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A Process-Model Perspective on Recent Changes in the Carbon Cycle of North America

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Key Points:

- Land C sink dynamics for North America were evaluated using 19 state-of-the-art Dynamic Global Vegetation Models during 2000–2019
- North America has been a net C sink with a magnitude of 0.37 ± 0.38 PgC year^{-1} and an increasing trend over time
- We identify different spatial and temporal drivers of the variability in land C fluxes across the region, including fire and drought

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Continental North America has been found to be a carbon (C) sink over recent decades by multiple studies employing a variety of estimation approaches. However, several key questions and uncertainties remain with these assessments. Here we used results from an ensemble of 19 state-of-the-art dynamic global vegetation models from the TRENDYv9 project to improve these estimates and study the drivers of its interannual variability. Our results show that North America has been a C sink with a magnitude of 0.37 ± 0.38 (mean and one standard deviation) PgC year^{-1} for the period 2000–2019 (0.31 and 0.44 PgC year^{-1} in each decade); split into 0.18 ± 0.12 PgC year^{-1} in Canada (0.15 and 0.20), 0.16 ± 0.17 in the United States (0.14 and 0.17), 0.02 ± 0.05 PgC year^{-1} in Mexico (0.02 and 0.02) and 0.01 ± 0.02 in Central America and the Caribbean (0.01 and 0.01). About 57% of the new C assimilated by terrestrial ecosystems is allocated into vegetation, 30% into soils, and 13% into litter. Losses of C due to fire account for 41% of the interannual variability of the mean net biome productivity for all North America in the model ensemble. Finally, we show that drought years (e.g., 2002) have the potential to shift the region to a small net C source in the simulations (−0.02 ± 0.46 PgC

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year^{-1}). Our results highlight the importance of identifying the major drivers of the interannual variability of the continental-scale land C cycle along with the spatial distribution of local sink-source dynamics.

Plain Language Summary In recent decades terrestrial ecosystems in North America have absorbed more carbon (C) from the atmosphere than they have released, thus acting as a net land C sink. Nonetheless, several gaps remain in our understanding of how the newly assimilated C is partitioned among the various components of the land ecosystem, and about the impact of recent fires and extreme climatic events on the C stored in vegetation and the soil. In this study, we employed 19 state-of-the-art global dynamic vegetation models to advance our understanding of the land C dynamics over North America over the period 2000–2019. Our results suggest that 57% of the newly assimilated C over this period went into the vegetation, 30% to the soils, and the rest as litter. These new land C gains were found mostly over the temperate and boreal forest regions, which together accounted for 81% of the entire North American sink. Finally, we show that fire and drought are closely related to the year-to-year variability of the sink magnitude, and during extreme conditions (e.g., during 2002) they have the potential to reverse the land into a C source to the atmosphere.

1. Introduction

Land ecosystems over North America have generally been recognized as a carbon (C) sink over recent decades (Hayes et al., 2018; King et al., 2012; Pacala et al., 2007). This estimation has been consistent across multiple studies employing a plethora of different methods including dynamic global vegetation models (DGVMs) (Huntzinger et al., 2017), atmospheric inversions (King et al., 2015), direct C measurements from the atmosphere (Peters et al., 2007), forest inventories (Zhu et al., 2018), and reconciliation among multiple data constraints (Hayes et al., 2012). Arguably, the most complete synthesis is the State of the Carbon Cycle Report (SOCCR), in its first (2007) and second (2018) versions, which detail our understanding of the C dynamics across countries and land cover types of North America for recent decades (USGCRP, 2018). Although these reports have been critical for synthetizing published information, there remains a need to quantify how captured C is partitioned between the soil and the vegetation, to understand how extreme climatic events alter the C balance of the region, and to study the growing importance of fire and other disturbances as modulators of C exchange. Providing information on the effect of these processes will lead to improved estimates and better understanding of broad scale C dynamics for scientific endeavors and to inform policymakers.

Most of the challenges in estimating regional budgets are associated with the limitations and assumptions about how different approaches represent C dynamics across time in terrestrial ecosystems. First, one key synthesis of these multiple approaches are the State of the Art Carbon Cycle reports, which include included published estimates of change in fossil fuels emissions over the years, however they do not report a comparable temporal evaluation of the terrestrial C sink. These reports also did not quantify the split of the terrestrial C sink into vegetation, soil, and litter, fundamental from a management perspective. Second, forest inventories, while providing reliable data at a local and regional scale, are only conducted every 5–10 years due to complex logistical requirements and costs (Brown, 2002) (although some exceptions exist, like the Forest Inventory Analysis of the United States with an annual survey frequency). The long intervals between forest inventories limit our capability to study and interpret how the terrestrial C sink responds to interannual variability and synoptic or extreme climatic events (Didion et al., 2009). Third, while atmospheric measurements, inversions and satellite observations can provide yearly or seasonal estimates, they are unable to partition the atmosphere-land C flux between vegetation and soil components (Goetz & Dubayah, 2011; Sánchez-Azofeifa et al., 2009). DGVMs, have their own limitations such as the need for many inputs, uncertainties associated with the parametrizations of different processes, missing processes, and a low spatial resolution to resolve the effect of local land use management and disturbances (Hayes et al., 2012). However, despite these limitations, DGVMs provide means to study the response of the land C cycle to global change drivers from a comprehensive temporal (past and future), spatial (regional to global) and component (vegetation, soil, and litter) perspective (Kondo et al., 2018; Shiga et al., 2018; Sitch et al., 2015; Teckentrup et al., 2021) and are useful for attributing changes in the C cycle to its drivers, processes and regions or biomes, and to complement results from other approaches.

DGVMs have been previously employed to study the C balance and change at both regional and global scales. For North America there have been several examples of studies conducted at the continental scale as well as for specific countries. At the continental scale, King et al. (2015) employed DGVMs to compute the mean net biome productivity (NBP) by land ecosystems in recent decades; Shiga et al. (2018) explored drivers of interannual variability of the land C sink; Hayes et al. (2012) compared how estimates from multiple modeling approaches can be reconciled with inventory-based data; and Tian et al. (2015) integrated process-based modeling with inventory data to provide an estimate of the land C sink in the context of a full greenhouse gas budget. At the country scale, Murray-Tortarolo et al. (2016) used DGVMs to attribute the changes in C stocks and fluxes across Mexico as they relate to climate, land use and CO_2 fertilization; for the United States, Melillo et al. (1995) pioneered the usage of DGVMs to estimate land NBP in contemporary simulations and future scenarios, and Bachelet et al. (2015) employed DGVMs to calculate future scenarios of C stocks across the country in relation to projected land use and fire regimes; and in Canada, Shafer et al. (2015) used a high-resolution DGVM to estimate changes in vegetation distribution under different climate change scenarios.

Synthesis and comparative studies using DGVMs are useful in providing insights and exploring new research questions regarding the drivers of interannual variability and the impact of extreme events in the land C fluxes (Ciais et al., 2020; Fisher et al., 2018). A recent example is the Regional Carbon Cycle Assessment Project (RECCAP) coordinated by the Global Carbon Project (GCP) with the objective to collect and synthesize broad-scale data on the C cycle across different regions of the world. RECCAP seeks to accelerate the analysis and estimation of regional C budgets based on DGVMs and their comparison with other data sources to define baselines for land-based mitigation efforts (Ciais et al., 2020). In the first coordinated version (RECCAP v1), important advances were made regarding our understanding of land C dynamics for North America (King et al., 2015), where the key role of land to ocean C fluxes (Regnier et al., 2013) and international C flows (Peters et al., 2012) were recognized. In the current endeavor (RECCAP v2), additional efforts are being made to improve our understanding of the role of disturbances (e.g., fire), extreme events, and the partition of land C fluxes into their individual components (e.g., vegetation and soil; Ciais et al., 2020; Poulter et al., 2022). These efforts are expected to be applied and reproduced from regions to sub-regions and individual countries to help guide science questions and policy efforts using a common framework.

The objective of this work is to provide a process-model perspective of the C balance of North America over recent decades (2000–2019) following the RECCAP-2 framework (Ciais et al., 2020). Our specific objectives are to investigate: (a) how individual components (e.g., vegetation, soil, and litter) of the terrestrial biosphere contribute to the C sink in the model simulations and how they have changed through time; (b) how extreme climate events such as drought have altered C fluxes across the region; and (c) how fire impacts land C dynamic in the simulations. We provide information for North America at the continental scale and across four sub-regions defined as Canada, United States, Mexico, and the Central American plus Caribbean countries (CA + C).

