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Multiple constraint analysis of regional land–surface carbon flux

D. P. TURNER[1]*, M. GÖCKEDE[1], B. E. LAW[1], W. D. RITTS[1], W. B. COHEN[2], Z. YANG[1], T. HUDIBURG[1], R. KENNEDY[1] and M. DUANE[1], [1]*Department of Forest Ecosystems and Society, Oregon State University, Corvallis, OR 97331, USA;* [2]*USDA Forest Service, Pacific Northwest Station, Corvallis, OR 97331, USA*

ABSTRACT

We applied and compared bottom-up (process model-based) and top-down (atmospheric inversion-based) scaling approaches to evaluate the spatial and temporal patterns of net ecosystem production (NEP) over a 2.5×10^5 km^2 area (the state of Oregon) in the western United States. Both approaches indicated a carbon sink over this heterogeneous region in 2003 (a relatively warm, dry year in western Oregon) and 2007 (near normal), with carbon uptake primarily in forested and agricultural areas. The statewide mean NEP for 2007 using the bottom-up approach was 80 gC m^{-2} yr^{-1}, which compares with 145 gC m^{-2} yr^{-1} for the top-down approach. Seasonality of daily NEP at the ecoregion scale showed similar patterns across the two approaches, but with less sensitivity to seasonal drought in the top-down model. In 2003, simulated annual NEP was lower than in 2007 for both scaling approaches, but the reduction was stronger with the bottom-up approach. Estimates of mean NEP on forested lands from a forest inventory approach, and from the CarbonTracker inversion scheme, bracketed that of our bottom-up approach (ratios to bottom-up estimates were 1.3 and 0.3, respectively). These results support the need for a multiple constraint approach to evaluation of regional trace gas budgets.

1. Introduction

Spatially explicit characterization of land–surface carbon flux is of increasing interest from both science and policy perspectives. It is clear that the terrestrial biosphere is a significant sink for CO_2 at the global scale, offsetting ~30% of all anthropogenic emissions in the 2000–2008 period (Canadell et al., 2007). However, the geographic distribution of net carbon uptake remains uncertain, and understanding of the mechanisms driving exchange processes between biosphere and atmosphere remains a challenge (Schimel, 2007). From a policy perspective, there are current national-level commitments to the United Nations Framework Convention on Climate Change to quantify carbon sources and sinks associated with land use (Parson et al., 1992). In addition, it will be necessary to monitor forestry- and agriculture-related carbon offsets—potentially including both reduced deforestation as well as increased afforestation—as they become incorporated into binding international agreements to limit net CO_2 emissions (DeFries et al., 2006). At the global scale, there is enough uncertainty about the land flux to limit our ability to use observations of CO_2 concentrations to monitor global and regional fossil fuel emissions independent of national level reporting (NRC, 2010).

Approaches to estimating carbon flux in a spatially explicit manner at the regional scale include those based on purely statistical relationships (Papale and Valentini, 2003; Xiao et al., 2010), 'bottom-up' ecosystem modelling (Masek and Collatz, 2006) and 'top down' inversion analyses based on observations of CO_2 concentrations (Peylin et al., 2005; Peters et al., 2010). Results of these different approaches are rarely juxtaposed with any degree of spatial detail, and when done these types of comparisons have often yielded modest levels of agreement at best (Pacala et al., 2001; Janssens et al., 2003). Optimally, covariance matrices that cover a wide range of spatial and temporal scales are needed for these comparisons, but efforts in that direction are just beginning (Gerbig et al., 2009; Desai et al., 2010).

Bottom-up process modelling of regional terrestrial carbon fluxes permits incorporation of spatial information on climate, soils, vegetation cover type and disturbance history (Chen et al., 2003; Law et al., 2004). Thus a variety of observational datasets may be used for model calibration and validation (Wang et al., 2009), and the modelling framework allows for numerical experiments that facilitate examining the mechanisms and uncertainties associated with the simulated stocks and fluxes over daily to seasonal and interannual timescales. Notable in terms of validation is that in areas covered by forest inventory programs,

*Corresponding author.
e-mail: david.turner@oregonstate.edu
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bottom-up estimates of carbon stocks and changes in stocks can be compared to aggregated inventory data (Turner et al., 2007). Opportunities for evaluation of simulated wall-to-wall carbon fluxes, including croplands and other non-forest ecosystems, over a regional domain are more limited because monitoring programs in non-forest cover types are less developed.

Atmospheric inverse modelling approaches estimate surface CO_2 exchange processes based on a time series of CO_2 concentration observations which have footprints of up to 10^6 km^2 (e.g. Gloor et al., 2001). Simulations of surface flux are fed into transport models and discrepancies between predicted and observed CO_2 concentrations are used to revise the surface flux estimates. Recently, improvements in mesoscale atmospheric transport models (e.g. Ahmadov et al., 2009; Lauvaux et al., 2009), source characterization for anthropogenic CO_2 (Gurney et al., 2009), and an increasing density of CO_2 measurement sites, have opened up the possibility of regional inversions over domains on the order of 10^4–10^6 km^2 with spatial resolution on the order of 5–40 km (Matross et al., 2006; Lauvaux et al., 2008; Schuh et al., 2010). Such high-resolution top-down modelling has the potential to provide new insight into mechanisms and controls on the carbon cycle that are relevant at the landscape scale.

In this study, we report a comparison of regional bottom-up and top-down carbon flux estimates for a 2.5×10^5 km^2 area in the western United States (Fig. 1). There has been extensive work on bottom-up modelling of land–surface fluxes in this region focused primarily on forestland and cropland (Law et al., 2004; Turner et al., 2004, 2007), and on evaluation of forest carbon stocks and fluxes using forest inventory data both for model calibration of stocks with age and comparison of aboveground wood NPP (Van Tuyl et al., 2005; Hudiburg et al., 2009; Latta et al., 2009, 2010) thus offering the opportunity for a relatively well-constrained comparison of the two approaches. Our comparisons cover annual sums for the regional CO_2 budget as well as daily time series of CO_2 fluxes for subregions of the domain. Results are presented for two data years (2003 and 2007), which differed in climate.

