North America's net terrestrial CO_2 exchange with the atmosphere 1990-2009

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Abstract

Scientific understanding of the global carbon cycle is required for developing national and international policy to mitigate fossil-fuel CO_2 emissions by managing terrestrial carbon uptake.

Toward that understanding and as a contribution to the REgional Carbon Cycle Assessment and Processes (RECCAP) project, this paper provides a synthesis of net land-atmosphere CO_2 exchange for North America (Canada, United States, and Mexico) over the period 1990-2009. Only CO_2 is considered, not methane or other greenhouse gases. This synthesis is based on results from three different methods: atmospheric inversion, inventory-based methods and terrestrial biosphere modeling. All methods indicate that the North America land surface was a sink for atmospheric CO_2, with a net transfer from atmosphere to land. Estimates ranged from -890 to -280 Tg C yr^{-1}, where the mean of atmospheric inversion estimates forms the lower bound of that range (a larger land-sink) and the inventory-based estimate using the production approach the upper (a smaller land sink). This relatively large range is due in part to differences in how the approaches represent trade, fire and other disturbances and which ecosystems they include. Integrating across estimates, "best" estimates (i.e., measures of central tendency) are -472 ± 281 Tg C yr^{-1} based on the mean and standard deviation of the distribution and -360 Tg C yr^{-1} (with an interquartile range of -496 to -337) based on the median. Considering both the fossil-fuel emissions source and the land sink, our analysis shows that North America was, however, a net contributor to the growth of CO_2 in the atmosphere in the late 20th and early 21st century. With North America's mean annual fossil fuel CO_2 emissions for the period 1990-2009 equal to 1720 Tg C yr^{-1} and assuming the estimate of -472 Tg C yr^{-1} as an approximation of the true terrestrial CO_2 sink, the continent's source:sink ratio for this time period was 1720:472 or nearly 4:1.

1 Introduction

Only about 45% of the carbon dioxide (CO_2) released to the atmosphere by global human activities since 1959 (including the combustion of fossil fuels, cement manufacturing and deforestation and other changes in land use) has been retained by the atmosphere (calculated from data in Le Quéré et al., 2013). The remainder has been absorbed by the ocean and terrestrial ecosystems. Given observations of the increase in atmospheric CO_2, estimates of anthropogenic emissions, and models of oceanic CO_2 uptake, it is possible to estimate CO_2 uptake by the terrestrial biosphere (i.e., the land sink) as the residual in the global carbon budget (Le Quéré et al., 2013). Le Quéré et al. (2013) thus estimated the mean *global* land sink for 2002-2011 at 2.6 ± 0.8 Pg C yr^{-1}. Within the uncertainty of the observations, emissions estimates and ocean modeling, this residual calculation is a robust estimate of the *global* land sink for CO_2. However, both scientific understanding and policy considerations require more detail than is afforded by a global estimate since the magnitude, spatial pattern and temporal dynamics of the land sink vary considerably at continental and regional scales. Considerations of national and international policy to mitigate climate change by managing net terrestrial carbon uptake must account for this spatial and temporal variability. To do so requires more spatially-refined estimates along with an improved understanding of the major controlling factors and underlying ecosystem processes.

The REgional Carbon Cycle Assessment and Processes (RECCAP) project is an effort at regional refinement of terrestrial (and ocean) carbon fluxes based on a synthesis of multiple constraints (Canadell et al., 2011). An international activity organized under the auspices of the Global Carbon Project (Canadell et al., 2003; http://www.globalcarbonproject.org), the objective of RECCAP is "…to establish the mean carbon balance and change over the period 1990–2009 for all subcontinents and ocean basins" (Canadell et al., 2011, p. 81). RECCAP aims to achieve this objective through a series of regional syntheses designed to "…establish carbon budgets in each region by comparing and reconciling multiple bottom-up estimates, which include observations and model outputs, with the results of regional top-down atmospheric carbon dioxide (CO_2) inversions." Beyond the more spatially (regionally) refined estimates of carbon flux and processes, "[t]he consistency check between the sum of regional fluxes and the global budget will be a unique measure of the level of confidence there is in scaling carbon budgets up and down".

The objective of this study is a synthesis of net land-atmosphere CO_2 exchange for North America combining different approaches (i.e., atmospheric inversion, inventory-based methods and terrestrial biosphere modeling) over the period 1990-2009. The North American land area (21.748 10^6 km^2; Canada = 9.985 10^6 km^2, U.S. (including Alaska, excluding Hawaii) = 9.798 10^6 km^2; Mexico = 1.964 10^6 km^2) is approximately 16% of the global land area (excluding Greenland and Antarctica). North America's net land-atmosphere exchange is thus a potentially important fraction of the global land sink for atmospheric CO_2. In 2013, fossil-fuel and cement CO_2 emissions from North America (Canada, United States and Mexico combined) were second only to those from China (Le Quéré et al., 2014). Quantifying North America's net land-atmosphere CO_2 exchange, potentially offsetting at least a portion of North America's CO_2

emissions, is an important element of understanding and quantifying North America's contribution to the accelerating increase in atmospheric CO_2 concentrations (Le Quéré et al., 2014). Our approach was guided by a) Canadell et al. (2011); b) RECCAP syntheses for other regions (Dolman et al., 2012; Gloor et al., 2012; Haverd et al., 2013; Luyssaert et al., 2012; Patra et al., 2013; Piao et al., 2012; Valentini et al., 2014); c) guidelines found at the RECCAP website (http://www.globalcarbonproject.org/reccap/); and d) personal communications with J.G. Canadell as Coordinator of the RECCAP Science Steering Committee. This study focuses on estimates of land-atmosphere CO_2 exchange over Canada, the United States and Mexico. Although the inventory approaches included in this study are based on total carbon changes, we do not report flux estimates of other carbon gases such as methane and carbon monoxide or N_2O and other greenhouse gases. This study is a synthesis of the net contribution of the North American land surface to atmospheric CO_2 concentrations and is neither a carbon nor greenhouse gas budget for the region.

2 Methods

We estimated the annual net land-atmosphere exchange of CO_2-C (Tg C yr^{-1}) for North America using results from three different approaches to estimating carbon budgets over large areas: atmospheric inversion modeling, empirical modeling using inventory data, and terrestrial biosphere modeling. For each method, we provide estimates for the 1990-1999 and 2000-2009 decades and the entire 20-yr 1990-2009 period. We follow the convention that negative values of the estimated net land-atmosphere exchange represent net uptake of CO_2-C by the land surface (predominately in vegetation and soils) or a sink for atmospheric CO_2. Positive values thus represent a net release from the land to the atmosphere or a source of atmospheric CO_2. Lateral flows of carbon as they ultimately influence vertical exchange with the atmosphere, including the trade of grain, wood and fiber, are an important consideration in interpreting and comparing results from each of the approaches. The respective treatments of lateral fluxes in each of the approaches are discussed in the corresponding sections below. More generally, the different approaches include and exclude different contributions to the net land-atmosphere exchange (Figure 1). Those differences are likewise important in interpreting and comparing results and are described in the respective sections. Here we focus on reporting results aggregated for North

America; country-level breakdowns of the three approaches can be found in Hayes et al. (2012) for the 2000-2006 time period.

2.1 Atmospheric Inversion Models (AIMs)

The methods of atmospheric inversion modeling have been described previously in detail by Enting (2002), Gurney et al. (2008; 2003; 2002), Baker et al. (2006), Peters et al. (2007), Butler et al. (2010), Ciais et al. (2011) and others. As summarized by Hayes et al. (2012), AIMs combine data from an observation network of atmospheric CO_2 concentrations with models of surface CO_2 flux and atmospheric transport to infer from an inversion process the net land-atmosphere exchange of CO_2-C. Because they provide an integrated estimate of all CO_2 sources and sinks (over a given land area and time period) from the atmospheric perspective, inversions are sometimes referred to as a top-down approach (Canadell et al., 2011; Schulze et al., 2009). In estimating net land-atmosphere exchange, the influence of fossil-fuel emissions is assumed to be well-known and their influence is removed from the problem prior to solving for non-fossil fluxes (Peylin et al., 2013; Schulze et al., 2010). We use as our primary source the 11-model ensemble of RECCAP selected TransCom3 inversions (Peylin et al., 2013). The individual models are identified in Table 1 (p. 6703) of Peylin et al. (2013). North America here is defined by the combination of TransCom3 (Baker et al., 2006) regions “Boreal North America” and “Temperate North America” (Figure 2).