2. Methods

2.1. DGVM Data Set

We employed results from 19 DGVMs for the S3 runs of the TRENDY project v9 (Sitch et al., 2015) as conducted for the Global Carbon Budget 2020 (Friedlingstein et al., 2020). These runs include the transient effects of CO_2, climate, and land use change. All models followed the same protocols for pre-industrial spin-ups and historical simulations, they also employed the same forcings. A brief description of each model and their own parametrizations can be found in the supplementary material (Table S1 in Supporting Information S1) and further information is available in Friedlingstein et al. (2020). Their output included global monthly data for C fluxes and annual data for C stocks for the period 1901–2019 and regridded to a common 1-degree spatial resolution. For this analysis, we used a subset of the data containing only North America outputs for the period 2000–2019 and four sub-regions. The subregions included the three largest countries (Canada, United States, and Mexico) and a wider region representing Central America plus the Caribbean countries (CA + C). For the area-based calculations we employed the original model resolution, but for maps we used the common gridded datasets. These models (TRENDYv9) have been evaluated in depth by Seiler et al. (2022), but we also performed an alternative evaluation of NBP across North America (Figure S1 and S2 in Supporting Information S1).

The variables analyzed from the monthly model output included three stocks: vegetation C, soil C, litter C; and nine fluxes: NBP, gross primary productivity (GPP), net primary productivity (NPP), heterotrophic respiration (rH), autotrophic respiration (ra) and C fluxes from grazing, fire, instantaneous land use emissions (fluc) and crop and wood harvest. Most variables are included in the output of all models, but the latter three were only reported by a subset of models (Table S1 in Supporting Information S1). As a result, for most of the work we employed the ensemble for the reported NBP, only the section on fire employs NBP from the nine models that reported the flux. We recognize that current state-of-the-art DGVMs do not include the lateral transport of C, which has been identified as a substantial flux (albeit with associated uncertainty) from the land to the coastal ocean (Butman et al., 2016; Ciais et al., 2008; Hayes et al., 2018).

To compute annual averages, we calculated the land area which we extracted directly from each DGVM land mask, and we accounted for the land and ocean fractions (coastlines). Finally we employed the area affected by drought for Canada, United States and Mexico based on the North American Drought Monitor (https://drought-monitor.unl.edu/NADM/Home.aspx), which employs a common definition of drought based on multiple products for the whole region (Lawrimore et al., 2002) and the total soil moisture content (MRSO) as reported by the DGVMs.

2.2. NBP Definition and Key Limitations

We followed the definition of NBP from the TRENDYv9 project (Sitch et al., 2015) (Equation 1). Equation 1 shows the NBP calculation employed as a common framework in the TRENDYv9 protocol. NPP stands for net primary productivity, rH for heterotrophic respiration, D stands for disturbance and fluc for instantaneous emissions due to land use change. NBP was reported directly by all models and the reported values were used in the subsequent analysis. Each model calculated NBP following the above formula, although not all models include fire, grazing, harvest and fluc fluxes. NBP was extracted directly for the models and for all cases a positive value indicates a sink of C from the atmosphere and vice versa.

$$\mathrm{NBP} = \mathrm{NPP} - \mathrm{rH} - \mathrm{D}\,(fire + grazing + harvest + fluc) \tag{1}$$

One fundamental limitation of such definitions is the lack of land to ocean fluxes, from the land-ocean-aquatic continuum (LOAC). These fluxes are fundamental to the land C dynamics (Regnier et al., 2013), but current DGVMs do not account for them, which could potentially mean a general overestimation of terrestrial NBP (Friedlingstein et al., 2020) or higher respiratory fluxes that are C inputs in the LOAC. Second, while the models are forced with a similar data set for land-use and land cover change (Klein Goldewijk et al., 2017), each model includes its own assumptions about how land use change, land practices and disturbance (fire, grazing and harvest) are implemented, precluding the addition of such fluxes into an ensemble mean. Hence, to account for disturbance, we assumed the disturbance flux to be the difference between NBP minus NPP minus rH.

2.3. Attribution

To identify the drivers of temporal variability in the North American C cycle, we performed a simple attribution analysis based on the temporal trend of the annual NBP ensemble of TRENDYv9 S1 (CO_2), S2 (CO_2 + Climate) and S3 (CO_2 + Climate + LUC) simulations. The absolute NBP (S3) was deconstructed as the NBP in simulations that only account for the effects of CO_2 fertilization (S1), climate (S2–S1) or land use change (S3–S2). The procedure was done for the whole of North America and sub regions. We recognize that this approach does not allow to separate the individual effects of temperature and precipitation, it does not account for interactive effects (e.g., temperature × CO_2) nor considers the loss of additional sink capacity when attributing changes to land use change. That said, this analysis provides a first order approach to understand the drivers governing the C cycle in the region.

2.4. Data and Statistical Analyses

We employed five different types of analyses summarizing model outputs of C flux and stock change variables by: decadal averages, annual time-series, spatial averages, the times and locations of extreme events and linear regressions between fire and NBP, and soil moisture/drought and NBP. For decadal averages, we calculated the annual average for each variable in each model, then their means for each of two recent decades (2000–2009 and 2010–2019), and finally the model ensemble mean, and standard deviation based on inter-model spread. Additionally, we calculated the change in C stocks (ΔC) as the difference between total accumulated C in the vegetation, soil, and litter at the end of each decade minus the C stock reported at the beginning of each decade.

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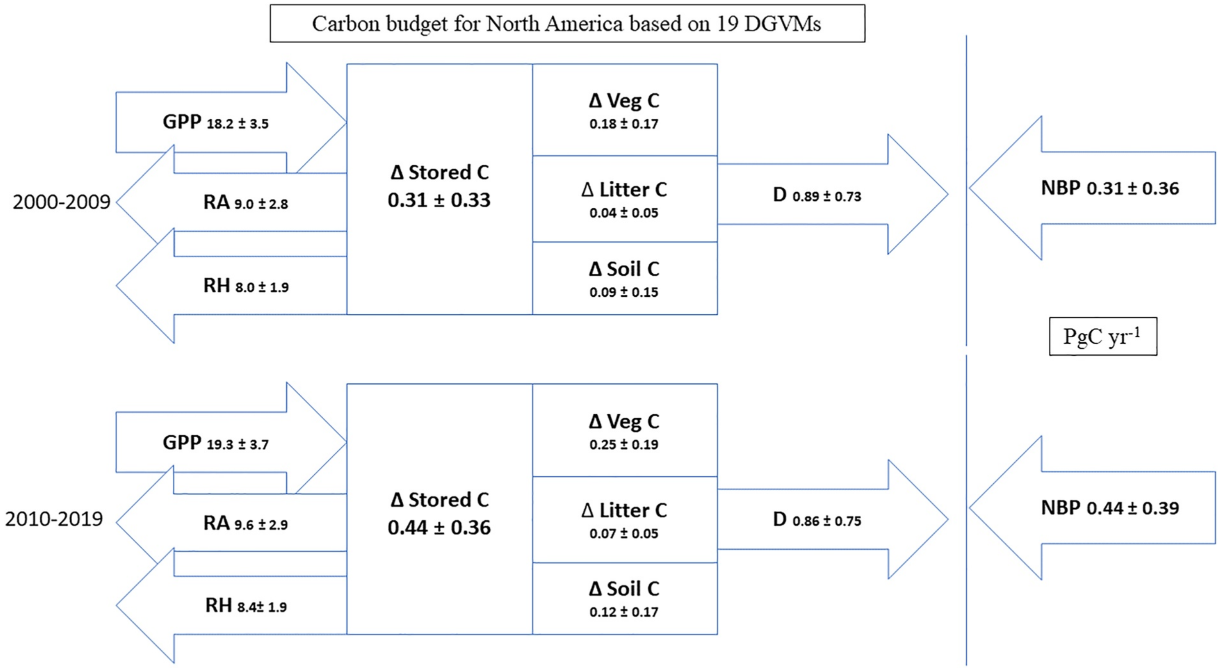

Figure 1. Land C cycle for North America during 2000–2019 by decade in PgC year^{-1}. Boxes indicate changes in C stocks (annual average based on each decade) and arrows indicate net fluxes. All errors represent 1 standard deviation based on model spread. A positive NBP indicates a net land C sink from the atmosphere. GPP stands for gross primary productivity, RA for autotrophic respiration, RH for heterotrophic respiration, Veg for vegetation, D for disturbance fluxes and NBP for net biome productivity.

These steps were followed for estimates at the continental scale across North America and for each one of the four sub-regions.

To estimate temporal trends and variability, we calculated the annual sum of NBP and fire emissions for each model and then the average and standard deviation for the model ensemble estimates of each variable. We then applied a non-parametric Mann-Kendall test to estimate the temporal trend for each variable for 2000–2019. In addition, from these time-series data we identified the year with the lowest and highest NBP in each decade, and we tested the relationship between fire and NBP at the continental scale and for each one of the four sub-regions.

With regards to the spatial patterns, we calculated the annual gridded mean for NBP for the model ensemble. This was done for the full annual time-series (2000–2019), each decade, and for the years with the lowest NBP in each decade (representing extreme climate negatively impacting the land C sink). We also employed this spatial ensemble to compute NBP by vegetation cover type based on the ESA-CCI land cover map for the year 2019 (ESA, 2017). The land cover map was rescaled to a 1 × 1° grid based on the most common land cover present on the lower resolution grid. We then grouped the categories into five groups: temperate forest, boreal forest, tropical forest, grassland/shrubland (includes croplands), and other (i.e., tundra, desert, and polar).