2. Methods

2.1. Overview

For this study, bottom-up estimates of CO_2 exchange fluxes between biosphere and atmosphere are simulated using the Biome-BGC model (Fig. 2). Bottom-up model runs were performed over the 1980 to 2007 period with climate from the DAYMET interpolation scheme. For the top-down modelling, Göckede et al. (2010a) developed a high-resolution atmospheric inverse modelling framework (Fig. 3) customized for the Oregon domain, which optimized a simple diagnostic CO_2 flux model based on a time series of calibrated CO_2 concentration measurements for 2006. The top-down results presented herein use the methodology from Göckede et al. (2010b), which was built on an extended database of CO_2 observations from three sites, covering the year 2007, and upgraded versions of external datasets for advected CO_2 and fossil fuel emissions. Once parameters were optimized based on the 2007 CO_2 observations, the surface flux model was

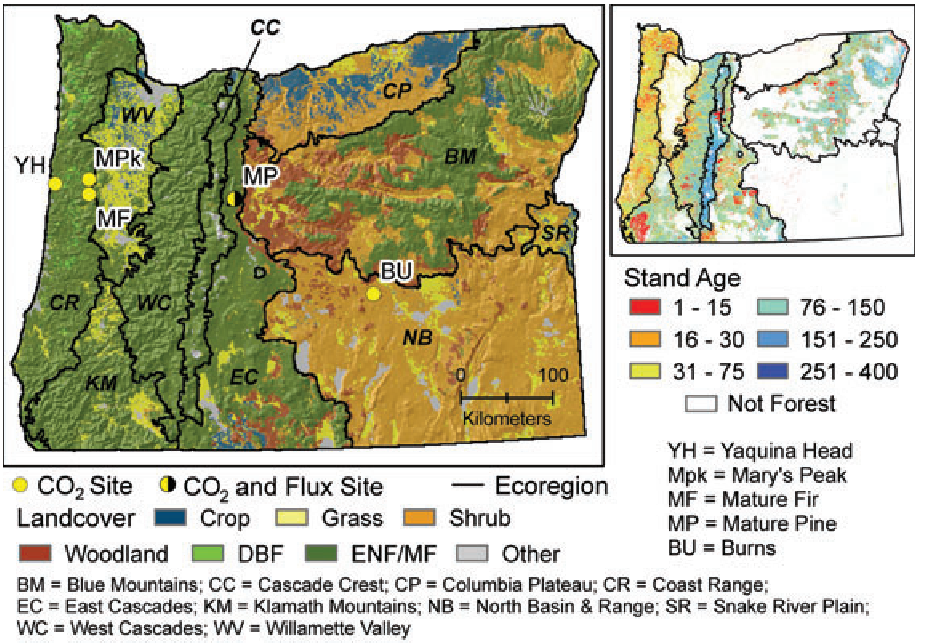

Fig. 1. Land cover (left-hand panel) and stand age (top right-hand panel) over the study area. CO_2 measurement sites and eddy-covariance flux sites are indicated on the land cover map. Initials on the land cover map indicate ecoregions

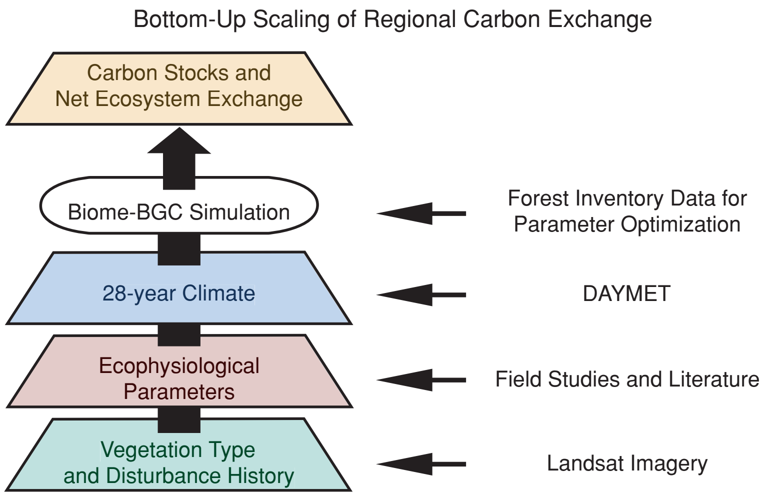

Fig. 2. Schematic for bottom-up approach.

run in forward mode using input data for 2003 (drier in western Oregon) and 2007. With these complimentary bottom-up and top-down model runs, we were able to make comparison of daily and annual NEP at the 1 km spatial resolution in 2003 and 2007, with aggregation to ecoregion and study area means as needed. We also compared our simulated fluxes with year-specific NEP flux estimates from the CarbonTracker inversion scheme (Peters et al., 2007) and with multiyear mean NEP flux estimates based on state-level forest inventory data.

2.2. *Bottom-up modelling*

Daily fluxes of gross primary production (GPP), autotrophic respiration (R_a), heterotrophic respiration (R_h) and NEP were simulated in a spatially distributed mode with the Biome-BGC model over the study domain (the state of Oregon) in the western United States (Fig. 1). Biome-BGC (V4.1.2) is a daily time step, process-based, biogeochemistry model that includes the carbon, hydrological and nitrogen cycles. Carbon cycle processes include photosynthesis, R_a, R_h, allocation and mortality (in the case of forests). Simulated hydrological processes include interception, transpiration, evaporation and runoff. For a given grid cell, a model spin-up is run (∼1000 yr) and disturbance history (see below) is specified to bring the simulation up to the last year of available input data. In this study, Biome-BGC was applied over a 1 km^2 grid, with up to five separate model runs per grid cell based on the most frequent combinations of vegetation cover type and disturbance history. We did not try to account for emissions from wood and crop products that have been removed from the land base. Our previous applications of Biome-BGC have been at the landscape (Turner et al., 2003), regional (Law et al., 2004) and state (Turner et al., 2007) levels. The domain and methods in this study are similar to those in Law et al. (2006) and Turner et al. (2007) and will be described only briefly here.