2.2 Terrestrial Biosphere Models (TBMs)

Terrestrial biosphere modeling employs a model of terrestrial ecosystem carbon dynamics deployed on a geospatial grid to simulate the exchange of carbon with the atmosphere, primarily as CO_2 (Hayes et al., 2012; Huntzinger et al., 2012; Schwalm et al., 2010). The models differ in which ecosystem processes they include and how they conceptually and mathematically represent them. Some, for example, include carbon release to the atmosphere from fire and other disturbances; others do not (see Hayes et al., 2012; Huntzinger et al., 2012). In order to estimate the net land-atmosphere exchange of CO_2 with TBMs, the models must minimally include the processes of CO_2 uptake from the atmosphere in gross primary production (GPP) and the release of CO_2 to the atmosphere in ecosystem respiration (Re), whether separated into autotrophic (Ra) and heterotrophic (Rh) respiration (Re = Ra + Rh) or not. Net primary production (NPP) is the balance between GPP and Ra (NPP = GPP – Ra). Net ecosystem production (NEP) is the balance between GPP and Re (NEP = GPP – Re or, equivalently, NEP = NPP - Rh). Net Biome Production (NBP) is defined by Schulze et al. (2000) as NEP minus nonrespiratory losses such as fire and harvest. It is defined by Chapin et al. (2006) as Net Ecosystem Carbon Balance (NECB) estimated at large temporal and spatial scales (where NECB is the net rate of organic and inorganic C gain by or loss from and ecosystem), and by RECCAP as NEP plus and/or minus all vertical and horizontal fluxes in and out of an ecosystem. NEP is a subcomponent of net ecosystem exchange (NEE) which is "…the net vertical exchange of CO_2 between a specified horizontal surface and the atmosphere above it over a given period of time" (Hayes and Turner, 2012). NEE is equivalent to the net land-atmosphere exchange of CO_2. However, NEP is often the only net exchange with the atmosphere simulated by TBMs (Hayes et al., 2012; Huntzinger et al., 2012). Thus NEP for these models is, with sign reversed, a minimal approximation of NEE or the net land-atmosphere exchange of CO_2. When the processes of CO_2 release from fire, land cover change, or other disturbances are included in the model (as in NBP), the approximation of net land-atmosphere exchange is even closer. It should be noted, however, that while some TBMs include CO_2-C loss from fire, very few, if any, include the trade and lateral transport of harvested wood or agricultural products and their subsequent release of CO_2, or the influence of insect outbreaks. These models, as a class, also generally ignore CH_4 emissions from livestock and N_2O emissions from agriculture. But these absences do not impact our estimate of net land-atmosphere CO_2 exchange from these models

Our source for results from TBMs was Version 2 of the 10-model ensemble of the GCP/RECCAP-Trendy activity (http://www-lscedods.cea.fr/invsat/RECCAP/V2/). The models in this ensemble are identified as Dynamic Global Vegetation Models (DGVMs), a subset of the larger class of TBMs (Sitch et al., 2008). We used the net biosphere production (NBP) from these models, which includes GPP, Re, and fire emissions, as the near equivalent of NEE approximating the net land-atmosphere exchange of CO_2-C. We extracted the results for North America from these global models, with North America defined by the "Boreal North America" and "Temperate North America" regions of Transcom3 (Figure 2) (Baker et al., 2006).

2.3 Inventory-based

Inventory-based methods for estimating net land-atmosphere CO_2 exchange use a combination of field survey, disturbance and land-use and management data, collectively referred to as 'activity data', to estimate net carbon emissions over time (IPCC, 2006). In general, repeated measurements and activity data are used to estimate *changes* in carbon stocks over time, and in this study CO_2 exchange with the atmosphere is inferred from these changes by decomposing them into additions and losses of carbon among the major pools (Hayes et al., 2012; Pan et al., 2011). The inventory-based flux estimates are based on a calculation that includes both the change in ecosystem carbon stocks (from live biomass and dead organic matter pools) as well as the change in stocks from product pools that considers the fate of carbon harvested from the ecosystem as a result of anthropogenic land management and use. Whether, how, where and when carbon stock changes in product pools, including those resulting from trade, are considered as sources or sinks depends on the accounting approach. The different "approaches" represent variations on the conceptual framework for reporting land-atmosphere CO_2 emissions and removals in greenhouse gases inventories. Within each approach, there can be different "methods" based on the underlying data sets and calculations used to estimate these emissions and removals. The inventory-based accounting approaches are conceptually similar and follow common guidelines, though the details of the methods differ by country (i.e., Canada, the U.S. and Mexico) and sector (e.g., forest lands and crop lands).

For comparison with estimates from the TBMs and AIMs, here we report net land-atmosphere exchange of CO_2 from inventories using two different accounting approaches: the "production approach" and the "atmospheric flow approach", which differ in where and when the emissions of carbon from harvested products are assigned (IPCC, 2006). The production approach assigns product emissions to the producing country (i.e. the country in which the carbon was harvested). The atmospheric flow approach assigns product emissions to the consuming country, based on stock change in the domestic product pool after adjusting for international imports and exports of harvested products. In both cases, the stock change estimates for harvested wood product (HWP) pools include "inherited emissions" from products harvested prior to our time period of analysis. In crop lands, the change in harvested crop product (HCP) pools is zero on an annual basis, so only the adjustment for international imports and exports influences the sink / source estimates (and only when using the atmospheric flow approach). The exception is in our estimates for

Mexico, where data on neither carbon stock changes nor the fate of harvested products are currently available to researchers (Vargas et al., 2012). For Mexico we therefore use the "default approach" (IPCC, 2006), which assumes no change in the product pools and so only carbon stock changes resulting from forest growth, deforestation and reforestation / afforestation are included. As such, we calculate only one inventory-based estimate for Mexico, but we add this same estimate to the continental totals in both the production and atmospheric flow approaches.

The two approaches are complimentary in terms of assessing the role of a particular country / sector in the global carbon budget both spatially and temporally. The distinction between the two is important in terms of comparison with other scaling approaches (Hayes et al., 2012). In general, most TBMs essentially employ the production approach where, if they consider harvested products at all, product carbon is typically assumed to be emitted from within the same grid cell as it was harvested. Thus, stock change estimates using the production approach are more appropriate for comparing inventory-based estimates with those of TBMs. On the other hand, we calculate an inventory-based flux estimate using the atmospheric flow approach as the more appropriate comparison with the AIMs. As they are based on atmospheric CO_2 observations combined with a transport model, AIMs should – in theory – detect a sink where the carbon was originally taken up in vegetation and a source where and when the product carbon is ultimately returned to the atmosphere through consumption or decay. These fluxes may, however, be below detection levels with current AIM technologies.

We used activity data based on national GHG inventories from Canada and the U.S. to estimate the contribution of forestlands to the net land-atmosphere exchange of CO_2-C for North America. Per IPCC Guidelines (IPCC, 2006), only "managed" forest lands are considered in the inventories, which excludes a large area of forest primarily in the boreal zone (i.e., the northern extent of Canada's forested area as well as interior Alaska). The Canada forest inventory uses the "gain-loss" methodology, which starts with data from a compiled set of inventories of forest carbon pools, which are then modeled forward based on the components of change, including growth, soil C respiration, natural disturbance and forest harvest (Kurz et al., 2009; Stinson et al., 2011). For the U.S., forest carbon stock and stock change estimates are based on the "stock change" methodology using repeated measurements in a design-based forest inventory (Bechtold and Patterson, 2005; Smith et al., 2013; USDA Forest Service, 2013). Aboveground standing tree (both live and dead) carbon pools are directly estimated from allometric equations (Woodall et al., 2011) of individual trees measured across the national plot network, while all other forest pools are estimated from models applied at the plot-level based on specific forest attributes (Smith et al., 2013; Smith et al., 2006; USEPA, 2012).