To directly compare the interannual variability of NBP with fire, and drought affected area and soil moisture we employed linear regressions based on the annual average for the whole region. Thus, we estimated total annual fire emissions, along with the total annual area affected by drought and the mean soil water content for North America over 2000–2019. We then performed a simple linear regression, and presented the level of statistical significance and the correlation coefficient for each case.

All calculations and figures, including maps, were made using R statistical software (R Core Team, 2021).

3. Results and Discussion

3.1. Decadal Trend for North America and Sub-Regions (Years 2000–2019)

During the past two decades, terrestrial ecosystems of North America are simulated to be a net C sink according to the model ensemble mean (Figure 1) and each individual model (Figure S1 and S2 in Supporting Information S1).

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Table 1
Summary of Land C Budgets for North America for Recent Decades (1990–2019) From Different Methodological Approaches

Study	Period	Method	NBP (PgC year^{-1})
King et al. (2015)	2000–2009	Inverse models	0.89 ± 0.40
King et al. (2015)	2000–2009	DGVMs (Trendy V5)	0.36 ± 0.11
Hayes et al. (2012)	2000–2006	Inverse models	0.93 ± 0.67
Hayes et al. (2012)	2000–2006	Forward models	0.51 ± 0.72
Hayes et al. (2012)	2000–2006	Inventory-based	0.32 ± 0.25
Tian et al. (2015)	2001–2010	Process-based models and inventory data	0.50 ± 0.27
Peters et al. (2007)	2000–2018	Atmospheric inversions (Carbon Tracker)	0.56 ± 0.50
SOCCR2 (USGCRP, 2018)	2004–2013	Synthesis of Multiple products	0.63 ± 0.16
Hu et al. (2019)	2007–2015	Atmospheric inversion ensemble	0.70 ± 0.34
This study	2000–2009	DGVM Ensemble (Trendy V9)	0.31 ± 0.36
This study	2010–2019	DGVM Ensemble (Trendy V9)	0.44 ± 0.39
This study	2000–2019	DGVM Ensemble (Trendy V9)	0.37 ± 0.38
Average			0.55 ± 0.41

Note. The uncertainty across all products was calculated by a normal sum distribution by applying a square root of the average variance weighted by the number of years in each product.

NBP was lower during 2000–2009 (0.31 ± 0.36 PgC year^{-1}, mean and one standard deviation) compared to 2010–2019 (0.44 ± 0.39 PgC year^{-1}) and was consistent with an estimated increase in total stored C for each decade (0.31 ± 0.33 and 0.44 ± 0.36 PgC year^{-1} respectively). More than half of the newly stored C by the land sink was accumulated in the vegetation (57 ± 25%), a third of the fraction in the soil (30 ± 19%) and a minor component in the litter (13 ± 6%).

These results are consistent with recent estimates, which report North America as a terrestrial C sink during these two decades. For example, SOCCR2 (USGCRP, 2018) included bottom-up and top-down approaches and estimated a C sink over North America (not including CA + C) for the period 2004–2013 equivalent to 0.63 ± 0.16 PgC year^{-1}. Using a DGVM ensemble from a previous TRENDY version (V5), King et al. (2015) reported a sink of 0.36 ± 0.1 PgC year^{-1} from 2000 to 2009, which they compared to a sink of 0.89 ± 0.40 PgC year^{-1} derived from atmospheric inversions. Using inverse atmospheric models, Peters et al. (2007) estimated a net sink of 0.65 PgC year^{-1} for the period 2000–2005, but this estimate has been recently updated for the period 2000–2018 with the value of 0.56 PgC year^{-1} and a range of 0.1–1 PgC year^{-1} (CT2019B, 2019). Tian et al. (2015) employed an integrated process-based ecosystem model with inventory data to provide an estimate of 0.50 ± 0.27 PgC year^{-1} for 2001–2010. Using a set of 18 atmospheric inversions, Hu et al. (2019) found a C sink of 0.70 ± 0.34 PgC year^{-1} for the period 2007–2015 (Table 1). Hayes et al. (2012) employed inverse models, forward models, and national forest inventories to provide an estimate of 0.93 ± 0.67, 0.51 ± 0.72, and 0.32 ± 0.25 PgC year^{-1} for each group of products respectively during 2000–2006.

Based on the consistency of these studies, it is very likely that North America has been a net sink of atmospheric C from 2000 to 2019 with a mean value across all studies of 0.55 ± 0.41 PgC year^{-1}. However, the comparison between estimates should be taken with caution, as the various estimates are for different time periods and might not be equal in terms of mass-balance; even when similar models are employed. For example, the value estimated by King et al. (2015) of 0.36 ± 0.28 PgC year^{-1} from a previous TRENDY version, are consistent with our findings, as the NBP flux considers all disturbance fluxes; however, Hayes et al. (2012) and SOCCR report (Hayes et al., 2018) values 25%–30% higher than ours, not only because of a different time-period, but likely the result of different mass-balance approaches (e.g., NEE vs. NBP).

We postulate that DGVMs correctly reproduce this pattern across North America, but we recognize that none of these calculations include lateral C fluxes such as C fluxes from trade of crops and wood products or terrestrial to oceanic C transport (Ciais et al., 2008), or disturbance pulses such as hurricanes or insect outbreaks. The magnitude of lateral fluxes and pulses may be proportional to the overall sink, but these fluxes have been associated with

Table 2
NBP (2000–2019) and Land Surface Area of Each Subregion of North America Based on the DGVMs

Region	Area (mill km^2)	NBP (PgC year^{-1})
Canada	11.6 ± 1.8	0.18 ± 0.12
United States	9.7 ± 0.8	0.16 ± 0.17
Mexico	2.14 ± 0.4	0.02 ± 0.05
CA + C	0.98 ± 0.5	0.01 ± 0.02
North America	24.42 ± 3.5	0.37 ± 0.38

Note. Differences in land area arise from model resolution and individual grids particularities (e.g., water bodies and coastline definitions). CA + C stands for Central America and the Caribbean.

high uncertainty across North America (Hayes et al., 2018). Consequently, there is a need to improve estimates of lateral fluxes and disturbance pulses to estimate changes in and reliably predict the regional-to-global C budget.

When split by sub-regions (Table 2; Table S2 in Supporting Information S1), it is evident that the C sink in the DGVMs is driven equally by Canada (0.15 ± 0.11 and 0.20 ± 0.12 PgC year^{-1} in each decade respectively) and the United States (0.14 ± 0.16 and 0.17 ± 0.17 PgC year^{-1}), with minor contributions from Mexico (0.02 ± 0.05 and 0.02 ± 0.05 PgC year^{-1}) and CA + C (0.01 ± 0.02 and 0.01 ± 0.02 PgC year^{-1}). Higher contributions from Canada and the United States arose not only from their markedly larger surface area extents, but also from their higher fluxes per unit area (Can: 18; United States: 16; Mex 9; CA + C 10 gC m^{-2} year^{-1}). Results from the models suggest that most of the decadal increment in the North America C sink is likely influenced by an accumulation of C in the vegetation of the United States and Canada (gaining 2.05 and 2.10 PgC over these two decades respectively). C fluxes from disturbances were always higher in the United States (−0.42 ± 0.34 PgC year^{-1}) accounting for more than half of all emissions across North America (−0.87 ± 0.74 PgC year^{-1}) and representing three times the magnitude of the net C losses for Mexico and CA + C combined (−0.08 ± 0.05 and −0.07 ± 0.05 PgC year^{-1} respectively).

The model results by sub-regions show larger discrepancies when compared to published studies. For example, Canada has been generally recognized as a minor C sink, with values of 0.01–0.03 PgC year^{-1} (Hayes et al., 2018; Pan et al., 2011) or 10 times smaller than that estimated by the DGVM ensemble. While the DGVMs estimate a gain of 0.18 ± 0.12 PgC year^{-1} per decade, other studies suggest that Canadian ecosystems act as a small C sink (0.1–0.3 PgC year^{-1} in Pan et al., 2011; or 0.017 PgC year^{-1}, Kurz et al., 2013) or even a small C source (−0.016 PgC year^{-1}; ECC, 2017) because of increased harvesting, fire, insect outbreaks, and reduced soil C mean residence time (MRT). Furthermore, there is evidence that fire and timber harvest suppress any C gained in Canadian boreal forests, which are two factors not included in most DGVMs (fire: 9/19 and harvest: 7/19) and could lead to a three-factor overestimation of the C sink across this ecosystem (Wang et al., 2021).