Climate inputs to the model include daily maximum and minimum temperature, precipitation, mean daytime vapour pressure deficit and mean daytime photosynthetically active radiation (PAR). The climate dataset for this study covered the period from 1980 to 2007, four additional years beyond the Turner et al. (2007) analysis. The distributed climate was based on the DAYMET model, which interpolates between meteorological stations based on topography and meteorological first principles (Thornton et al., 1997). Soil texture and depth were specified from U.S. Geological Survey coverages (CONUS, 2007). Vegetation type was based on the National Land Cover Database (NLCD, Vogelmann et al., 2001) with supplemental information

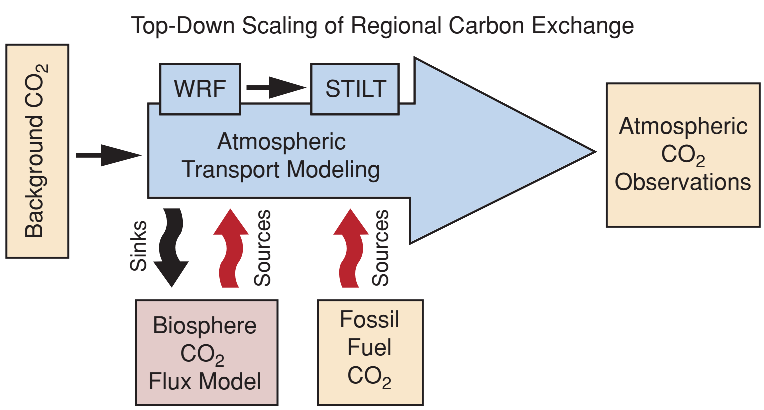

Fig. 3. Schematic for top-down approach. WRF, Weather Research and Forecasting model, STILT, Stochastic Time Inverted Lagrangian Transport model.

from the Oregon Gap Analysis Program (GAP, Kagan et al., 1999) for the juniper woodland vegetation type. Both NLCD and GAP data were based on Landsat imagery (∼30 m resolution).

Recent (1970–2007) disturbance history on forested pixels was from Landsat-based change detection analysis (Cohen et al., 2002; Kennedy et al., 2010). The only exception was wildfire in the period from 1985 to 2007, which was from the Monitoring Trends in Burn Severity (MTBS, 2009) database (Eidenshink et al., 2007), also Landsat-based. In that data set (Schwind, 2008), the year of the fire is specified and fire intensity is classified as high, medium or low. Biome-BGC was adapted to simulate these different fire severities based on the combustion factors in Campbell et al. (2007).

Disturbances previous to 1970 were prescribed on the basis of estimated stand age, again based on Landsat imagery. Stand age for all pixels not disturbed since 1970 was initially mapped as a continuous variable that was derived from ecoregion-specific relationships between stand age and Landsat spectral data at a set of USDA Forest Service Inventory and Analysis plots (Cohen et al., 1995; Duane et al., 2010). To reduce the number of forest type by disturbance history combinations in each 1 km cell, the continuous ages were binned into young (30–75), mature (76–150), old (151–250) and old-growth (>250) age bins and assigned the bin interval midpoint for stand age. Effective fire suppression in our region began about the same time as increased logging (e.g. Hessburg and Agee, 2003). Thus, stands less than 80 years old were assumed to have originated with a clear-cut harvest, and stands greater or equal to 80 years old were assumed to have originated with a stand-replacing fire.

To account for cropland harvesting, Biome-BGC was modified such that a prescribed proportion of aboveground biomass on a prescribed date was removed from the site. In ecoregions where crops are largely irrigated, the soil water constraint on photosynthesis and heterotrophic respiration was turned off.

Biome-BGC parameters were largely derived from the survey of White et al. (2000) and representative values for the six cover types used in this analysis are listed in Turner et al. (2007). For the evergreen needle leaf forest cover type, a final parameter optimization on two of the parameters (leaf nitrogen as rubisco, annual mortality) was performed at the ecoregion scale using wood biomass data provided by the U.S. Forest Service Forest Inventory and Analysis plots (FIA, Waddell and Hiserote, 2005; Hudiburg et al., 2009). Stand age was specified from the plot data and live woodmass at the end of a simulation run at that location was the basis for comparisons with observations. Observed live woodmass was based on plot measurements of tree diameters.

2.3. Top-down modelling

The atmospheric inverse modelling framework (described fully in Göckede et al., 2010a,b) follows a ‘classic’ top-down modelling strategy, outlined, for example, in Gerbig et al. (2003). Atmospheric transport modelling is used to develop an influence function that links a receptor location to spatially distributed sources and sinks. This influence function is coupled to modelled terrestrial biosphere fluxes of CO_2 to simulate the impact of photosynthesis and respiration on atmospheric CO_2 time series. Given anthropogenic fossil fuel emissions and advected background concentrations, this approach allows one to simulate a time series of CO_2 concentration for any given location and timeframe within the model domain. A Bayesian optimization approach is used to adjust flux base rates for individual surface types in the biosphere flux model.

Continuous, well-calibrated atmospheric CO_2 measurements from three monitoring sites [Mary’s River mature fir (MF), Metolius mature pine (MP) and Burns (BU)] in Oregon were used as input data for the inverse model (see Fig. 1). All sites were equipped with the same custom-built basic instrument setup. To minimize the potential influence of boundary layer mixing biases (e.g. Peters et al., 2010), we restricted the dataset used for the atmospheric inversion to afternoon averaged CO_2 (2–6 PM). To constrain boundary conditions, we extracted information from the CarbonTracker database (Peters et al., 2007, see also http://carbontracker.noaa.gov) to assign CO_2 concentrations to air masses at their initial entry into our model domain, and used fossil fuel CO_2 emission fluxes from a gridded dataset provided by the VULCAN project (Gurney et al., 2009). CarbonTracker data was validated against CO_2 observations from two additional monitoring sites [Yaquina Head (YH) and Mary’s Peak (MPk] not used in the inversion, and a polynomial was applied to correct for a seasonally varying offset (maximum offset of 1.0 ppm).

The terrestrial biosphere CO_2 flux model used in the inverse modelling framework (BioFlux, Turner et al., 2006; Göckede et al., 2010a,b) resolves the fluxes of GPP, R_a and R_h in hourly time steps. GPP is estimated with a light use efficiency (LUE) approach, modulated by scaling factors to take into account the influence of indirect radiation, temperature, VPD, water availability and stand age. R_a is split into maintenance and growth respiration, mainly influenced by actual photosynthesis and air temperature, while R_h is calculated as an exponential function based on soil temperature, with additional scalars for soil moisture and stand age effects. Land cover and stand age inputs were similar to those used in the bottom-up modelling, and subgrid heterogeneity scale (<1 km) was handled in the same manner, that is, separate model runs for up to five combinations of cover type by disturbance history per grid cell. Initial parameter optimization for mesic and xeric conifer forests, respectively, was based on observations of GPP and NEP at two AmeriFlux eddy-covariance sites (Wind River and Metolius Mature Pine), while all other land cover types were trained on outputs from Biome-BGC model runs (see Turner et al., 2006).