Both the production and atmospheric flow approaches were used to estimate contributions of HWP to Canadian and U.S. carbon fluxes. In the atmospheric flow estimate for the U.S., the HWP stock change calculations from the production approach (Skog, 2008) were adjusted for both imports *and* exports from international trade (USEPA, 2012). For Canada, however, the atmospheric flow estimate includes only exports; HWP imports to Canada are known to be very small relative to exports and are not tracked. As noted above, data on changes in HWP are not available for Mexico, and therefore the contribution of HWP is not part of the estimate of carbon fluxes for Mexico.

The estimates of net land-atmosphere CO_2 exchange from cropland in Canada and the U.S. are based on carbon stock change in agricultural soils and by imports and exports of agricultural commodities. Annual carbon flux from the herbaceous biomass in harvested crops is considered to be net zero because of the fast turnover time (decay and consumption) of this pool, with the exception of the transfer of residue carbon to soils, and the amount of carbon removed in HCP and exported from the region. In the case of agricultural soils, annual soil carbon stock change is estimated directly from activity data since soil carbon stocks are not commonly reported (West et al., 2011). Data on carbon stock change in crop land soils from Canada (Environment Canada, 2013) and the U.S. (West et al., 2011) were used, and estimates of carbon in HCP imports and exports were avaiable from each country (*Canadian Socio-Economic Information Management System*, Statistics Canada and *Foreign Agricultural Trade of the United States*, USDA Economic Research Service).

The contribution of lands in Mexico to the continental estimates of net land-atmosphere CO_2 exchange is derived from that country's Fifth National Communication to the United Nations Framework Convention on Climate Change (SEMARINAT / INECC, 2012). The data represent the carbon accounting for the Land Use, Land-Use Change and Forestry (LULUCF) sector, and includes estimates of carbon emissions and removals resulting from changes in biomass, the conversion of forests and grasslands to agricultural use, the abandonment of farmland, and carbon stock changes in mineral soils. These estimates use the default accounting approach based on a gain-loss method where mean carbon stock density by land cover type is distributed according the areal extent of each type at an initial point in time, and stock change is estimated according to the area of land-use change over a subsequent period of time (de Jong et al., 2010).

To these forest land and crop land estimates we also added the estimates of net land-atmosphere CO_2 exchange for the “tundra” region of North America (i.e., Alaska and northern Canada), as reported in the study by McGuire et al. (2012). That study also included modeled estimates, but here we used a synthesis of the observations as analogous to an “inventory” of that region’s carbon fluxes. While we add estimates for this large region from an existing study, our continental total estimates do not otherwise include land-atmosphere exchanges from other ecosystem types for which inventories were not available (e.g., arid lands, grasslands, temperate wetlands, shrublands or areas of woody expansion into tundra and grassland areas previously not forested and not meeting the definition of managed forest). Arid lands generally have low carbon stocks, but in wet years or decades could be an additional sink (Poulter et al., 2014) or source (Thomey et al., 2011) missed by the general exclusion of these lands from inventories. Similarly, a potential contribution to the North American sink is missed by the absence from the national inventories of woody encroachment into previously non-wooded lands (Hayes et al., 2012; King et al., 2012).

2.4 Estimating decadal mean net land-atmosphere exchange

For each of the multi-model approaches (AIMs and TBMs) we first estimated for each decade and the entire 1990-2009 period (n = 10 and 20, respectively) the mean and population standard deviation (σ) of each model’s time series of annual net exchange for North America. The standard deviation, describing the variability of annual values about the decadal or period mean, is an index of the model’s interannual variability for the period. We then averaged the model-specific time averages and standard deviations to estimate the multi-model mean and population standard deviation for each ensemble (n = 10 for the AIM ensemble and n = 10 for the TBM ensemble) for each decade and the entire 1990-2009 period. The resulting multi-model means are the estimate of net land-atmosphere exchange of CO_2-C for each method and time period. There are different opinions of how to best characterize "uncertainty" in CO_2 flux estimates, whether to use, for example, the standard deviation, standard error, 95% confidence intervals, inter-percentile/quartile ranges, or semi-quantitative characterizations such as that used by the IPCC in communicating confidence in scientific findings. For comparison with other RECCAP regional syntheses, we followed Luyssaert et al. (2012) and Ciais et al. (2010) in using the population standard deviation of the multi-model means as a metric of the "uncertainty" (i.e., variability) in the multi-model estimates.

The two inventory-based estimates (the production approach and the atmospheric flow approach) are both derived from the three regional source data sets (the land carbon stock inventories of Canada, the United States, and Mexico). There is no multi-inventory ensemble from which to estimate across inventory means and standard deviation. The apparent interannual changes in stocks of the U.S. and Mexico confound inventory uncertainty with actual year-to-year variations in changes in stocks and are unlikely to be a reliable estimate of interannual variability in net exchange with the atmosphere. The Canadian GHG inventory does use annual information on harvest, natural disturbances and land-use change (Stinson et al., 2011), and thus interannual variability resulting from activity data is reflected in those estimates. They do not, however, include changes due to interannual variation (or long term trends) in atmospheric chemistry and climate. Similarly, the inventories exclusion of arid lands and range lands means that these approaches also miss interannual variation associated with temporal patterns of precipitation in those regions (Poulter et al., 2014). Accordingly, we estimate net land-atmosphere exchange of CO_2-C from the inventory-based approaches using a single value, the time-averaged mean for each period, and do not report the time-averaged standard deviation either as an index of interannual variability or as a measure of uncertainty.

2.5 Fossil-fuel emissions

We also estimated the fossil-fuel source for North America to characterize the land sink relative to fossil-fuel emissions (King et al., 2007a) or the continent's source-to-sink ratio (King et al., 2012). Estimates were made following Andres et al. (2012) using data from (Boden et al., 2013). As with the inventories, we combined emissions data from Canada, the United States, and Mexico to estimate North American emissions.

3 Results

Table 1 compares the estimates of average annual net land-atmosphere exchange of CO_2-C for North America across the different methods. Table 2 compares the interannual variability. Most notable in Table 1 is the substantially larger estimate for the continental land sink (negative net land-atmosphere CO_2 exchange) from the atmospheric inversions as compared to the estimates from the other methods. The difference is on the order of at least a factor of two or more. This pattern has been noted before, most recently in the syntheses of Hayes et al. (2012), Huntzinger et al. (2012) and King et al. (2012).

Because we consider the estimates from the three different methods (Table 1) to all be scientifically credible, the central tendency of the distribution of those estimates can by synthesizing or integrating across the estimates provide some indicators of “best” estimates. Unfortunately the small sample size (n=4) and the asymmetry or skew introduced by the atmospheric inversion estimate (Figure 3) makes the arithmetic mean and standard deviation across the methods an unreliable estimate of central tendency and spread in the estimates. However, because the mean is so commonly used to integrate across estimates, we report the across method mean ± 1 sample standard deviation (s) in Table 1. The median and interquartile range as measure of central tendency and spread of such a skewed distribution are perhaps a more appropriate “best” estimate (Table 1 and Figure 3). The small sample size makes calculation of the mode (i.e., the most frequent/likely value) difficult or a misleading estimate of central tendency. However, inspection and a simple histogram of the estimates suggests a modal estimate of <400 Tg C yr^{-1} as an alternative, if imprecise, across-method estimate for 1990-2009.