Across the United States, DGVMs report a smaller C sink than previous studies (the values reported in this work account for the whole United States, but we also provide estimates for the conterminous United States and Alaska separately in Table S3 in Supporting Information S1). For example, Pacala et al. (2007) reported a net C sink of 0.49 PgC year^{-1} for the year 2003, for 2004–2006 Crevoisier et al. (2010) estimated a net sink of 0.51 PgC year^{-1}, and during 2004–2013 Hayes et al. (2018) found a sink of 0.36 PgC year^{-1}. These values are higher than the estimate from the models of 0.16 ± 0.17 PgC year^{-1} (for 2000–2019), but the issue might be arising from how NBP is computed. These published estimates are closer to the DGVMs when C from aquatic ecosystems is not included in the total budgets (0.44 PgC year^{-1} for Pacala et al., 2007 and 0.23 PgC year^{-1} for 2004–2013 in Hayes et al., 2018, when not accounting for wetlands, rivers, and lakes). Despite these relatively small differences, all lines of evidence suggest that the United States has been a C sink for the past two decades, with most of the C being added into the vegetation pool.

For the case of Mexico and CA + C region, broad uncertainties remain regarding their role as a C sink or source. In that sense, land ecosystems in Mexico were found to be a small C sink of 0.02 ± 0.05 PgC year^{-1}, but during seven out of the 20 years it was a small source. Published estimates for Mexico also vary widely, as this country has been characterized as a small sink of 0.05 PgC year^{-1} in Hayes et al. (2018) and 0.03 PgC year^{-1} by Murray-Tortarolo et al. (2016), but other studies situate Mexico as a small source of −0.05 PgC year^{-1} (Pacala et al., 2007), −0.02 PgC year^{-1} (De Jong et al., 2000) and −0.01 PgC year^{-1} (Mendoza-Ponce et al., 2018). For the case of the CA + C region there is a lack of information to properly parameterize models and estimate C budgets (Villarreal & Vargas, 2021). However, Jang et al. (2014) situates the region as a small sink of 0.012 PgC year^{-1} for the period 2000–2009 using atmospheric inversions from Carbon-Tracker, but the constraint for the region is remarkably poor and data should be interpreted carefully. Based on these results, we postulate that land ecosystems across these regions have likely been C neutral over these two decades, with small annual deviations driven by interannual variability (IAV) in climate, fire and land use, but with high uncertainty due to lack of data for appropriate model parameterization and validation.

3.2. Attribution of Temporal Evolution of NBP From 2000 to 2019

We found a significant increasing trend in the simulated North American annual NBP over the period 2000–2019 for the model ensemble (Mann Kendall tau = 0.345, $p = 0.03$) and for half of the individual models (Figures S1 and S2 in Supporting Information S1). The DGVM ensemble analyzed in this study suggests a 40% increase in NBP from the 2000–2009 to the 2010-2019 decades. However, when NBP is decomposed by country/region, only Canada shows a statistically significant increasing NBP trend (Mann Kendall tau = 0.368, $p = 0.03$) (Figure 2b). Thus, the decadal increase in modeled NBP across the region is driven by a higher C uptake in Canada. Nonetheless, despite the clear increase in decadal NBP, for both cases the linear trend disappears when the year 2002 is not included in the time series (the particularities of this year are described in the sections below).

The analysis of the components of NBP indicates that this growth seems to be driven primarily by a larger GPP in the second decade (18.21 ± 3.5 to 19.3 ± 3.7 PgC year^{-1}), which would be consistent with previous studies suggesting a CO_2 fertilization effect on photosynthesis for the region (Lim et al., 2004). However, when we analyzed NBP drivers, we did not find an NBP increment in the CO_2-only (S1) runs, with the United States showing even lower NBP rates in the second decade (Table 3). These results agree with the most recent findings by Wang et al. (2020), who showed that the CO_2 fertilization effect might be declining in recent decades (Wang et al., 2020). Nonetheless, the mechanisms involved in the CO_2 fertilization effect are highly complex (Walker et al., 2021) and a large debate exists on the subject (Sang et al., 2021). Our results using these DGVMs suggest a positive and incremental effect of CO_2 on GPP, but widely balanced by a similar enhancement of soil rH, leading to a constant long-term NBP. This implies that the modeled decadal increment in NBP is not attributable to the CO_2 effect.

There are two potential explanations for the observed increase in NBP: (a) a larger sink due to reforestation, or (b) a positive effect of climate variability. The net effect of land use change in the modeled ensemble is always negative and remarkably constant across decades and subregions (Table 3); despite observed increased C uptake due to reforestation across the region (Pugh et al., 2019). In contrast, the effect of climate (S2–S1 runs) on NBP is opposite in both decades, with a negative impact during 2000–2009 and positive in 2010–2019. This pattern is particularly evident in the United States, where the contribution of climate to NBP went from −0.05 to 0.04 PgC year^{-1}, but balances to zero for the full period. These results may be related to low precipitation rates during the first decade, and higher-than-average over the second. Strong droughts were registered in 2000–2004, while record nationwide precipitations were recorded in 2018 and 2019.

The most interesting case on the impact of climate variability on NBP was Canada. Across the country, we found a persistent and positive effect of climate across both decades (Table 3). Canada is the only North American region displaying an increasing C sink and climate is the only driver with a positive and incremental decadal effect. Thus, it is likely that most of the North American modeled trend in NBP is driven by the climate consequences on NBP across Canada. In contrast to the United States, this pattern is unlikely driven by precipitation, which displays a similar decadal mean across the country (547 vs. 540 mm based on Harris et al., 2014); but it is likely attributable to increasing temperatures. Higher temperature has been linked to longer growing seasons and higher leaf are index (LAI) over the Northern Hemisphere forests in these DGVMs (Murray-Tortarolo et al., 2013), which translates into higher GPP, vegetation C, and NBP. Nonetheless, a recent study evaluating the models used in our study (Seiler et al., 2022) suggests that models are precisely overestimating these parameters (LAI, NBP and soil C) and their response to temperature. Thus, it is likely that models overestimate the C sink over Canada, not just because of incomplete disturbance parametrization and modeling, but also by overestimating the positive effect of increasing temperatures in the country.

3.3. Interannual Variability of NBP

One important aspect of IAV is the range of variation in the C sink. King et al. (2012) and Hayes et al. (2018) reported a C sink that ranged from 0.33 to 0.93 PgC year^{-1} with increasing values over time from 2004 to 2013. In that sense, North America was always characterized as a C sink in recent decade, which is consistent with previous studies (King et al., 2015; Peters et al., 2007). While the highest values of the C uptake are consistent with our results, we also found the possibility of North America acting as a C source in 2002, which has not been previously reported. Over these two decades, the only year where terrestrial ecosystems acted as a C source was 2002, with a value of −0.02 ± 0.46 PgC year^{-1} (Figure 2a). This result should be interpreted carefully, as

