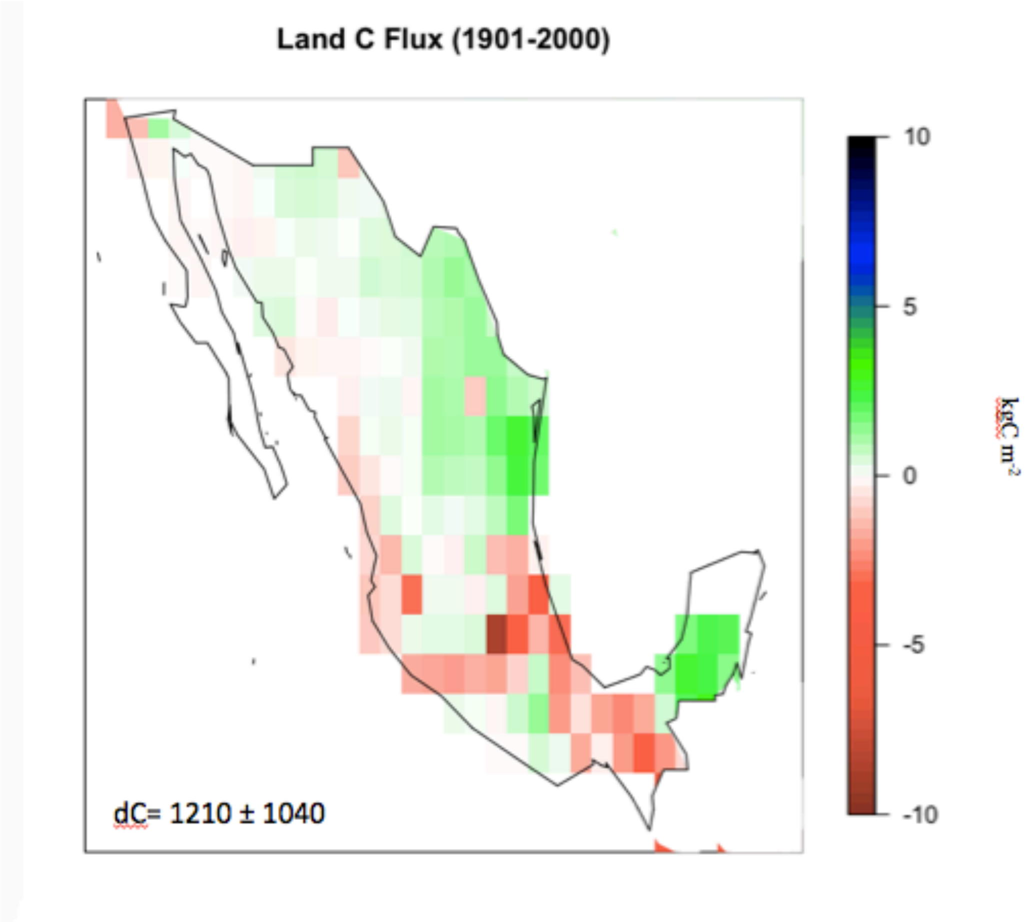

Figure 6: Total change in land C during 1901-2000 (kgC m^{-2}). A positive sign indicates C gain. dC= total change in stored C (TgC).