Results in Table 2 are suggestive of some tendency for an increase in interannual variability in net land-atmosphere exchange in the 2000-2009 decade relative to the preceding 1990-1999 decade. However, given the relative short 10 year spans and intradecadal variability, any apparent trend should be considered cautiously, and the standard deviation for the entire 20-yr period a sounder indicator of interannual variability in North America's terrestrial sink. Across approaches, the atmospheric inversions show somewhat greater interannual variability than the TBMs (Table 2). Raczka et al. (2013) similarly showed that TBMs consistently underestimated the amplitude of interannual variability with respect to flux tower records across North America.

Figure 4 displays the fossil-fuel-CO_2 emissions for the three countries, their sum, and the sum of all countries around the world (i.e., global emissions). Solid lines represent annual emissions and dashed lines represent the decadal mean of emissions. For most political units shown, the decadal means well represent the annual emissions at this scale. Only for global emissions, especially in the latter decade, is the decadal mean a poor representation of the annual emissions. Emissions from Mexico and Canada are too similar in magnitude to be easily discernible from each other in this figure.

Table 3 displays the numerical details of Figure 4 as well as relative percentages of smaller political units to larger political units. In terms of mass emitted globally in calendar year 2010, out of 216 countries, the U.S. is the second largest emitter, Canada is ranked #9, and Mexico is ranked #13. Prior to 2006, U.S. emissions ranked #1; thereafter China has had the largest emissions (Global Carbon Atlas, 2013; Le Quéré et al., 2014). In 2010, North America as a whole is ranked #2 behind China. For the period 1990-2009, uncertainty (in Tg C yr^{-1}) was higher in Mexico (~10% of mean), lower for Canada (~2% of mean) and substantially lower in the U.S. (~0.02% of the mean) (Table 3).

Table 4 is as Table 1 but with the entries replaced by the estimates of the terrestrial sink as a percentage of North American fossil fuel emissions. These proportions range across methods and decades from nearly 60% to as low as 5%, with a "best" estimate of perhaps 20-30%. There is no clear decadal trend in the sink as a proportion of fossil-fuel emissions; some methods suggest an increase, others a decrease, and, with the exception of the inventory-based estimates, the changes are small. But again, as in Table 2, the relatively short record means any apparent change over time in the sink strength relative to fossil fuel emissions should be considered cautiously and should not be considered significant, statistically or otherwise.

Table 5 is as Table 1 but with the entries replaced by the estimates as a percentage of the global land sink estimated by difference to balance the global carbon cycle (Le Quéré et al., 2013). The average global net land-atmosphere exchanges are -2460, -2320 and -2390 Tg C yr^{-1} for the periods 1990-1999, 2000-2009 and 1990-2009, respectively. While a crude comparison because the global terrestrial sink is not thought to be uniformly dispersed geographically, the numbers in Table 5 around 15% are in keeping with the approximately 16% of the global land surface (minus Greenland and Antarctica) represented by North America (minus Greenland). North America is approximately 21% of the Northern Hemisphere land surface. While the majority of the global land sink is likely in the Northern Hemisphere (Field et al., 2007), it is unlikely that the entire global sink is in the Northern Hemisphere. Nevertheless, the atmospheric inversion estimates of the North American sink at slightly less than 40% of the global sink suggest a North American sink disproportional to North America's share of the Northern Hemisphere land surface. However, the across-method mean and mode estimates (Table 5) indicate a sink approximately proportional to North America's relative land area as part of the Northern Hemisphere.

4 Discussion and Conclusions

All estimates of North America's net land-atmosphere exchange of CO_2-C synthesized in this study are negative values (Table 1), indicating a net exchange from atmosphere to land (i.e., net land uptake of CO_2-C). We therefore conclude, along with most previous assessments, that the vegetation and soils of North America were a sink for atmospheric CO_2 over the decades of 1990-2009. Our estimates of the net land sink for 1990-2009 range from as large as -890 ± 409 Tg C yr^{-1} (multi-model mean ± σ) to as small as -280 Tg C yr^{-1}, with the estimates from atmospheric inversions and from the inventory-based production approach the large and small ends of that range, respectively. The ranges for the decades 1900-1999 and 2000-2009 are -929 ± 477 Tg C yr^{-1} to -83 Tg C yr^{-1} and -890 ± 400 Tg C yr^{-1} to -270 Tg C yr^{-1}, respectively. The atmospheric inversion and inventory-based production approach are again the high and low ends of those ranges. The State of the Carbon Cycle Report's (SOCCR) (King et al., 2007b) synthesis and assessment of the North American carbon cycle estimate of the North American terrestrial sink circa 2003 based on inventories was -500 Tg C yr^{-1} with uncertainty of ±50% [1] (Pacala et al., 2007). Our inventory-based estimates are lower than that of the SOCCR because while our estimates include the contribution of tundra they are based on forest and cropland inventories and exclude additional but highly uncertain sinks such as woody encroachment into previously non-woody ecosystems, wetland sinks, and sequestration in rivers and reservoirs included in the SOCCR estimate. The SOCCR found woody encroachment to be a relatively large sink of -120 Tg C yr^{-1}, second only to the forest sink, but with uncertainty of >100%. We feel justified in leaving these additional uncertain sinks out of inventory-based estimates until the uncertainty is reduced by further study. These additional sinks contribute, however, to the estimates from the AIMs and TBMs and may be partially responsible for their larger sink estimates relative to inventory-based estimates. A post-SOCCR assessment for circa 2000-2005 synthesizing atmospheric inversion, TBM and inventory-based approaches estimated a North American land sink of -634 ± 165[2] Tg C yr^{-1} (King et al., 2012). Our "best" estimate for 2000-2009 based on the average across methods is -472 ± 281 (mean ± s) (Table 1). Our "best" estimate based on the median of the estimates from different methods is -360 Tg C yr^{-1} with 68% percent of the estimates (equivalent to the proportion represented by ± 1 standard deviation) in the range -638 to -316 Tg C yr^{-1}. Synthesizing across these syntheses, we conclude the North American land sink for the first decade of the 21st century was most likely in the range of -300 to -600 Tg C yr^{-1} but with a relative uncertainty of ±65-78% to be highly (95%) confident that the actual value lies within even that large range.

We have made no attempt to resolve temporal trends in the estimates of net land-atmosphere exchange due to the relatively short time frame. However, Kurz et al. (2008) found that Canada's managed forests switched from being a GHG sink to a source in 2002 as a result of large insect outbreaks, and those forests have been a carbon source for all but two (2008-2009) of the subsequent years (through 2012) (Environment Canada, 2014; Stinson et al., 2011). If there had

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[1] The range relative to the estimate of -500 Tg C yr^{-1} which the authors were highly (95%) confident included the actual value. This is not a coefficient of variation comparable to the standard deviation used in this paper as a measure of uncertainty (i.e., variability) surrounding a mean estimate. It is also not the 95% confidence interval although it is more comparable to that measure of uncertainty than the standard deviation used here.

[2] Multi-method mean ± 1.96 standard error of the mean.

been no change in disturbance in either the United States or Mexico over that period, the North American sink might be expected to decline between the decades of 1990-1999 and 2000-2009. There is perhaps some suggestion of a shift in that direction in the AIM estimates and perhaps the TBM estimates (Table 1), but the uncertainties are very large and any conclusion, as noted above, is tentative at best. Moreover, the inventory-based estimates suggest an increase in the sink (Table 1). Increases in natural disturbances (a declining sink) are off-set by simultaneous decreases in harvest rates (an increasing sink) and these two opposing trends in the activity data may make it difficult to identify a clear overall trend in the CO_2 balance using inventory-based methods. Decadal changes in disturbance like those reported by Kasischke et al. (2013) likely influence the North American sink, but a clear definitive signal of that influence in the estimates given their uncertainties is elusive.