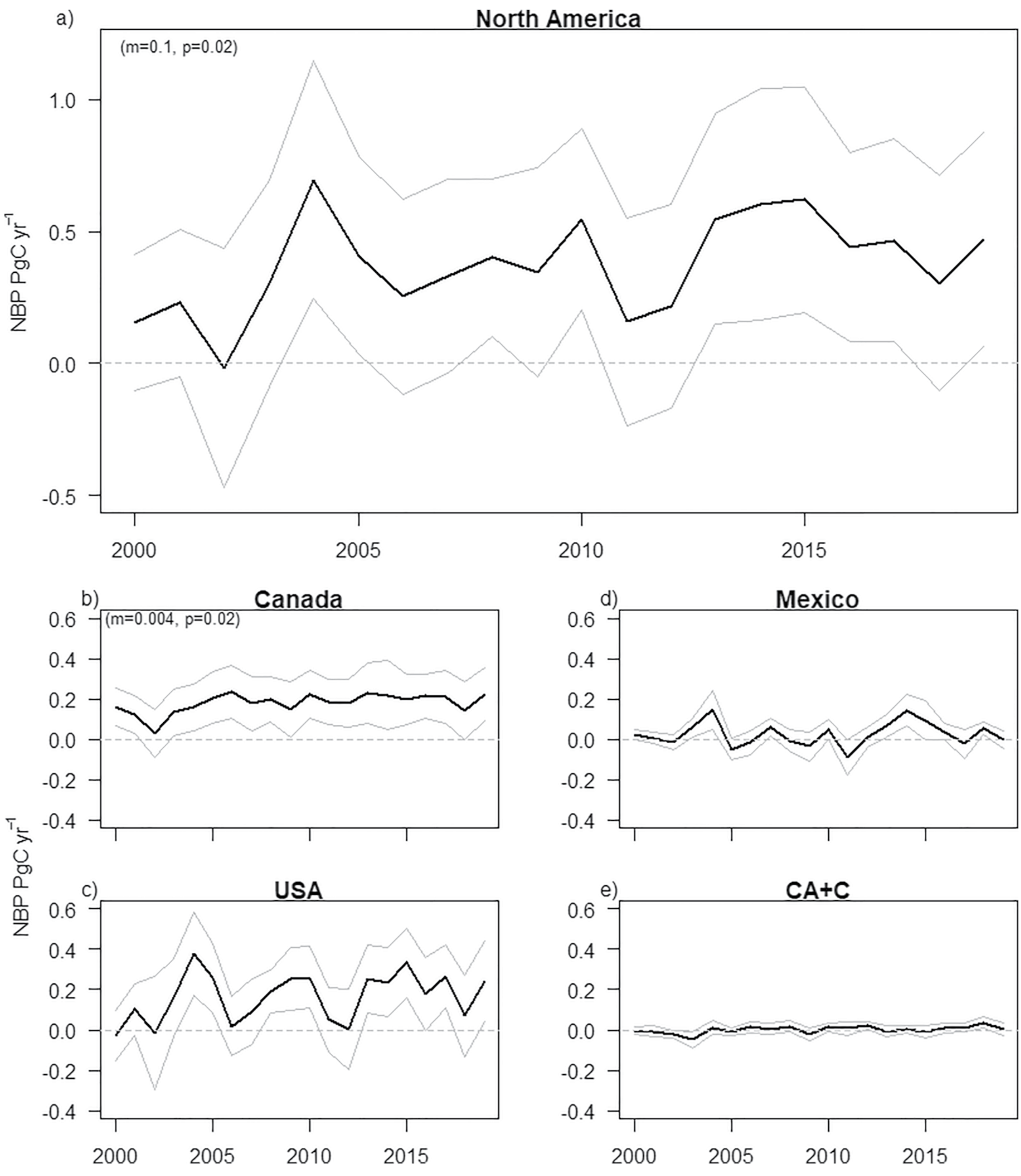

Figure 2. Temporal evolution of net biome productivity in North America and by country/region for the period 2000–2020. All figures are displayed in PgC year^{-1} and represent the ensemble mean (black line) plus and minus one standard deviation (gray lines). Positive values indicate a net sink of C from the atmosphere. When a statistically significant trend was found the *p*-value is presented in the panel (as determined by a Mann Kendall monotonic trend test), along with the slope for these 20 years; however, for both North America and Canada the linear trends are no longer statistically significant when the year 2002 is not considered.

the pattern was only present in half of the models but represents a potential reversal of the C budget during dry conditions. In addition, while the modeled 2011 C balance still indicates a small sink, Mexico, and CA + C were all a C source (reported in 81% and 50% of the models respectively) and the United States was a negligible sink (0.05 ± 0.16 PgC). These 2 years might prove to be important to understand the multiple drivers and feedbacks of C dynamics across the region and as case studies to improve future DGVMs predictions under different climate change scenarios.

Table 3
Attribution of NBP Across North America and Sub-Regions Based on Three Different Components: CO_2 Fertilization, Climate, and Land Use Change

PgC $year^{-1}$	CO_2 (S1)	Climate (S2–S1)	Land use change (S3–S2)	Net NBP (S3)
Canada				
2000–2009	0.17 ± 0.03	0.03 ± 0.06	−0.05 ± 0.00	0.15 ± 0.11
2010–2019	0.18 ± 0.03	0.07 ± 0.04	−0.05 ± 0.01	0.20 ± 0.12
2000–2019	0.18 ± 0.03	0.05 ± 0.06	−0.05 ± 0.01	0.18 ± 0.12
United States				
2000–2009	0.28 ± 0.12	−0.05 ± 0.20	−0.09 ± 0.03	0.14 ± 0.16
2010–2019	0.24 ± 0.18	0.04 ± 0.21	−0.10 ± 0.03	0.17 ± 0.17
2000–2019	0.26 ± 0.15	0.00 ± 0.21	−0.09 ± 0.03	0.16 ± 0.17
Mexico				
2000–2009	0.05 ± 0.04	−0.01 ± 0.06	−0.02 ± 0.00	0.02 ± 0.05
2010–2019	0.05 ± 0.03	−0.01 ± 0.06	−0.02 ± 0.00	0.02 ± 0.05
2000–2019	0.05 ± 0.04	−0.01 ± 0.06	−0.02 ± 0.01	0.02 ± 0.05
CA + C				
2000–2009	0.04 ± 0.02	0.01 ± 0.02	−0.05 ± 0.07	0.01 ± 0.02
2010–2019	0.07 ± 0.04	0.00 ± 0.02	−0.04 ± 0.08	0.01 ± 0.02
2000–2019	0.06 ± 0.04	0.00 ± 0.02	−0.05 ± 0.08	0.01 ± 0.02
North America				
2000–2009	0.54 ± 0.16	−0.02 ± 0.23	−0.21 ± 0.04	0.31 ± 0.36
2010–2019	0.54 ± 0.21	0.10 ± 0.24	−0.21 ± 0.06	0.44 ± 0.39
2000–2019	0.54 ± 0.18	0.04 ± 0.24	−0.21 ± 0.05	0.37 ± 0.38

Note. All values indicate mean NBP and one standard deviation.

Apart from 2002, both Canada and United States were mostly a C sink across models (79% of the time for the United States and 90% for Canada), but we recognize that the United States had a larger IAV (the standard deviation across all years and models was CAN:0.20 vs. United States: 0.26 PgC $year^{-1}$). In contrast, Mexico and CA + C oscillated between being an annual net source and sink (e.g., they were a sink 64% and 58% of the times respectively across all models across all years) through time, with net values always close to zero.

3.4. NBP and Fire

Over North America, simulated C emissions associated with fire disturbance were present every year, ranging from a minimum of 0.28 ± 0.20 PgC $year^{-1}$ in 2010 to a maximum of 0.35 ± 21 PgC $year^{-1}$ in 2007, with an average of 0.32 ± 0.24 PgC $year^{-1}$ for the 2000–2019 period. The United States had the highest fire emissions with an average C loss of 0.12 ± 0.07 PgC $year^{-1}$, followed by Canada with 0.07 ± 0.09 PgC $year^{-1}$, Mexico with 0.07 ± 0.05 PgC $year^{-1}$, and CA + C with 0.02 ± 0.01 PgC $year^{-1}$ (Figure 3). However, when the emissions were normalized by area (i.e., area-weighted), both Mexico and CA + C had greater values (32.1 and 20.4 gC m^{-2} y^{-1}) than the United States and Canada (12.3 and 6.0 gC m^{-2} y^{-1}). Total country fire emissions are relevant to the global C budget, but area-weighted emissions provide insights for land management and policy makers. For example, the higher area-weighted emissions in Mexico and CA + C are likely the reflection of increased deforestation and land degradation (Corona-Nuñez et al., 2020; Rios & Raga, 2019) (although some DGVMs struggle to correctly simulate fires from forest degradation).

We found a strong correlation between the IAV of fire emissions and the IAV of NBP for the DGVMs that reported both fluxes (nine out of 19) ($r^2 = 0.41$, $p < 0.01$; Figure 4), which remained even when fire is not included in the total NBP computation ($r^2 = 0.33$, $p < 0.01$). This suggests that both variables might be responding to similar interannual drivers (e.g., climate and land use) that could result in confounding feedback. Consequently, disentangling their relationship and identifying specific drivers is fundamental to predict future fire emissions and their impact on NBP. We propose that the link between land management, fire emissions and climate need to be addressed at the individual subregion to gain a better perspective of the patterns across North America.

For the case of Canada, estimates of fire emissions from a combination of models and inventory data yield an average of value of 0.028 PgC $year^{-1}$ (0.002–0.095) (Schultz et al., 2008), using models of fuel consumption and climate (0.172 PgC $year^{-1}$; Amiro et al., 2009), to employing satellite data (0.280 PgC $year^{-1}$; Wiedinmyer et al., 2006). The most recent study by Wang et al. (2021) estimates emissions as high as 0.073 PgC $year^{-1}$ just from the aboveground biomass of boreal forests. Thus, while DGVMs estimates (0.07 ± 0.09 PgC $year^{-1}$) are on the lower range of previous studies, it seems that DGVMs are underestimating fire emissions across Canada. However, when fire emissions were decomposed by its drivers, we also found that the DGVMs predict lower fluxes in the runs that include transient climate (S2: 0.06 ± 0.08 PgC $year^{-1}$), which is opposite to recent findings attributing higher wildfire frequency to rising temperatures and decreased humidity (Wang et al., 2015; Wotton et al., 2010). We highlight that models tend to disagree on the magnitude of fire fluxes for the region, with a standard deviation greater than the model mean ensemble. In addition, the correlation between fire IAV and NBP for the country is remarkably low ($r = -0.18$), which is not the case for the rest of North America (Figure 4). These factors might explain the large NBP reported by the models for Canada, as well as the increasing trend, and suggest a pressing need to correctly reproduce fire dynamics and associated C emissions, particularly including the compounding effect of climate change and fire.