Data sources used in the top-down modelling component but not for Biome-BGC include gridded MODIS FPAR data (downloaded from NASA archives, https://wist.echo.nasa.gov/api/), required to indicate what fraction of incoming PAR (FPAR) is actually absorbed by the vegetation canopy. MODIS data comes at 1 km spatial resolution and 8-d temporal resolution, and was gap-filled here using a temporal interpolation routine (Zhao et al., 2005). Another difference in data sources between the two modelling approaches is that the spatial surface meteorology data to drive BioFlux was provided by a mesoscale meteorological model (WRF, Weather Research and Forecast, www.wrf-model.org), which is part of the transport module used in the top-down approach. WRF was operated at 6 km resolution in the inner model domain covering most of western and central Oregon, and 18 km resolution for the outer parts, and provided the same meteorological parameters as DAYMET in daily resolution. All data were reprojected onto a spatial grid in 1 km resolution corresponding to the DAYMET grid, and temperature and radiation were subsequently interpolated into sub-daily timestep. Finally, we used PRISM (Parameter-elevation Regressions on Independent Slopes Model, Daly et al., 2008) datasets as a reference to adjust the monthly sum of precipitation simulated by WRF.

Three parameters in the flux model (base rates for GPP, R_a and R_h) were optimized using 2007 CO_2 observations at the three measurement sites, then the flux model was run in 2003 and 2007 in the forward mode, with year-specific inputs of climate and MODIS FPAR. We assessed flux uncertainties based on posterior parameter covariance matrices multiplied with scaling factors that reflect the influence of surface meteorology, and included additional biases associated with offsets in advected CO_2 mixing ratios (Goeckede et al., 2010b).

2.4. *Comparing outputs from the bottom-up and top-down scaling approaches*

Comparisons across our scaling approaches for a given year or across years (2003 versus 2007) for a given scaling approach were made using sums, difference maps, and one-to-one plots for all 1 km^2 grid cells. Comparisons of daily mean NEP across scaling approaches within an ecoregion were made with time series plots. Uncertainty in the state-level fluxes was evaluated in part by comparisons of our top-down and bottom-up fluxes with NEP estimates derived from forest inventory change data and from the global-scale CarbonTracker inversion scheme (Peters et al., 2007).

3. Results

3.1. *Bottom-up approach*

After parameter optimization using mean wood mass by age class per ecoregion from inventory data, the mean woodmass per ecoregion across all FIA plots showed good agreement between the plot-level observations and the simulations ($R^2 = 0.93$, RMSE = 1.92 kgC m^{-2}, Fig. 4). The statewide mean NEP for 2007 was 80 gC m^{-2} yr^{-1} (total of 20.4 TgC yr^{-1}, Table 1). The highest NEP sinks (Fig. 5) were in forested areas (48% of total area), notably in the Coast Range where soil fertility is high, climate is most favourable for tree growth (Latta et al., 2009), and stand ages are generally young because of intensive management (Hudiburg et al., 2009). Forests in the Cascade Mountains were moderate NEP sinks because of a less favourable climate and a combination of management for wood production on private lands, recovery from the recent era of heavy harvesting on public lands, and large areas of older low NEP forests on public lands (Turner et al., 2007). The East Cascades (EC) and Blue Mountain (BM) ecoregions are considerably drier than the Coast Range (CR) and West Cascades (WC) ecoregions and are managed less intensively than west side forests, so had correspondingly lower NEP. Areas of recent wildfire, such as the 2002 Biscuit fire (200 000 ha) in the SW corner of the state (Campbell et al., 2007), had large negative NEPs, as did areas of recent harvest (Fig. 5).

Mean cropland (5% of total land) NEP in 2007 was 143 gC m^{-2} yr^{-1}, reflecting the removal of harvests and a balance of residue inputs with outputs from heterotrophic respiration. Woodlands (6% of total area) had a mean NEP of

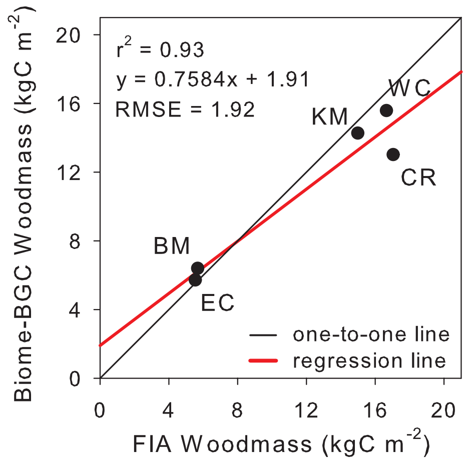

Fig. 4. Comparison of mean wood mass from bottom up simulations and forest inventory data (Hudiburg et al., 2009) by ecoregion.

Table 1. Statewide totals (TgC yr^{-1}) for gross primary production (GPP), autotrophic respiration (R_a), heterotrophic respiration (R_h) and net ecosystem production (NEP) for 2003 and 2007 from bottom-up and top-down approaches.