The North American land sink is only a fraction of the fossil fuel emissions from the region for that same period (Table 4). The source:sink ratio for the 1990–1999 decadal average ranges across methods from approximately 1628:83 (nearly 20:1, the estimate from inventories using the production approach) to as low as 1628:929 (nearly 2:1, the atmospheric inversion estimate). For the 2000–2009 decade that range is from 1812:270 (nearly 7:1) to 1812:890 (approximately 2:1), with the inventory-based production approach and atmospheric inversion approach again generating that range. For the entire 1990–2009 period that range is from 1720:280 (approximately 6:1) to 1720:890 (nearly 2:1). Based on "best" estimates of the land sink for that entire period, the ratio is in the range of 1720:360 (nearly 5:1) based on the median estimate and 1720:472 (nearly 4:1) based on the average estimate. In the SOCCR the North American source:sink ratio circa 2003 was estimated at approximately 3:1 (King et al., 2007a). King et al. (2012) also estimated a source:sink ration of approximately 3:1 for the period 2000-2005. The larger potential value of 4:1 reported here is attributable to a smaller estimate of the sink based on the median value of the multiple methods (Table 1). Considering both the fossil-fuel emissions source and the land sink, North America was a net contributor to the growth of CO_2 in the atmosphere in the late 20th century and early 21st century, with emissions exceeding the land sink by at least a factor of three.

Both methods (AIMs and TBMs) for which we could calculate the time-average standard deviation as a measure of interannual variability show greater variability in the 2000-2009 decade than in the previous decade. However, as noted in the Results above, the relatively short record and the averaging by decade make us hesitant to draw any conclusions about changes in interannual variability from decade to decade for any of the approaches. A time series analysis of variability over a longer time period is likely needed to determine whether the North American land sink has been increasing or decreasing, and any such trend may well vary with approach. We can say, however, that the AIMs show larger variability than the TBMs (Table 2). Whether this is due to the inversions "seeing" variable net land-atmosphere exchanges not well represented in the TBMs or to or to some unidentified source of error in the AIMs is unclear. Findings by Poulter et al. (2014) showing the influence of Southern Hemisphere arid grasslands in wet years on interannual variation in the global carbon sink suggest that it may very well be the former. The work of Raczka et al. (2013) showing that TBMs systematically underestimate NEE relative to North American flux towers also points to the conclusion that AIMs are capturing interannual variability in net-land atmosphere CO_2 exchange not well represented by TBMs.

Different methods for estimating the net land-atmosphere exchange of CO_2 of North America continue to generate different estimates of that flux (Hayes et al., 2012; Huntzinger et al., 2012; King et al., 2012) as in this study. Although the different methods all attempt to estimate the same net land-atmosphere flux, the methods account for different components of that exchange (Figure 1). The atmospheric inversions are influenced by all land-atmosphere exchanges. The TBMs only account for net exchange from those ecosystems and processes that they actually simulate, and the inventory-based estimates are limited to the ecosystems that are actually included in the inventories (e.g., managed forests, as defined by those responsible for the inventory, but not arid lands, grasslands, croplands, wetlands and other non-forest categories). These differences in fluxes captured by the different methods likely contribute to the different estimates.

Disturbance, natural and human, plays an important role in determining North America's net land-atmosphere CO_2 exchange (Kasischke et al., 2013; King et al., 2012). Indeed, much if not most of the early 21st Century North American land sink can be attributed to the recovery of forests from earlier disturbance, primarily human clearing and harvesting in the United States

(Goodale et al., 2002; Hayes et al., 2012; Huntzinger et al., 2012; King et al., 2012; Myneni et al., 2001; Pacala et al., 2007; Pan et al., 2011). On annual to decadal time scales, the contributions from disturbance are generally greater than those from enhanced GPP with rising atmospheric CO_2 or in response to variations in weather (Luyssaert et al., 2007). The variety of disturbance types, heterogeneity in the spatial and temporal characteristics of disturbance regimes and disturbance intensity, and the many ways disturbance can impact terrestrial ecosystem processes in North America (Kasischke et al., 2013), lead to complexity in quantifying the specific contribution of disturbance to net land-atmosphere exchange. The source-sink consequences of disturbance change over time (Amiro et al., 2010; Liu et al., 2011). For example, a forest fire releases CO_2 to the atmosphere during combustion (a source), the reduction in canopy results in an imbalance between GPP and Re which can reduce the sink represented by a formerly aggrading forest or convert the landscape to a source while Rh exceeds NPP with lags between Re and Rh (Harmon et al., 2011). Over time, as the forest recovers, NPP exceeds Rh, and the regrowing forest is a sink for atmospheric CO_2 (Kurz et al., 2013).

The three approaches for estimating net land-atmosphere CO_2 exchange differ in how they perceive or represent contributions from disturbance. Atmospheric inversion modeling captures the influence of disturbance contributions to patterns in atmospheric CO_2 concentrations, but cannot generally attribute those changes to disturbances or disturbance types without additional effort involving carbon monoxide or other atmospheric gases, carbon isotopes, or structured attribution analyses (Keppel-Aleks et al., 2014; Randerson et al., 2005). Inventory-based estimates capture the impact of disturbance on changes in carbon stock but the carbon accounting might (e.g., the Canadian forest inventory) or might not (e.g., the U.S. and Mexico forest inventories) explicitly consider disturbances. In the US, knowledge from other sources about areas burned (and other disturbances) can be used to inform GHG emissions estimates and allow for at least some attribution of specific disturbance to changes in carbon stocks even when disturbances are not explicitly accounted. Terrestrial biosphere modeling can attribute land-atmosphere CO_2 exchange to specific disturbances, but only those which the model explicitly represents and the models differ considerably in which disturbance types they include and how they represent those disturbances and the consequences for CO_2 exchange with the atmosphere (Hayes et al., 2012; Huntzinger et al., 2012; Liu et al., 2011; Sitch et al., 2013). For example some models include fire as an internal prognostic variable, others as an external forcing and some not at all (Huntzinger et al., 2012; Sitch et al., 2013). Incomplete or mis-representation of disturbances by the TBMs likely contributes to differences between the TBM estimate and the AIM and inventory-based estimates. Williams et al. (2012) used information on age structure from U.S. forest inventory data to parameterize the disturbance and recovery processes of a carbon cycle model similar to the TBMs reported on here. They found a much smaller net carbon sink for conterminous U.S. forests than previous estimates using those inventory data in stock-change approaches like those of the inventory-based estimates here (Williams et al., 2012). The same source of data used in different methods can yield different results. Particulars of how disturbance is represented in inventories are also likely responsible for some portion of the difference between AIM and inventory-based estimates of net-atmosphere CO_2 exchange.

Within-method uncertainties also contribute to the differences in estimates and the uncertainty surrounding those estimates (Enting et al., 2012). Each method involves numerous assumptions and myriad sources of uncertainty: transport uncertainty, limited atmospheric data and inversion methodology in the atmospheric inversions; parameter, process and input data uncertainty in the TBMs; and uncertainty in estimating carbon stock from a limited number of observations of tree height and diameter in forest inventories are just a few examples. In principle the different estimates should agree, but the uncertainty in a method's estimate may cloud that agreement. Multiple and diverse sources of uncertainty within methods make the reconciliation of the estimates by reducing uncertainty more difficult.

The approaches also differ in their coverage of subregional heterogeneity in ecosystem types. Atmospheric inversions estimate the total land–atmosphere CO_2 exchange from a given region, including any fluxes associated with carbon traded across the region's boundaries, while inventory-based approaches estimate only those exchanges from ecosystem types represented in the inventories (most commonly forest and cropland), and may or may not represent trade of products from those ecosystem types. As such, estimates from AIMs may capture fluxes missed by inventory-based estimates, while inventory-based estimates can attribute emissions to specific ecosystems thereby assisting in the management of carbon sources and sinks. Likewise, the estimates from TBMs only include those ecosystem types and fluxes simulated by the models but can attribute those fluxes to particular processes and ecosystems that might be managed.