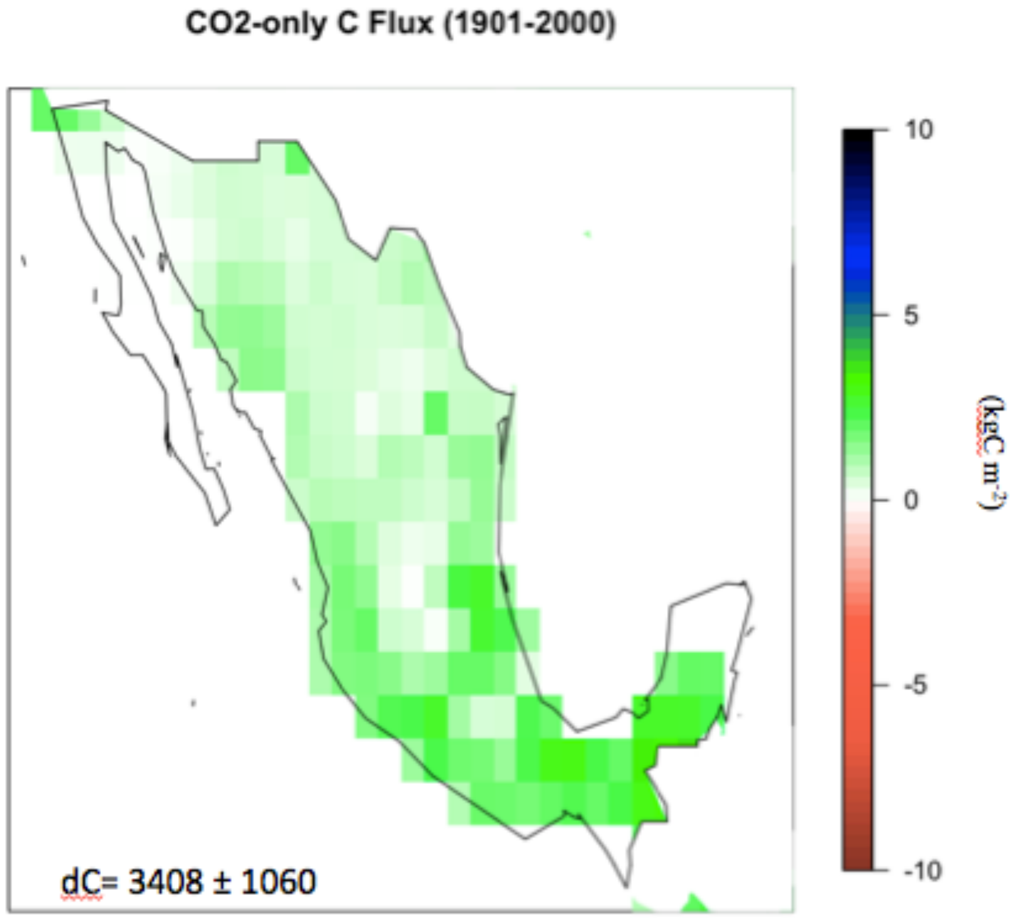

Figure 7: Change in total stored C by the effect of CO_2-only over the period 1901-2000 (kgC m^{-2}). A positive sign indicates C gain. dC= total change in stored C (TgC).

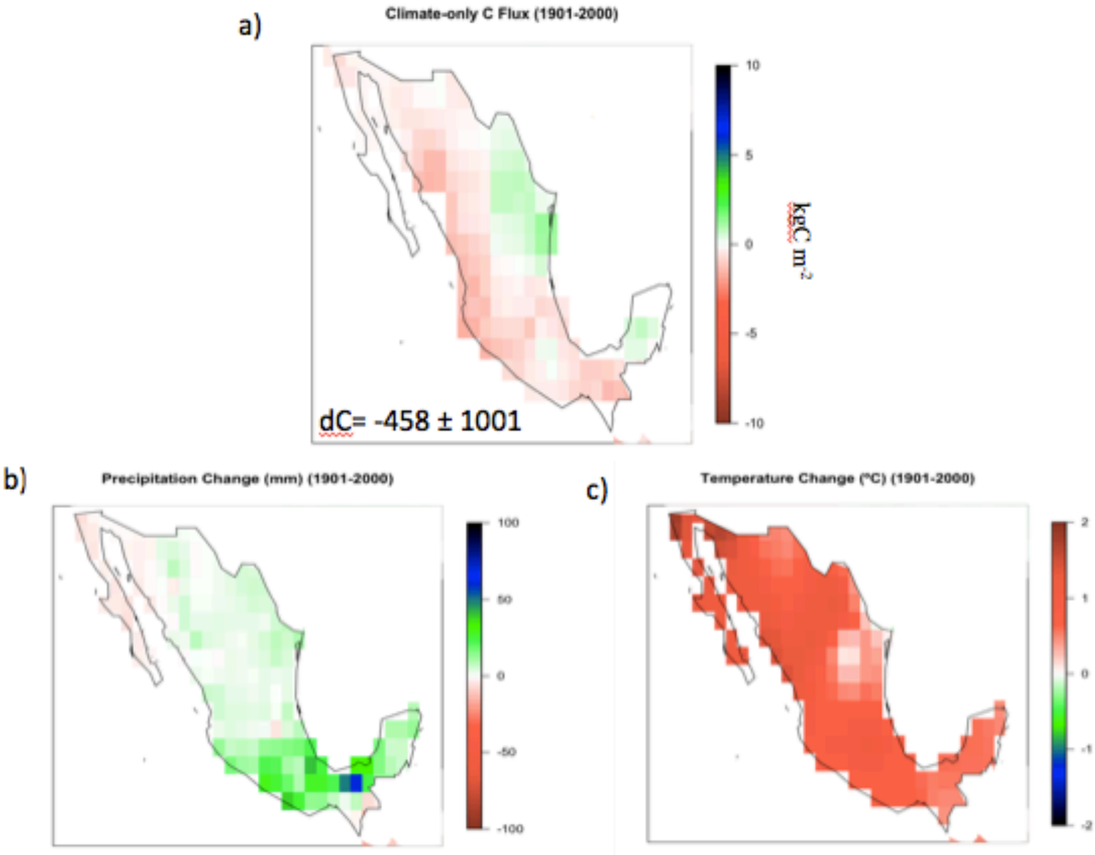

Figure 8: top) Change in stored C by the effect of climate-only for the period 1901-2000 (kgC m^{-2}). A positive sign indicates C gain. dC= total change in stored C (TgC). Bottom) change in climate (precipitation and temperature) for the same time-period.