	Bottom-up		Top-Down	
Carbon flux	2003	2007	2003	2007
GPP	266.5	302.2	207.0	219.6
R_a	168.5	185.3	112.2	111.2
R_h	95.0	96.8	74.4	72.7
NEP	3.0	20.2	20.4	35.7

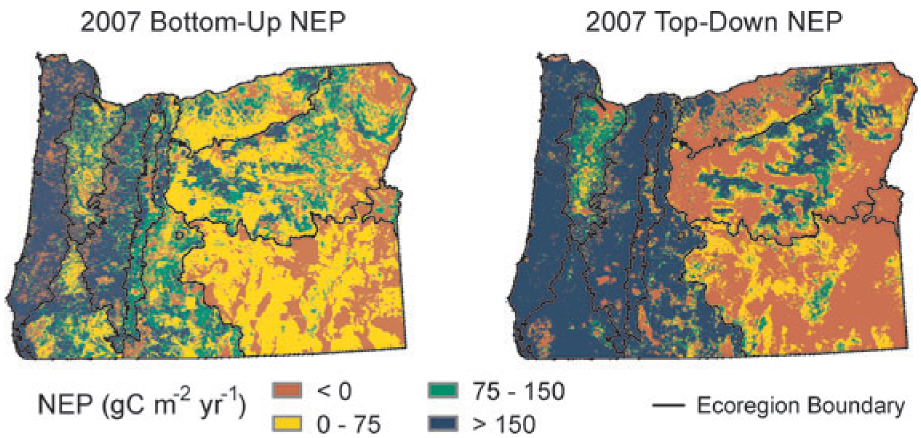

Fig. 5. Bottom-up and top-down annual NEP for 2007.

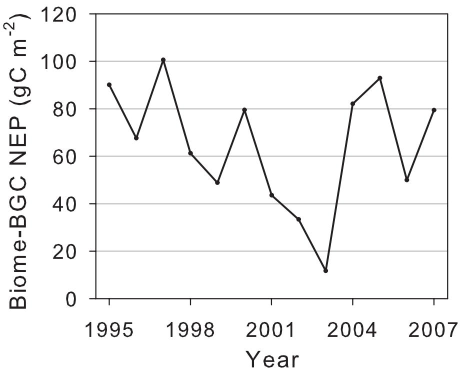

Fig. 6. Interannual variation for bottom-up region-wide mean NEP over the 1995–2007 interval.

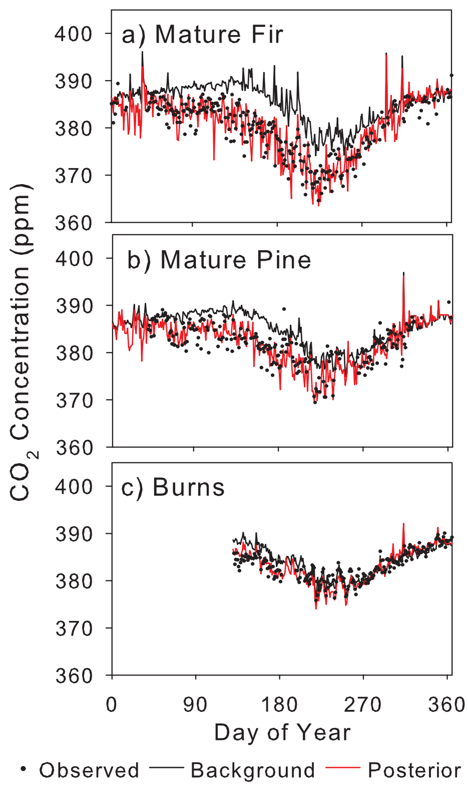

Fig. 7. Time series for CO_2 concentration data at the (a) Mature fir, (b) Mature Pine and (c) Burns sites in 2007.

88 gC m^{-2} yr^{-1}, grasslands (8% of total land) a mean of –18 gC m^{-2} yr^{-1} and shrublands (36% of total land) a mean of 7 gC m^{-2} yr^{-1}. Large areas of shrubland in SE Oregon shift from minor source to minor sink from year to year depending on interannual variation in climate.

The simulated statewide NEP for 2003 was 15 gC m^{-2} yr^{-1} (Table 1). That year had the lowest simulated mean NEP for the 10-year period from 1995 to 2007 (Fig. 6). Mean NEP across that interval was 68 gC m^{-2} yr^{-1}. The NEP reduction in 2003 compared to 2007 was associated with declines in both GPP and ecosystem respiration ($R_a + R_h$), but greater declines in GPP (Table 1).

3.2. *Top-down approach*

Afternoon CO_2 concentration data at the three reference sites in 2007 showed the seasonal drawdown associated with the northern hemisphere growing season, and significant day-to-day variation associated with synoptic flow and local terrestrial source/sink activity (Fig. 7). The differences between the background concentration and the simulated concentration give an indication of the strength of the biospheric sink (MF > MP > BU). The difference between predicted concentrations using the prior parameters and the optimized parameters gives an indication of the magnitude of the correction imposed by the inversion. For the most part, these corrections altered the predicted concentrations to a lesser degree than did the initial imposition of the biosphere flux on the background concentrations. However, there were appreciable reductions in the RMSEs for observed versus simulated afternoon CO_2 at the MF and MP sites (Table 2).

Table 2. Regression statistics after parameter optimization at the 3 CO_2 measurement sites. RMSE reduction refers to the difference between prior and posterior fits.

Site	Posterior RMSE	RMSE reduction (%)	R^2 (posterior)
Mature Fir (MF)	2.81	22.6	0.78
Mature Pine (MP)	2.42	9.8	0.70
Burns (BU)	1.64	2.1	0.77

Table 3. NEP (gC m^{-2} yr^{-1}) estimates from alternative scaling approaches.

Approach	Year		
	2003	2007	Mean[a]
Domain			
All land			
Bottom-up	15	80	48
Top-down	83	145	114
CarbonTracker	30	70	50
Forest Only			
Bottom-up	41	166	103
Top-down	207	321	264
CarbonTracker	14	47	30
Forest Inventory	NA	NA	133

Note: NA, not applicable.
[a]Mean is for 2003 and 2007 except for Inventory where it is 2000–2005.

With the posterior parameters, the overall mean NEP for 2007 was 145 ± 31 gC m^{-2} yr^{-1} (total of 35.7 TgC yr^{-1}, Table 1). The NEP sinks for the 2007 top-down analysis were primarily in the forests of the western part of the state, with isolated strong source areas associated with recent fires and clearcuts. Weak source areas were indicated in the WV ecozone and the relatively warm dry areas in eastern OR. The mean NEP in 2003 was 83 ± 27 gC m^{-2} yr^{-1} (total of 20.4 TgC yr^{-1}).