Differences in the treatment of trade, fire, insects, land-use change, methane and methane conversions, arid regions, and permafrost and peatland processes are among the many possible contributions to differences in estimated net land-atmosphere exchange among and within the approaches. Years of research have provided information on these various components, but no single comprehensive, integrated, agreed upon treatment of them in their entirety exists for attribution of the net flux estimated by the AIMs, to guide national carbon inventories, or for implementation in TBMs. Efforts to resolve differences among approaches and specific attribution of the North American sink will likely require a community effort to test specific hypotheses involving, initially at least, one or a very small combination of these components. Recent indications by Poulter et al. (2014) of the influence of arid lands under El Nino conditions combined with the uncertain contribution of woody encroachment to the North American land sink (Hayes et al., 2012; King et al., 2007a) suggest more attention to woody biomass changes in arid and semi-arid environments as a promising area of investigation. This attention might include focus on these lands and dynamics in an inter-model comparison of TBMs or structured synthesis and perhaps additional observations of carbon inventories for these regions.

There is some indication of convergence in the estimates from the different methods across previous syntheses (Hayes et al., 2012; King et al., 2007b; King et al., 2012) and the work presented here, suggesting a North American land sink in the first decade of the 21st century in the range of -300 to -600 Tg C yr^{-1}. Convergence of inventories with AIMs has been shown for one data-rich region of North America for one year (Schuh et al., 2013), but the level of observational and analytic effort put into this study has not yet been replicated at the continental scale. However, with additional synthesis and assessment within continents, the North American Carbon Program's Regional and Continental Interim Synthesis activities (Huntzinger et al., 2012; Schuh et al., 2013), for example, and with inter-continental syntheses like RECCAP (Canadell et al., 2011; Ciais et al., 2010) there may be further convergence and improved understanding of remaining differences. Either or both will improve not only scientific understanding of the carbon cycle but the input into considerations of national and international carbon policy as well.

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Table 1. Mean ± 1 standard deviation (*s*) of annual net land-atmosphere exchange of CO_2-C (Tg C yr^{-1}) for North America by decade and the 1990-2009 period.

Method	1990-1999	2000-2009	1990-2009
Atmospheric inversion[a]	-929 ± 477	-890 ± 400	-890 ± 409
Inventory: atmospheric flow approach[b]	-159	-348	-356
Terrestrial biosphere modeling[c]	-370 ± 138	-359 ± 111	-364 ± 120
Inventory: production approach[b]	-83	-270	-280
"Best" estimates			
Mean ± s	-385 ± 382	-467 ± 285	-472 ± 281
Median (interquartile range)	-264 (-510 to -140)	-354 (-492 to -328)	-360 (-496 to -337)
Mode	> -500 < 0	> -400 < 0	> -400 < 0

[a] The multi-model mean and standard deviation of the time-period means of the RECCAP selected TransCom3 inversions of Peylin et al. (2013).

[b] See Methods. Note that there is single inventory estimate and thus no "multi-model" mean or standard deviation.

[c] The multi-model mean and standard deviation of the time-period means of ten RECCAP-Trendy models' time-averaged annual NBP (see Methods)

Table 2. Interannual variability of annual net land-atmosphere exchange of CO_2-C (Tg C yr^{-1}) for North America by decade and for the 1990-2009 period. The population standard deviation (σ) of annual exchange is used as an index of interannual variability.

Method	1990-1999	2000-2009	1990-2009
Atmospheric inversion[a]	316 ± 156	368 ± 115	364 ± 129
Terrestrial biosphere modeling[b]	218 ± 73	250 ± 52	239 ± 58
"Best" estimates			
Mean ± s	267 ± 69	309 ± 83	302 ± 88
Median (interquartile range)[c]	267 (242 to 292)	309 (280 to 338)	302 (270 to 333)

[a] The multi-model mean (± 1 s) of individual within-model standard deviations from the time-averaged (see Table 1) atmospheric inversion estimates of net land-atmosphere exchange (see Methods) for each time period for the RECCAP selected TransCom3 IAV models (Peylin et al., 2013).

[b] The multi-model mean (± 1 s) of individual within-model standard deviations from the time-averaged annual NBP (Table 1 and Methods) for each time period for ten RECCAP-Trendy models.

[c] With only two estimates there is no asymmetry in the distribution as evidenced by the equivalence of mean and median; likewise there is no mode.

Table 3. Mean, standard deviation, uncertainty, and relative percentage of emissions for various political units and years. The standard deviation of the time-averaged mean is indicated by s. Uncertainty is our best assessment of how well we know the mean, integrating the variability of the data with knowledge of the quality of the data. North America's percentage of global total does not equal the sum of its components due to rounding. Flux data from Boden et al. (2013); uncertainty estimate from Andres (unpublished data).

	years	mean (Tg C)	s (Tg C)	uncertainty (Tg C)	Emissions % of N.America	emissions % of global total
Canada	1990-1999	129.34	6.42	2.59	8	2
	2000-2009	147.75	4.51	2.95		
	1990-2009	138.54	10.75	2.77		
Mexico	1990-1999	93.54	5.75	9.45	6	2
	2000-2009	115.47	7.92	11.66		
	1990-2009	104.50	12.96	10.55		
United States	1990-1999	1404.90	69.42	28.10	86	22
	2000-2009	1548.94	38.89	30.98		
	1990-2009	1476.92	91.39	29.54		
N. America	1990-1999	1627.78	80.11	34.95	100	25
	2000-2009	1812.16	43.44	39.41		
	1990-2009	1719.97	112.48	37.18		
Global	1990-1999	6169.80	162.90	203.72	---	100
	2000-2009	7471.66	653.98	271.50		
	1990-2009	6820.73	806.73	237.61		

Table 4. Mean annual net land-atmosphere exchange of CO_2-C for North America by decade as a percentage of North American fossil fuel emissions (from Table 3). Note that these are independent proportions and do not add to 100%.

Method	1990-1999	2000-2009	1990-2009
Atmospheric inversion	57%	49%	52%
Inventory: atmospheric flow approach	10%	19%	21%
Terrestrial biosphere modeling	23%	20%	21%
Inventory: production approach	5%	15%	16%
“Best” estimates			
Mean	24%	26%	27%
Median	16%	20%	21%
Mode	< 31%	< 28%	29%

Table 5. Estimates of mean annual net land-atmosphere exchange of CO_2-C for North America by decade and for 1990-2009 as a proportion of the global mean annual net land-atmosphere exchange for those same periods.

Method	1990-1999	2000-2009	1990-2009
Atmospheric inversion	38%	38%	37%
Inventory: atmospheric flow approach	6%	15%	15%
Terrestrial biosphere modeling	15%	15%	15%
Inventory: production approach	3%	12%	12%
“Best” estimates			
Mean	16%	20%	20%
Median	11%	15%	15%
Mode	< 20%	< 22%	< 21%