The fire emissions characterization for the United States is complicated as previously published studies display a large variation in their estimates. While calculations from the models of 0.12 ± 0.07 PgC $year^{-1}$ are within previously reported values, the large uncertainty arising from the large spread in the model estimates when compared

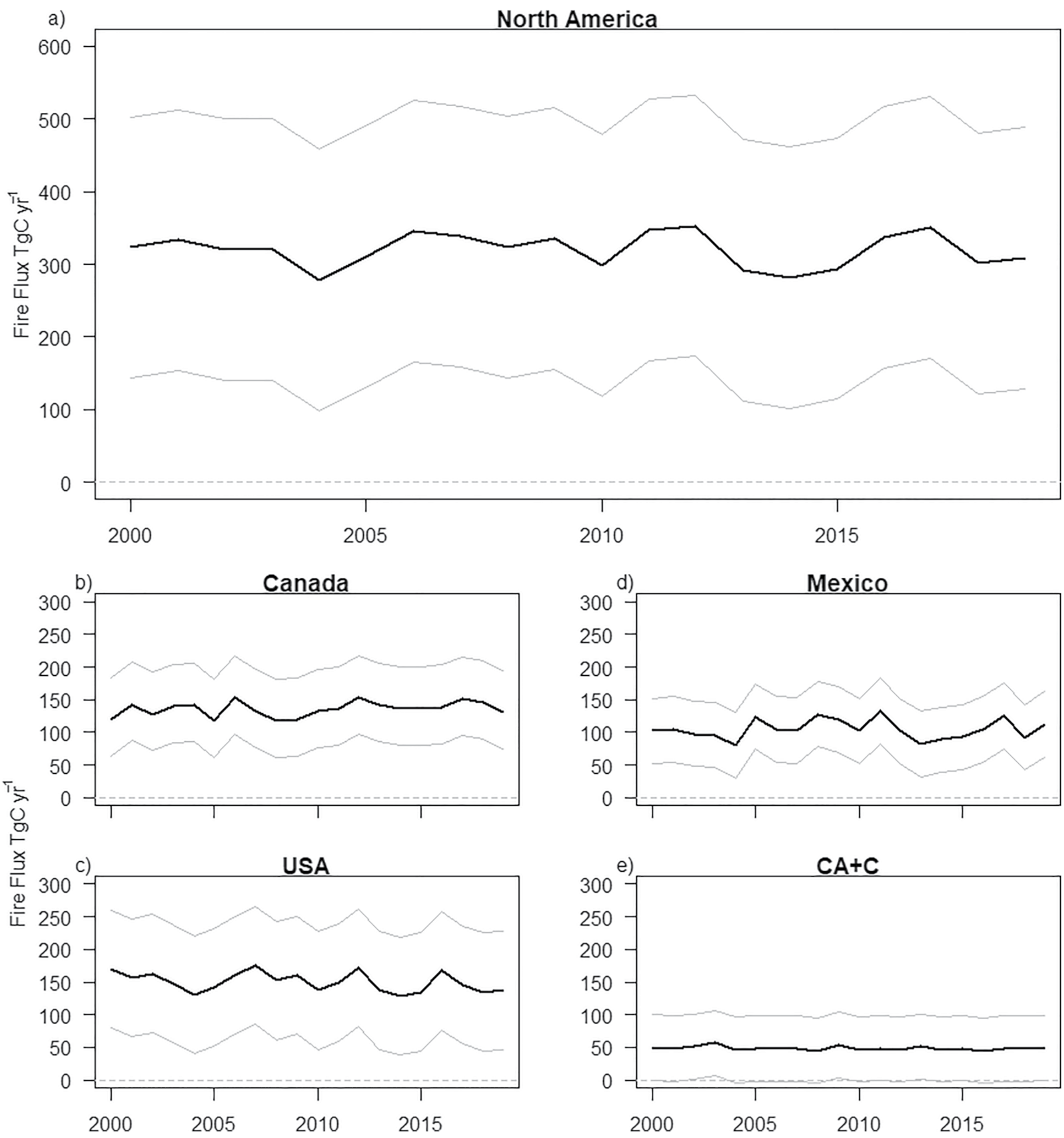

Figure 3. Fire C fluxes coming from terrestrial ecosystems across North America and its individual subregions during 2000–2019. Panels show the mean ensemble fire fluxes (black line) plus and minus one standard deviation (gray lines). Dashed lines mark zero fire emissions. Estimation comes from nine out of 19 dynamic global vegetation models. In order to help visualization, fire fluxes are reported as inverted values, thus positive indicates a flux to the atmosphere.

to other sources of data is evident. The lowest estimation for the long-term mean (2002–2011) is 0.032 PgC year^{-1} from satellite data from the Global Fire Emissions Database (GFED), and the highest is 0.222 PgC year^{-1} from the national emissions inventory, with intermediate values of 0.097 PgC year^{-1} from the fire inventory from the National Center for Atmospheric Research (NCAR) and 0.140 from the Environmental Protection Agency (EPA) (Larkin et al., 2014). One key feature of the C cycle of the region was the strong correlation ($r = -0.67$) between fire and NBP IAV for the country, meaning that at least 46% of the variation in the land-atmosphere C flux is explained by fire. Nonetheless, if the correlation between fire and NBP is real or a model artifact is hard to discern with current available data; thus, further research is needed to benchmark the spatial and temporal variability of fire emissions across the United States.

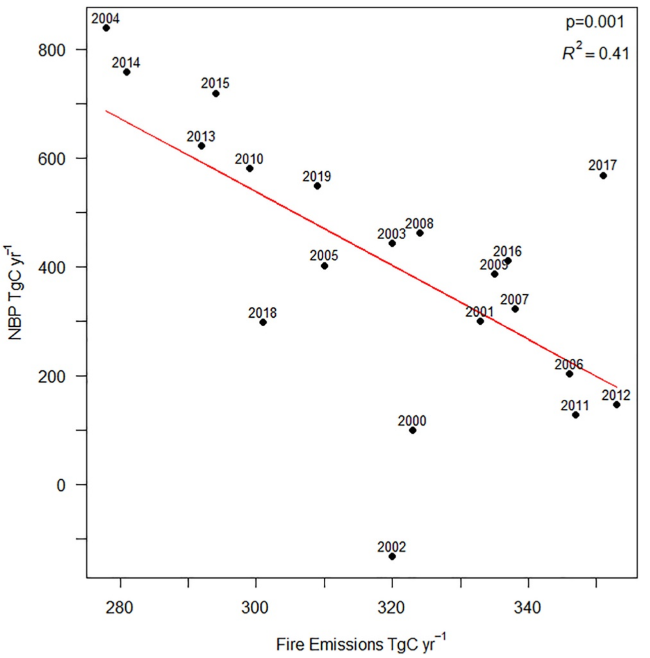

Figure 4. Linear regression between fire emissions and terrestrial net biome productivity (NBP) for North America across the period 2000–2019. The relationship remains even after the fire fluxes are not added in the NBP computation ($r^2 = 0.33$, $p < 0.01$). Only NBP from models which include fire was considered (9). For visualization purposes fire fluxes were inverted, thus a higher value indicates larger fluxes to the atmosphere.

The case of fire emissions in Mexico and CA + C is noteworthy due to the large fire emission values and the possible impact on the IAV of the C cycle. For these regions, fire C emissions are twice the value of NBP, and there is a large correlation between both fluxes (for Mexico $r = -0.83$, for CAM $r = -0.79$). A previous study showed that fire across Mexico represented at least 19% of the total C emissions from 2011 to 2018 and was 11 times higher than deforestation (Corona-Nuñez et al., 2020). Furthermore, fire emissions have tripled over the last decade and most of the IAV has been driven by the El Niño Southern Oscillation climate pattern (Corona-Nuñez et al., 2020). A similar case has been made for Central America, where the high fire IAV has been attributed to climate variability (Giglio et al., 2013), with previously reported values (0.051 PgC year^{-1}) in a similar range to our findings (Ward et al., 2018). The larger magnitude of the simulated fire emissions compared to the NBP, would also suggest that over these two decades the natural fire cycle for the regions cancels the C gained by the vegetation. However, despite the consistency between observed and modeled fire data, the modeled effects of climate and land use change on fire emissions are negative in these regions (when comparing S2 and S3 runs against S1), which is inconsistent with the fire management and history in the region (Rodríguez-Trejo et al., 2011).