3.3. Comparison across scaling approaches

Total NEP in 2007 for the bottom-up approach was considerably lower than that from the top-down approach. The spatial distribution of NEP for the two approaches agreed in having forested areas as the predominant carbon sink, with strong source areas associated (>100 gC m^{-2} yr^{-1}) with recent forest disturbances such as the Biscuit fire. The ratio of mean NEP on forested land to mean NEP for all cover types was 1.8 for the bottom-up approach and 2.0 for the top-down approach (Table 3). The largest differences in magnitude were in the relatively dry EC and KM ecoregions (Fig. 8) where the top-down approach indicated much higher C sinks.

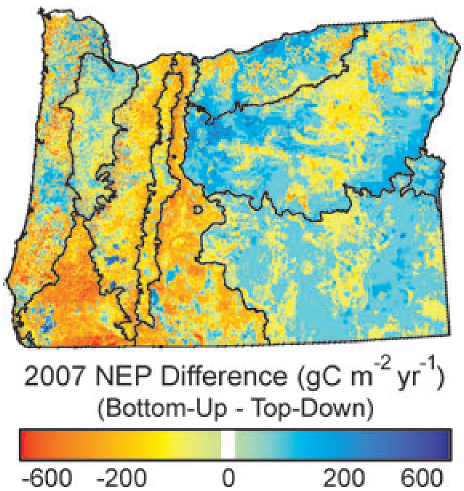

Fig. 8. Difference map (bottom-up – top-down) for NEP for 2007.

Both approaches showed strong seasonality in simulated NEP (Fig. 9), a pattern that is consistent with flux tower observations in the region (Falk et al., 2008; Thomas et al., 2009). The summer maxima were of similar magnitude for both approaches in the CR and WC ecoregions but the top-down approach had higher maximum NEPs in the EC and KM ecoregions. The difference in mean NEP between 2003 and 2007 was much greater in the bottom-up approach than the top-down approach. 2003 NEP was 19% of 2007 NEP compared with 57% in the case of the top-down simulation (Table 1).

4. Discussion

4.1. Assessment of bottom-up approach

Estimates of woodmass provide a baseline check on carbon cycle simulations over forested areas. Our use of FIA data for Biome-BGC parameter optimization would be expected to reduce bias in comparisons of area averaged woodmass between the simulations and the FIA observations, but it cannot correct for possible error in mapping stand age. Forest inventory data suggests that ecoregion mean woodmass in Oregon varies by a factor of about three along the west to east precipitation gradient in Oregon (Hudiburg et al., 2009) and the Biome-BGC simulations largely captured that variation (Fig. 4). The geographic pattern of our grid cell (1 km^2) mean woodmass also compared

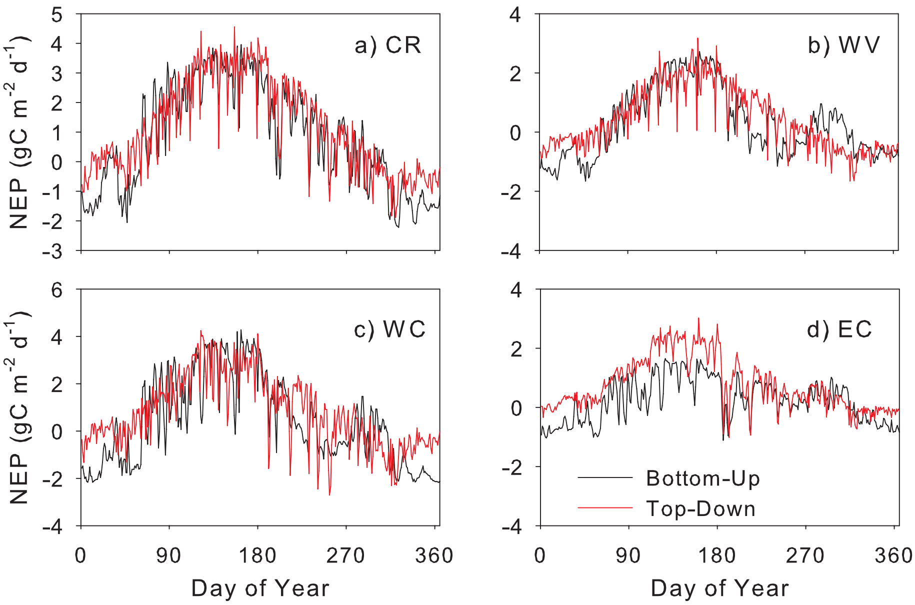

Fig. 9. Times series of mean daily NEP for 2007 from bottom-up and top-down approaches: (a) Coast Range, (b) Willamette Valley, (c) West Cascades, and (d) East Cascades ecoregions.

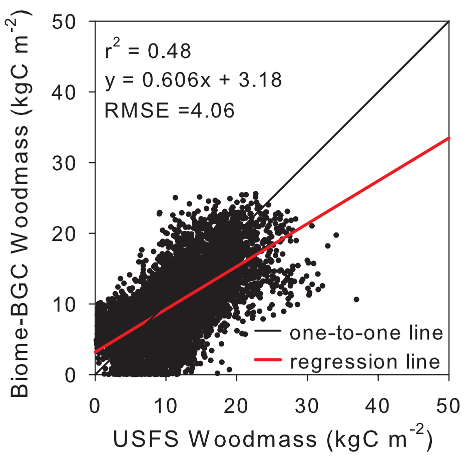

Fig. 10. Comparison of mean aboveground woodmass per cell (1 km^2) from Biome-BGC and Blackard et al. (2008).

well with results in Blackard et al. (2008), which similarly used FIA plot data, but scaled from plots to regions using remote sensing imagery (Fig. 10).

Standing woodmass in forests represent the net effect of growth rates and disturbance rates. For this analysis, we used age-specific biomass from a sample of inventory plots as reference data in our parameter optimization. The good agreement here between the simulations and observations of woodmass affirms the utility of combining remote sensing and process modelling for evaluation of forest carbon stocks and fluxes (Turner et al., 2004; Masek et al., 2006). However, this approach is dependent on characterizing recent disturbance history and stand age in older forests. Note that the detailed spatially explicit simulation of the disturbance regime performed for this analysis required extensive use of Landsat imagery, an approach not as yet feasible at the continental scale. Exploratory projects such as LEDAPS are pointing in that direction (Goward et al., 2008; Masek et al., 2008).