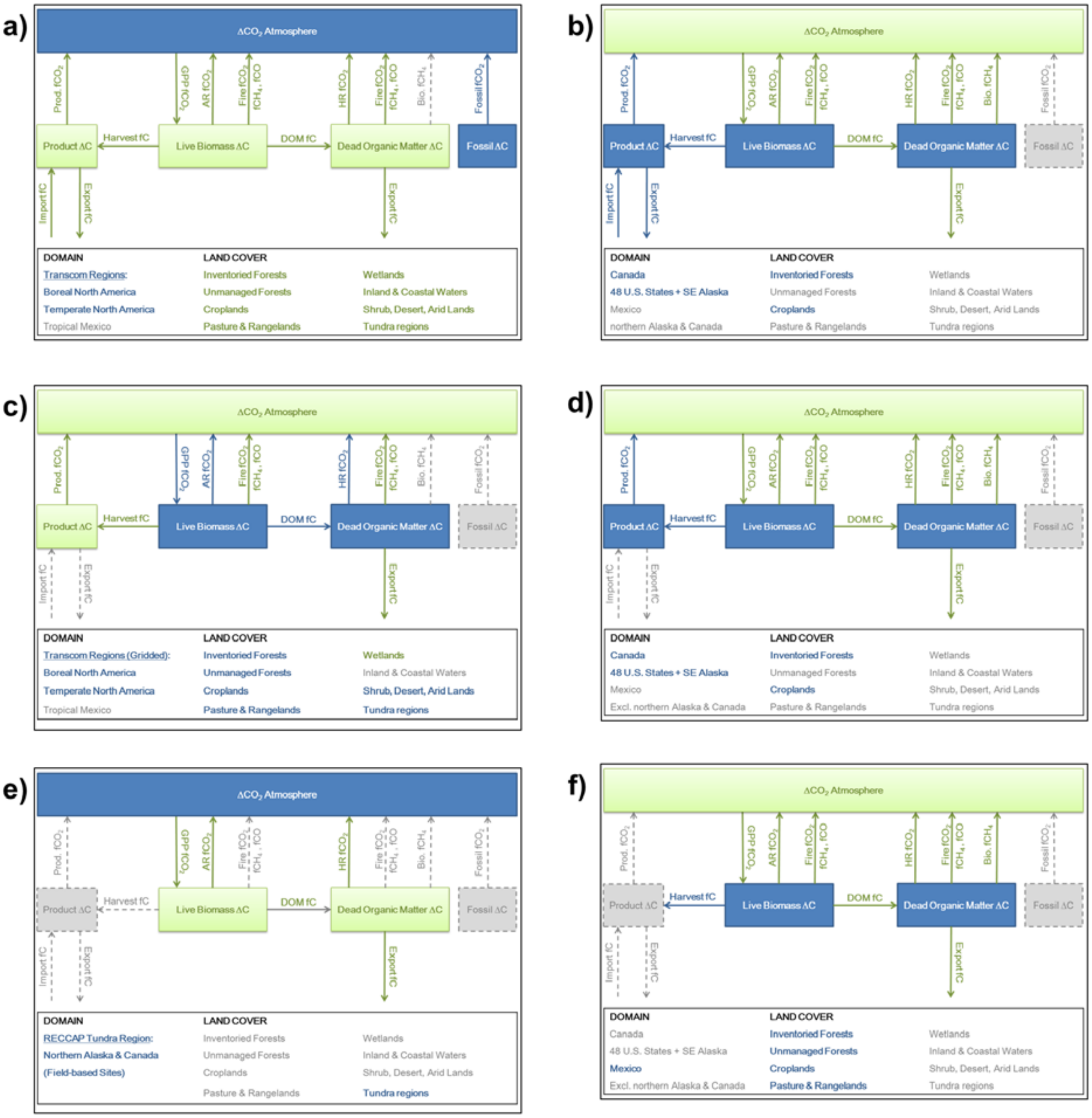

Figure 1. Carbon dioxide budget diagrams illustrating the spatial domains and component fluxes included in each approach and data set synthesized in this study: a) atmospheric inversion models (AIMs), b) atmospheric flow inventory, c) terrestrial biosphere models (TBMs), d) production approach inventory, e) tundra ecosystem flux measurement, and f) Mexico land-use change (default approach) inventory. In each diagram, flux components are shown in blue when explicitly estimated (i.e., observed, measured or simulated), in green when implicitly contributing to an aggregated flux but not estimated directly, and in gray when explicitly not included in the estimate.

Atmospheric methods (a, e) measure the concentration or flux of CO2 in the atmosphere, which implies all land-atmosphere CO2 exchange components (and excludes non-CO2 fluxes). AIMs (a) integrate CO_2 concentrations for large regions (Boreal & Terrestrial North America) and explicitly subtract out the contribution of fossil fuel emissions in order to quantify the terrestrial contribution. The eddy covariance flux measurements for the tundra region (e) are similar in concept, but are site-based and so are not influenced by fire, fossil or harvested product emissions. Inventory approaches (b, d, f) are primarily based on carbon stock change estimates in the major live biomass and dead organic matter pools. Mostly implicit in the inventories, then, are the fluxes in and out of these pools, with the exception of harvested carbon (crop and wood) removals that need to be tracked to determine the role of product consumption and decay emissions in the overall budget. The atmospheric flow approach (b) considers product imports and exports from international trade in calculating the stock change in the product pool, whereas the production approach (d) does not. The default approach (f) excludes the harvested product pools from the accounting. Finally, there is large variation in how TBMs (c) explicitly simulate, implicitly include, or explicitly exclude the various flux components; here, we represent a 'basic case' where all models simulate ecosystem production and respiration and track the major pools. TBMs differ widely, though, as to whether and how they simulate fire, harvest, product emission and dead organic matter export fluxes (i.e. riverine export). None of the models in this study include estimates of fossil fuel emissions, biogenic methane flux or the lateral transfer of product carbon via international trade.

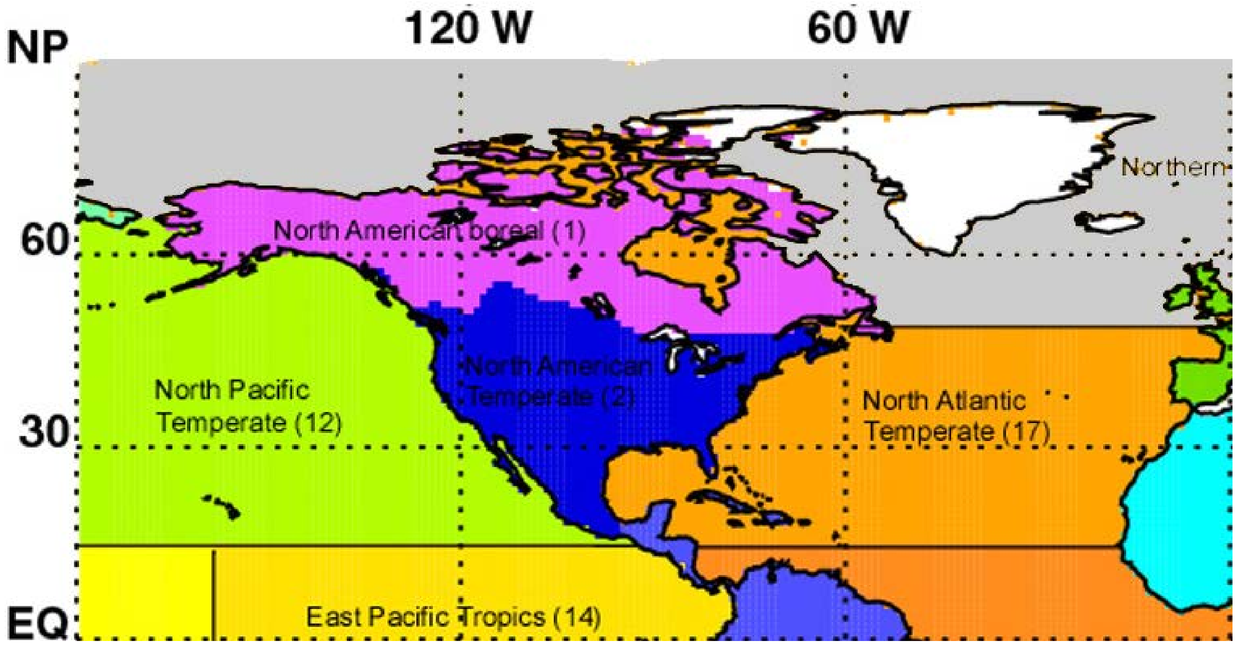

Figure 2. TransCom3 regions of the western Northern Hemisphere (Baker et al 2006). The combined North American Boreal and North American Temperate regions define North America for the Atmospheric Inversion Model (AIM) and Terrestrial Biosphere Model (TBM) approaches to estimating net land-atmosphere carbon exchange for North America. Adapted from http://transcom.project.asu.edu/transcom03_protocol_basisMap.php.