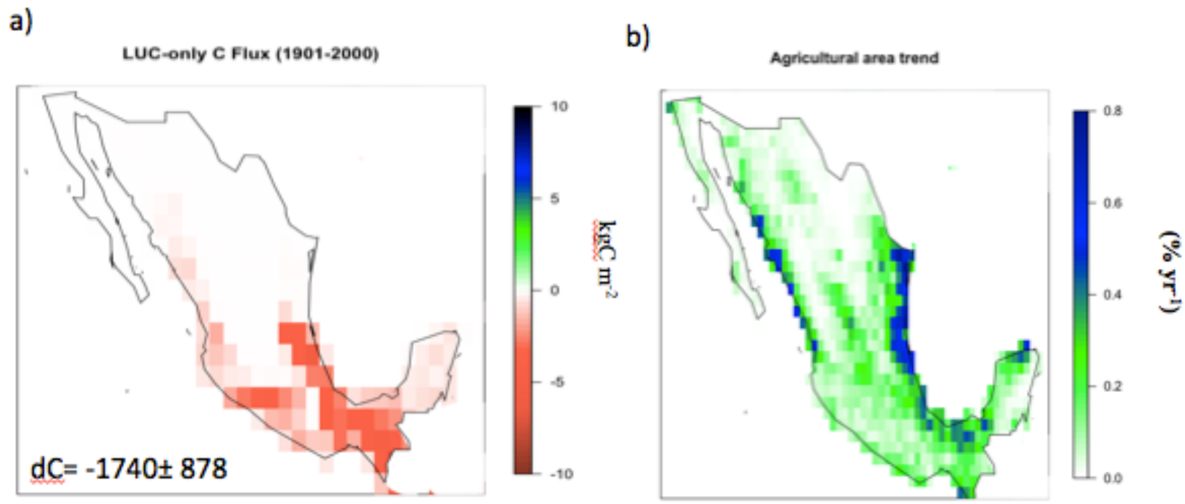

Figure 9: a) Change in stored C by the effect of LULCC-only for the period 1901-2000 (kgC m^{-2}). A positive sign indicates C gain. dC= total change in stored C (TgC). b) Agricultural area change for the same time period.

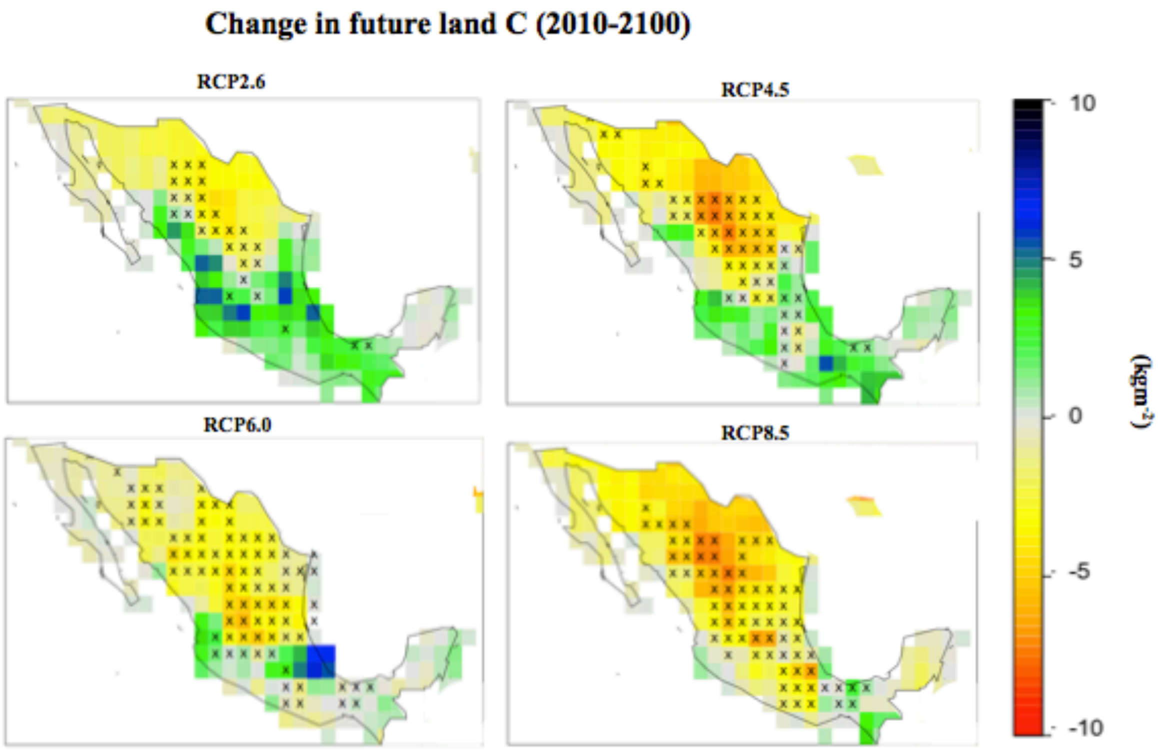

Figure 10: Gridded future change in total stored C for four RCPs for the period 2010-2100 (kgC m^{-2}). The stippling represents areas where >66% of the ESMs models agree on the sign of the flux.