Evaluation of simulated NEP on forest land is less straightforward than is the case for carbon stocks, but state-level data from USDA Forest Service Inventory and Analysis plots provide a first order check. The most recent inventory analysis of Oregon forests covers the period 2000–2005 (Smith et al., 2009; Donnegan et al., 2008). NEP can be approximated from the sum of change in stocks, forest harvest removals and direct fire emissions (Chapin et al., 2006; Tupek et al., 2010). The change in tree carbon stocks over the 2000–2005 period was ≈10 TgC yr^{-1} based on Oregon Department of Forestry harvest statistics (ODF 2006), mean harvest removals for the 2000–2005 period were 6.4 TgC yr^{-1} (Turner et al., 2007). Direct fire emissions vary widely from year to year in Oregon, with 2002 as an exceptionally high year (Turner et al., 2007). The 10-year average for the 1995–2004 period was 0.8 TgC yr^{-1}, which is likely the most consistent with an inventory system based on a multiyear sampling scheme. By this approach, mean forest NEP for the 2000–2005 period was 17.2 TgC yr^{-1}. Alternatively, for the purposes of reporting U.S. greenhouse gas emissions and sinks in compliance with the Framework Convention on Climate Change, the U.S. Forest Service uses a combination of plot data and modelling to estimate changes in forest carbon stocks (soil C is ignored here because of artefacts associated with land use change). The Forest Service estimate for the carbon sink in Oregon over the 2000–2005 period was 9.2 TgC yr^{-1} (Smith et al., 2007). Again, NEP can be estimated by adding back in harvest removals (6.4 TgC yr^{-1}) and direct fire emissions (0.8 TgC yr^{-1}), that is, $9.2 + 6.4 + 0.8 = 16.8$ TgC yr^{-1}. The forest land base for the inventory approach is 12.3×10^6 ha, thus using the mean of the two inventory-based approaches (17 TgC yr^{-1}), the average NEP was 138 g C m^{-2} yr^{-1}. Uncertainty on the Forest Service carbon stock change estimates are reported as 21% of the reported values at the 95% confidence level (EPA, 2010). If that proportional uncertainty is applied to the mean flux, then inventory-based mean NEP of 133 ± 29 compares reasonably well with mean forest NEP from the Biome-BGC simulations of 110 gC m^{-2} yr^{-1} over the 2000–2005 period (over an 11.4×10^6 ha area of forests and woodland).

A positive mean NEP is expected for Oregon forests under average climate conditions because of the extensive areas of young managed forests. Approximately half of the forest land in Oregon is privately owned and much of that is managed for wood production. Forested areas that are heavily managed, and in which the stand age class distribution has become even, are expected to be significant NEP sinks (Trofymow et al., 2008). The primary mechanism accounting for the carbon sink is that about half of forest NPP carbon is allocated to bolewood production, which is continuously removed by harvesting. Thus it is not returned to the atmosphere via R_h, as would be the case in an undisturbed forest. In a stand near carbon steady state, uptake by NPP is balanced by carbon effluxes from the live biomass pool associated with leaf and fine root turnover plus tree mortality. The inputs to the litter, soil organic matter and coarse wood debris pools are likewise balanced by heterotrophic respiration. Areas recently harvested, or burned, are carbon sources for a variable period after disturbance because of reduced NPP and rapid decomposition of wood residues (Humphreys et al., 2006; Meigs et al., 2009). Luyssaert et al. (2009) found a global average of 15 yr for temperate and boreal forests to become a carbon sink after stand replacing disturbance, and Law et al. (2001) found this timeframe is almost 20 yr in semi-arid forests. However, over most of the course of succession these managed stands are carbon sinks. Old-growth forests in the Pacific Northwest may have about a third lower NEP than mid-aged forests and in some cases they may be small sources of carbon depending on age, site and climate year (Law et al., 2003; Falk et al., 2008).

Croplands were also significant NEP sink in 2007 for the same reason as managed forests, that is, cropland yields are removed and heterotrophic respiration tends to be in equilibrium with the annual input of crop residues. Mean shrubland NEP in 2004 was close to zero, consistent with eddy flux measurements at shrubland sites elsewhere in the Great Basin (Obrist et al., 2003). Mean grassland NEP was slightly negative, consistent with the expectation that grasslands would generally be near carbon steady state.

Simulated statewide means for NEP in 2003 and 2007 are at the low and high end of the range of mean NEPs over the previous 10 yr (Fig. 6). Statewide NEP in the simulations is particularly sensitive to precipitation anomalies and tends to decrease as spring and summer precipitation anomalies became more negative. There is a drying trend at the state level between 1996 and 2002 (based on DAYMET data) and it drives the decrease in NEP over that period. The appreciably lower NEP in the West Cascades ecoregion in 2003 compared to 2007 is associated with a 30% lower summer precipitation in 2003. Summers are typically dry in the Pacific Northwest and tree photosynthesis is constrained by soil drought and high vapour pressure deficit late in the growing season (Waring and Franklin, 1979).

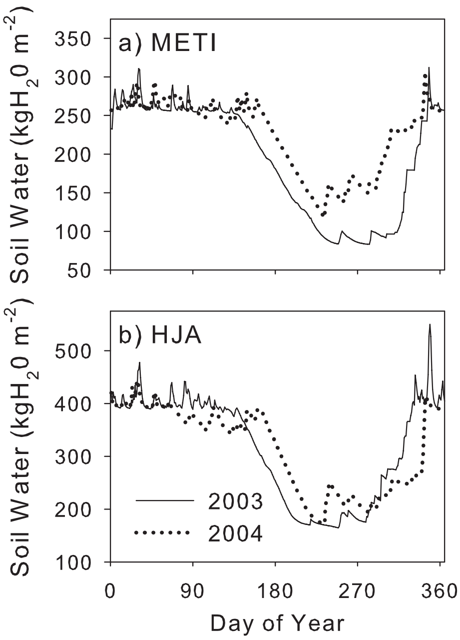

Fig. 11. Time series for simulated soil water content during 2003 and 2004 at sites in the East Cascades (METI, Metolius Intermediate Age site) and West Cascades (HJA, H.J. Andrews Long Term Ecological Research Station) ecoregions.