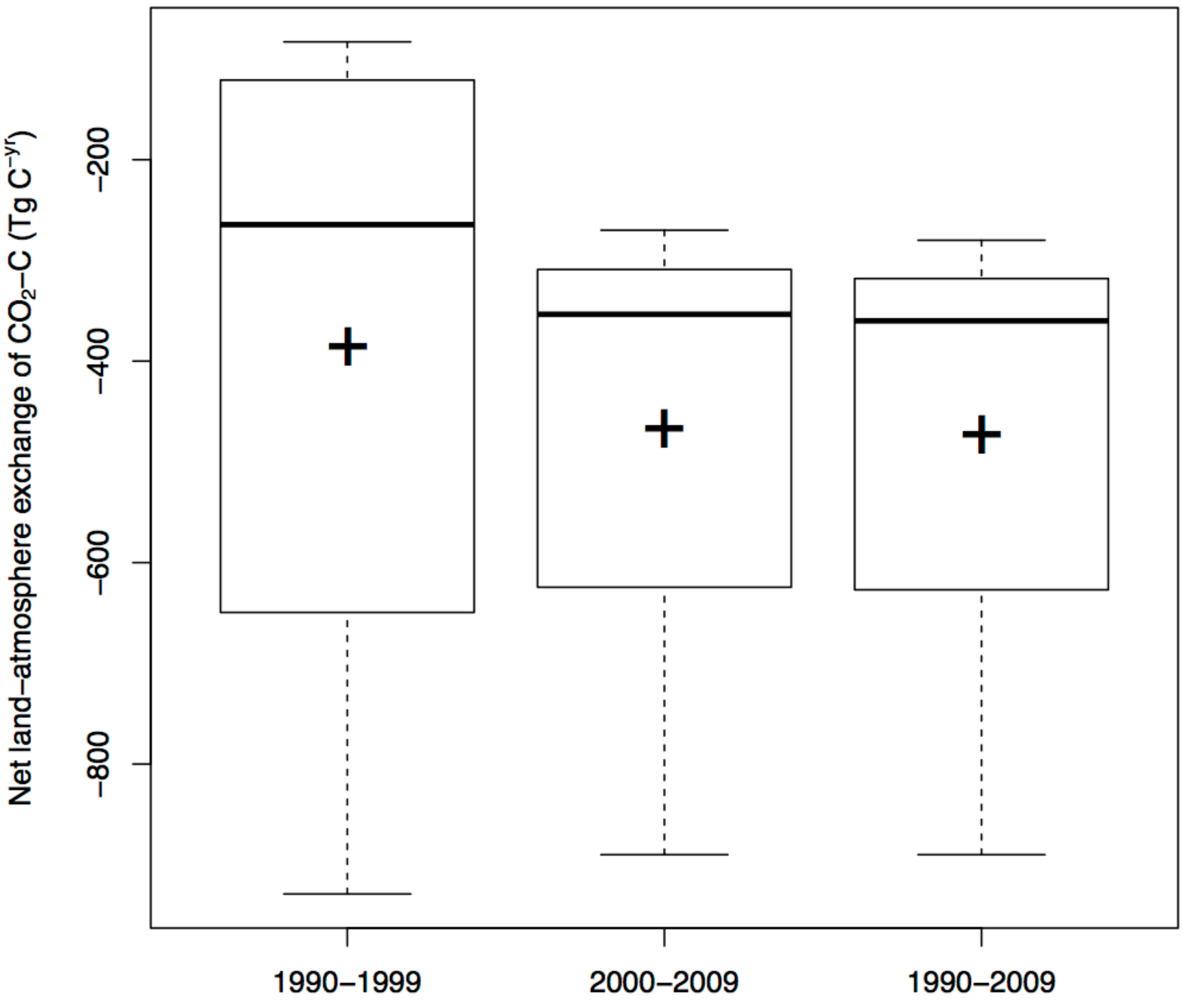

Figure 3. Box-and-whisker diagrams of the estimates from the different methods. The bold horizontal line indicates the median, the + the mean. The upper and lower bounds of the box are the “hinges” of the Tukey box-and-whisker algorithm of R’s boxplot and approximate the interquartile range. The whiskers indicate the minimum and maximum values.

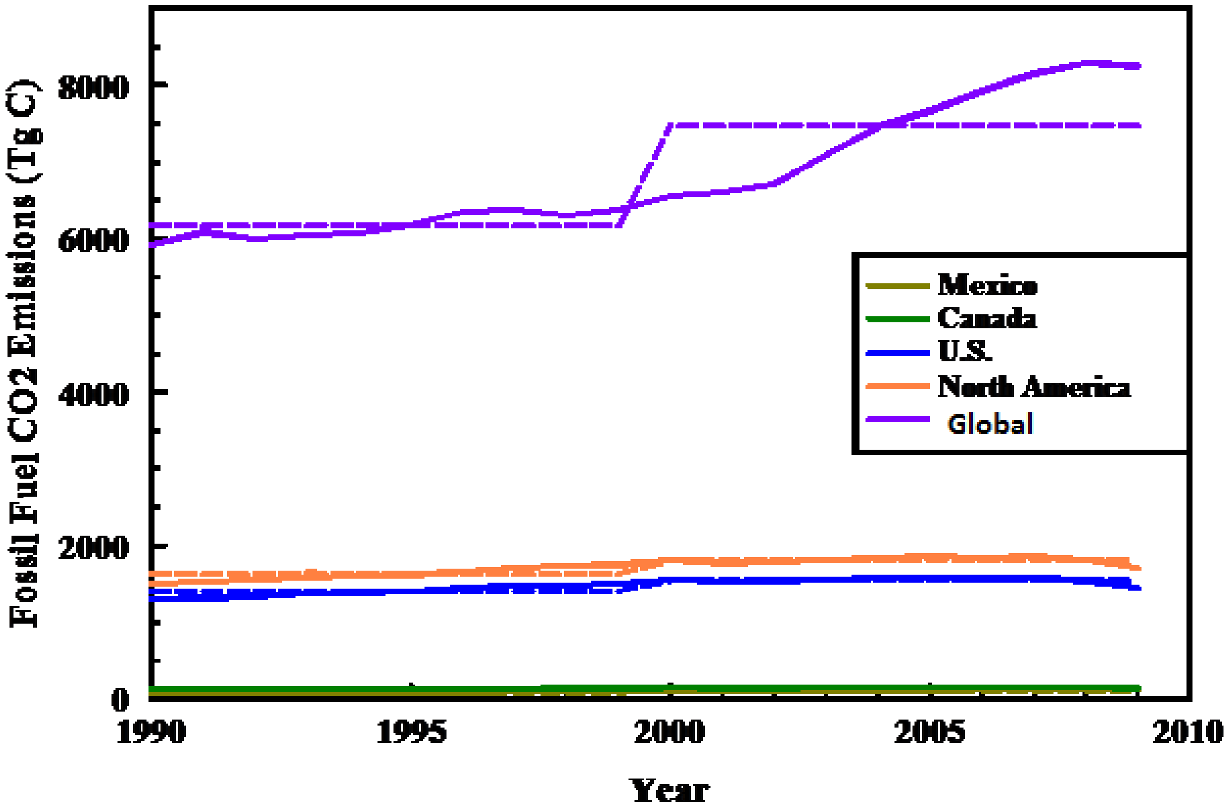

Figure 4. Fossil-fuel-CO_2 emissions for various political units. Solid lines represent annual emissions and dashed lines represent the decadal mean of emissions. The sum of countries is used to represent total global emissions in this plot. This allows comparison of emissions on an equal basis as all emissions are based on apparent consumption data and not production data (see Andres et al. (2012) for a fuller discussion of the differences). The global values used here are less than those in the CDIAC archive (http://cdiac.esd.ornl.gov/trends/emis/tre_glob_2010.html) mainly due to the exclusion of bunker fuels. Data from Boden et al. (2013).