3.5. NBP and Drought

We found a linear relationship between the total area affected by drought from the North American Drought Monitor, and the total NBP simulated from the DGVMs, for North America (Figure 5a) ($p < 0.01$). The relationship did not include CA + C as we did not find any available data as the regions are not included in the drought monitor; but despite this shortcoming, we found that at least 44% of NBP IAV can be explained by the drought-affected

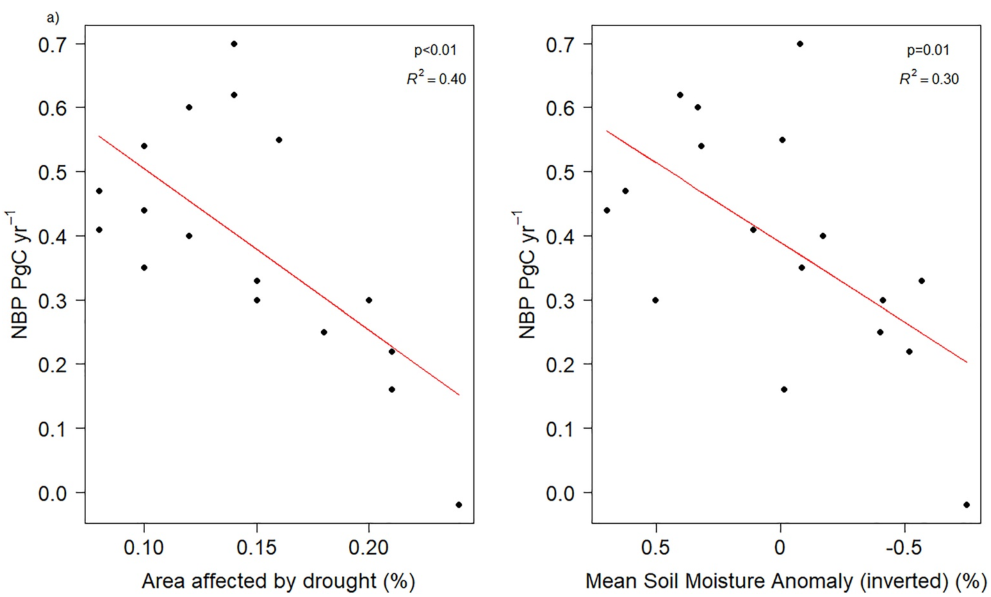

Figure 5. Linear regression between the area affected by drought and the mean annual net biome productivity (NBP) (a) as well as the mean soil moisture anomaly and NBP (b) for the whole of North America. The calculated drought affected area comes from the North American Drought Monitor and does not include CA + C and years 2000–2001 as we found no available data in either case. To compute the drought affected area we added the area affected by any kind of droughts (from abnormally dry to exceptional drought). Total soil moisture content was obtained directly from the models and the anomaly represents each year minus the average for the two decades. For visualization purposes, we presented the inverted anomaly, thus dry years are presented on the right and vice versa.

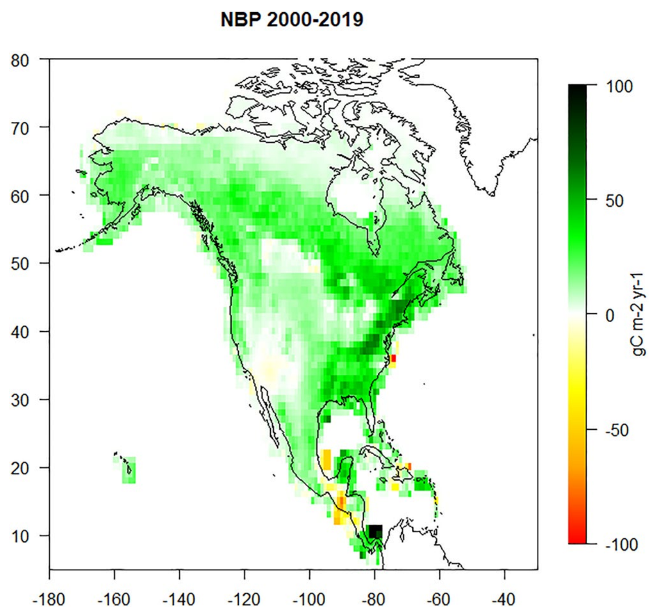

Figure 6. Mean gridded net biome productivity for the period 2000–2019 for North America. A positive value (green) indicates a net sink of C from the atmosphere, a negative value (yellow or red) indicates a net C source for the whole period.

area on its own. In addition, we found a similar relationship between the total soil moisture (mrso) anomaly from the DGVMs and their reported ensemble mean annual NBP (Figure 5b) ($p = 0.01$). Previous authors have found a similar link, for example, Mekonnen et al. (2017) reported a reduction of as much as 90% in the terrestrial C gain in North America during major droughts and in the past 30 years drought has been responsible for reducing NBP by 28%. Similarly, during 2000–2004 there has been a reported decline in stored C across western North America due to continued droughts (Schwalm et al., 2012). Thus, if climate change continues to exacerbate drought over North America it is likely that NBP will decline in consequence. In addition, although not analyzed here, the compounding effects of drought and fire have been shown to drive a large proportion of the land C emissions (Keppel-Aleks et al., 2014) and might represent an important future synergy of C-losses in North America under higher temperature conditions.

3.6. Spatial Variability of NBP

Spatially, most of North America was simulated to be a net sink of C (Figure 6). It seems models predict a net C sink despite land cover types and the highest uptake values seem to be located across cropland areas. In that sense, recent studies suggest that models underestimate the impact of disturbances, land use change and land practices to suppress C accumulation (Wang et al., 2021), and other factors that vary in space (e.g., soil fertility, nutrient deposition, and land management) are not resolved in most DGVMs, so it is unlikely that such homogeneity in the C sink exists if we explore the variability at higher spatial resolutions. For example, Canadian forests have mostly been cataloged as C sinks in DGVMs, but not by national forest inventories (Domke et al., 2020; Kurz et al., 2013). The latter show a decreasing sink or a source in recent decades, potentially driven by increasing disturbances such as pine beetle outbreaks (Kurz et al., 2008). This dramatic difference between modeled and observed estimates can result in opposite policy directions (Grassi et al., 2018, 2021; Ogle & Kurz, 2021), thus a better representation of the effect of disturbance in DGVMs (e.g., insect outbreaks, agricultural management, forest degradation) is urgent to provide better insights on the spatial distribution of the local sink-source dynamics.

We also identify two large regions that act as C sources in the DGVMs: across water-limited ecosystems in Southern California and Arizona, and across southern Mexico and most of Central America (Figure 6). Southern California and Arizona have experienced a continuous drought since 2011 (Seager et al., 2015) and the increase in observed wildfires over the last decade is likely contributing to a net C loss. An intensification of wildfires and drought has been associated with climate change (Mann and Gleick (2015); Williams et al., 2022), is contributing to desertification of the region (Overpeck & Udall, 2020), and has large impacts on vegetation encroachment and C losses (Lam et al., 2011). The second region is comprised by the states of Chiapas and Tabasco in southern Mexico along with the countries of Guatemala, El Salvador, and Nicaragua in Central America. This region has one of the largest deforestation rates across the Americas, because of land use change for cultivation and pastures (Kaimowitz, 1996). Thus, at least for these two regions, it seems that models are correctly reproducing the impact of climate and land use change on the C cycle.

We further explore the spatial patterns of the IAV of simulated NBP by analyzing the years with the smallest NBP in each decade (2002 and 2011) (years with the highest NBP have no clear patterns and are shown in the Figure S3 in Supporting Information S1). The year 2002—the only one which shows a net source of C- displays a loss of C for most of North America, with large negative values over the Prairie Provinces of Canada, Intramountainous Western United States, the North American deserts, and most of CA + C (Figure 7a). Hicke et al. (2013) showed that 2002 was particularly intense in terms of wildfires, affecting most of the western forest in the United States and over Canada. However, the main driver of these spatial patterns is likely the drought that began in late 1999 and ended in December 2002 (NOAA, 2002). For the regions with negative NBP, the soil moisture anomaly from the DGVMs was simulated to be −1.2% during this year. This event was particularly strong and long-lasting over United States central plains (NOAA, 2002) and over the Canadian prairies (Bonsal & Regier, 2007) (which may

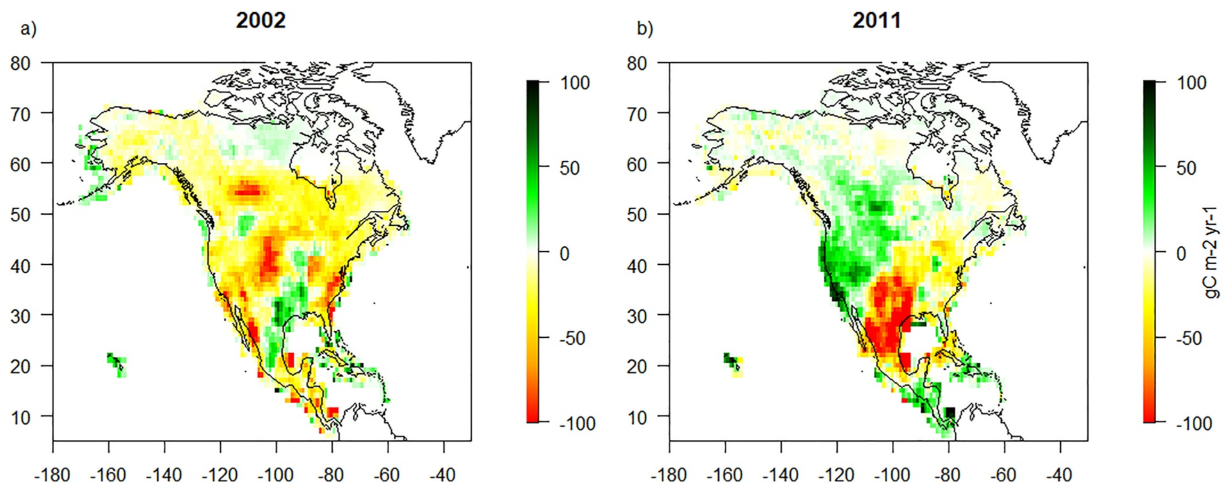

Figure 7. Spatial distribution of net biome productivity for North America during years with the lowest values for each decade. (a) 2002 and (b) 2011. For all panels positive values (green and black) indicate a net sink of C from the atmosphere and negative values (yellow and red) a net source.

also explain the positive NBP of the region, as the potential recovery after such event). The source of −0.02 PgC we estimated by the model ensemble is consistent with previous studies that attributed the change in C dynamics to a decrease in vegetation growth, driven by a general decline in precipitation and higher temperatures across the region (Zeng et al., 2005).

The negative spatial patterns for 2011 were less homogeneous and mostly centered across southern United States and Mexico, with the rest of North America being a net C sink (Figure 4b). This is consistent with the extensive and long-lasting drought that afflicted the southern United States and northern Mexico in the last decade (Seager et al., 2015) and that was correctly replicated in the model soil moisture anomaly, which was −1.4% for the C-source regions. The event lasted from January 2011 to April 2012 and was the worst drought in Mexico in the last 70 years (Murray-Tortarolo & Jaramillo, 2019), driven by a 12%–30% decrease in regional precipitation (Murray-Tortarolo & Jaramillo, 2019; Seager et al., 2015) and record-breaking temperatures (NOAA, 2011). As a result of this event, there was a large decline in terrestrial GPP, which led to a net loss of C from land, observable in the flux towers, inverse models, DGVMs, and the satellite data record (Liu et al., 2018; Parazoo et al., 2015).

3.7. NBP by Land Cover Type by Subregion

We compared the changes in simulated NBP among five categories of land cover type (Table 4). The C gains over the last two decades were taken up mostly by temperate forests (199 TgC year^{-1}, total gain from 2000 to 2019), followed by boreal forests (101 TgC year^{-1}) and lastly by the remaining categories (i.e., tropical forest, grassland/shrubland, and other; 70 TgC year^{-1}). The largest C sink is observed over the temperate forest in United States with 137 TgC year^{-1}, followed by boreal forests (74 TgC year^{-1}) and temperate forest (60 TgC year^{-1}) in Canada.

Table 4
Change in Net Biome Productivity by Land Cover Type and by Country/Region (TgC Year^{-1}) From 2000 to 2019

Vegetation type	United States	CAN	MEX	CA + C	North America
Tropical Forest	0	0	6	9	15
Temperate Forest	137	60	2	0	199
Boreal Forest	27	74	0	0	101
Grassland/Shrubland	19	11	7	3	41
Other (Tundra, Desert, Polar)	3	7	1	2	14
Total	187	152	17	14	370

Note. Positive values indicate a C sink.

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The results from the DGVMs are in line with previous studies reporting a large C sink across forested areas of United States. For example, Domke et al. (2020) reported a C uptake of 201 TgC year^{-1} for the forested areas of the country during 2003–2014. Similarly, Ryan et al. (2010) calculated a total C uptake of 15 PgC from 1935 to 2010, which is equivalent to 200 TgC year^{-1} over that time frame and Pan et al. (2011) estimated a C sink of 209 TgC year^{-1} for the period 1990–2007 from forest inventories. Based on all lines of evidence, it is very likely that forested regions across United States have been a persistent C sink over an extended period (as far back as 1935) and the models employed in this study seem to correctly simulate this behavior.

In contrast, Canadian boreal and temperate forests display large NBP variability depending on the approach employed in the calculation. For example, forest inventories situate the Canadian boreal forests as a small C sink (Kurz et al., 2013; Stinson et al., 2011). The most recent report by the IPCC estimated that the regional boreal forest of Canada has been a sink of about 0.044 PgC year^{-1} in the last decade (Canadell et al., 2021), a value three times lower than our estimations with the DGVMs. However, considerable discrepancies remain despite efforts to reconciliate NBP across forest inventories and DGVMs (e.g., Grassi et al., 2018), which have open research questions, including uncertainty about a lack of CO_2 fertilization effect captured in the national inventories or the lack of disturbance representation in models (e.g., insect outbreaks and wildfires) (Grassi et al., 2021; Ogle & Kurz, 2021). In addition, there are large spatial discrepancies on the extents employed to calculate the C fluxes; thus, while the DGVMs model the full region, the inventories only report managed forest lands. Furthermore, our previous results also indicate that models might be overestimating the positive effect of increasing temperatures on the Canadian C sink and underestimating its impacts on wildfire spread and recurrence. We conclude that DGVMs are likely overestimating the value of NBP across Canada, due to the limited representation of the growing impact of disturbances and possibly other key factors such as land degradation and nutrient deposition, but further efforts to reconcile both approaches are urgently needed to provide unified information for policy making.

Grasslands and shrublands in North America are widely distributed among the four subregions and represent an extensive area, yet this land cover type represents only 13% of the total C sink. For the whole region, grasslands (natural and cultivated) have been shown to represent 0.040 PgC year^{-1}, with more than half (0.027 PgC year^{-1}) located across the United States (Hayes et al., 2018), however these numbers are highly uncertain and need careful interpretation. Nevertheless, these results are generally similar to those reported by the DGVMs. Despite the general convergence of the estimates, most DGVMs usually struggle to separate natural grasslands from croplands and managed lands (Sun et al., 2021), resulting in large underestimation of the net C uptake and interannual variability when applied at the site level (MacBean et al., 2021).

Finally, the tropical forests in this analysis accounted for only 5% of the whole C sink, despite being potentially high C stocks and sinks. The area has been under extensive human pressures, mainly deforestation and land degradation (Vargas et al., 2012), which makes the estimation of the C cycle a difficult task. In that sense, calculations for the tropical forest across southern Mexico and CA + C vary widely depending on the approach employed in the calculation. For example, Cairns et al. (2000) computed a net C loss of −18.6 TgC year^{-1} during 1977–1992, while Murray-Tortarolo et al. (2016) estimated a net C gain of 11.7 TgC year^{-1} over 1990–2009 for tropical forests of Mexico. However, recent studies have also shown that forest degradation might have a larger impact on C losses than direct deforestation (Qin et al., 2021), a process not included in the models. As a result, it is likely that the region is acting as a net C source, but further large-scale studies are needed to reduce uncertainty and provide accurate information to benchmark DGVMs.

4. Conclusions

We presented a C budget for North America over the last two decades (2000–2019) for the whole region and four subdivisions (Canada, United States, Mexico, and Central America + the Caribbean: CA + C) based on an ensemble of terrestrial biosphere model simulation outputs. Results from the models indicate that the land ecosystems have been a C sink and assimilate an average of 0.37 ± 0.38 PgC year^{-1}. From this, two thirds of C is accumulated in the vegetation, mostly across temperate forests in United States and boreal forests in Canada. Over these 20 years (i.e., 2000–2019) we found no clear trend in modeled NBP, but the flux was strongly correlated with fire emissions and the area affected by drought, suggesting that water availability might be a fundamental modulator of C dynamics in the region.

We compared our results against the literature for each subregion to identify consistencies and missing gaps in our current understanding of their C budgets. For Canada, modeled NBP was generally higher than other estimates (e.g., forest inventories). This potential overestimation of NBP in the DGVMs, is likely driven by incorrect or nonexistent parameterization of fire and disturbances, as well as unrealistic responses of LAI to temperature. However, large discrepancies in reported forested area and processes included (e.g., lack of CO_2 fertilization in forest inventories) might also be responsible for the discrepancy. Given the importance of the region for C policies a reconciliation of estimates is urgently needed. For United States, the C budget was in line with previously published studies, but large discrepancies exist among the simulated values for fire emissions, which could explain as much as 41% of the IAV of NBP. Finally, both Mexico and CA + C seem to be C neutral, according to the DGVMs, across these two decades, likely representing a balance between a small C sink and large fire emissions.

Most of the current studies suggest that fire has increased across North America over the last 20 years and it is possible that this increment is exerting a larger control over the terrestrial NBP, both as a direct impact and as a long-lasting impact trough resetting forest succession. We also found evidence of a link between the area affected by drought and the IAV of NBP, with the driest years having the lowest NBP values, including the potential reversal of land from sink to source. Thus, we are seeing a strong relationship between the IAV of fire, drought and NBP across these two decades, which as far as we are aware, was not presented before in the literature. A key missing analysis due to data limitation would be to include the compounding effect of both drivers on NBP, to fully characterize the impact of climate extremes on the region. In addition, the results indicate that, when reporting fire emissions, area-weighted emissions might provide better insights regarding land management, therefore they might be more relevant as decision making tools.

Overall, DGVMs are an important and useful tool for characterizing the C balance of terrestrial ecosystems. Our study highlights several issues that could be incorporated or considered to improve models and our understanding of future terrestrial C cycle dynamics. Our findings highlight the importance of identifying attributions for interannual variability of the land C cycle and the spatial distribution of local sink-source dynamics. Incorporating the effect of droughts, fire, and other disturbances and their associated feedbacks may improve the representation of the C cycle in DGVMs, as these events have shown to intensify recently are likely to continue to do so in the future.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All data employed in this work is freely available at: https://blogs.exeter.ac.uk/trendy/ or at https://doi.org/10.5281/zenodo.7004433.

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