Based on 7 yr of continuous eddy covariance data, Thomas et al. (2009) concluded that carbon dynamics at the conifer-dominated Metolius River site in Oregon were primarily controlled by plant-available soil moisture, with temperature as a secondary but much weaker control. The NEE sink at that site in 2003 was ~50% of that in 2004 and 2007 (wetter years), and the drawdown in soil moisture occurred conspicuously earlier in the growing season (Thomas et al., 2009), as was captured in our Biome-BGC simulations there and elsewhere in the state (Fig. 11). Other eddy covariance towers in the region indicate a similar strong difference between 2003 and wetter years such as 2004 and 2007. The Wind River Canopy Crane eddy covariance site is a ~500 year old conifer stand in the Cascade Mountains just to the North of Oregon. NEP there was a source in 2003 (–100 gC m^{-2} yr^{-1}) whereas it was a sink (9 gC m^{-2} yr^{-1}) in 2004 when the dry season precipitation was nearly three times greater than in 2003 (Falk et al., 2008). At the Campbell River conifer forest on Vancouver Island, mean NEP across three tower sties was 109 gC m^{-2} yr^{-1} in 2003 compared to 153 gC m^{-2} yr^{-1} in 2004 (Krishnan et al., 2009). Great Basin grasslands, as well as xeric shrublands elsewhere, have also been shown to become carbon sources under droughty conditions (Prater et al., 2005; Scott et al., 2009). Examination of flux tower data during the anomalously warm and dry 2003 period in Europe likewise suggests an NEP decline under dry conditions (Reichstein et al., 2006; Granier et al., 2007).

Characterizing the uncertainty on the estimated mean NEP for 2007 from the bottom-up approach is complicated by many contributing factors. Previous studies have evaluated uncertainties in several components of the bottom-up modelling scheme including DAYMET climate inputs (Hasenauer et al., 2003; Daly et al., 2008), mapping of the forest disturbances (Cohen et al., 2002; Meigs et al., 2010), mapping of stand age (Duane et al., 2010) and Biome-BGC parametrization (White et al., 2000; Wang et al., 2009). Biome-BGC simulations have also been compared to fluxes from eddy covariance towers in the region, with varying levels of agreement (Thornton et al., 2002; Law et al., 2004, 2006; Mitchell et al., 2009). Suggested factors to account for discrepancies include incorrect specification of the soil water holding capacity, possible overestimation of autotrophic and heterotrophic respiration, and possible underestimation of nighttime R_e in the tower fluxes. For this analysis, we compensated for possible limitations in the modelling setup by using age-specific biomass from a comprehensive sample of forest inventory plots as reference data in our parameter optimization. Note that this parameter optimization approach places a greater constraint on multiyear mean fluxes that it does on interannual variation in fluxes.

In studies of the European carbon budget, uncertainty in the ultimate flux estimate is commonly quantified as range or the standard deviation of the variability across approaches (Luyssaert et al., 2009). We found a difference between the Biome-BGC-based NEP for forestland and inventory based NEP for forestland of 30 gC m^{-2} yr^{-1} for a multiyear average (relative to a mean across approaches of 118 gC m^{-2} yr^{-1}). Uncertainty would likely be higher for the statewide forest mean NEP for a given year. Uncertainty of NEP in absolute terms for nonforestland in Oregon (39% of total land) is smaller since mean NEP is smaller and much of the land is low productivity shrubland.

4.2. *Assessment of the top-down approach*

Day-to-day variation in CO_2 concentration was as much as 10 ppm, though usually smaller. This variability on short timescales is driven by a superposition of changes in the source/sink composition of the source area and climate variability. Very high differences between consecutive days are usually caused by frontal passages, which are characterized by both changes in atmospheric transport and changes in weather conditions (e.g. temperature, cloud cover) that alter the surface flux fields. The RMSE between observed and simulated atmospheric CO_2 concentrations (afternoon averages) ranged from 1.64 ppm at the BU site to 2.81 ppm at the MF site, similar to the goodness of fit found in other regional inversion studies (Matross et al., 2006; Ahmadov et al., 2009).

Dominant sources of uncertainty in regional inversions include (1) the representativeness of the CO_2 concentration observations, (2) simulation of vertical transport and mixing layer height, (3) the boundary conditions for CO_2 concentration and (4) characterization of fossil fuel sources (Gerbig et al., 2003, 2008; Peylin et al., 2005; Dolman et al., 2009). Gerbig et al. (2009) suggest that the near field influence of carbon sources and sink on short tower concentrations is quite high, hence increasing uncertainty when being used for inversions of regional fluxes. Here we did not explicitly address this issue but sensitivity studies with a denser network of tower observations could provide new insights.

Concerning the height of the mixing layer, a bias towards high heights during daytime when this layer reaches its maximum would force a high bias (increased C sink) in the inverted NEP fluxes, because a higher surface flux signal is required to cause the same concentration change, compared to a smaller air volume. Stephens et al. (2007) tested post-inversion results from 12 different inverse modelling frameworks, and found that in the Northern hemisphere most of them overestimated mixing layer height in summer, while underestimating it in winter. This bias led to higher simulated sinks in summer, and lower sources in winter, which combined to a net overestimation of the Northern hemisphere terrestrial biosphere sink strength. Our preliminary checks of simulated boundary layer heights against coarse resolution radiosonde data did not indicate a systematic overestimation of mixing layer heights in the Oregon domain (Göckede et al., 2010a). A thorough evaluation of the simulated mixing layer heights for the modelling framework presented herein was not possible to date because of the lack of more extensive and accurate reference datasets.

Regarding the CO_2 concentrations in boundary inflow, a high bias in these concentrations would also force an overestimation in the inverted biosphere C sink because a relatively large sink would be required to dilute the prescribed CO_2 concentrations in the inflow air down to our observed concentrations. Such was the case in the comparison made by Schuh et al. (2010) of two regional inversions over North America, one using CO_2 boundary conditions from a global inversion that included sinks (based on CarbonTracker) and one using CO_2 boundary conditions that were carbon neutral (based on SibCASA). Regional inversion using C neutral boundary conditions resulted in a larger C sink (0.65 versus 0.48 PgC yr^{-1}) after inversion because the boundary condition CO_2 concentrations were on average slightly higher than was the case for the boundary conditions specified by CarbonTracker.

The inverse modelling framework employed for this study is particularly susceptible to potential biases in advected CO_2 concentrations, because (1) it makes use of a global scale data product (CarbonTracker) to constrain CO_2 concentrations of incoming air masses, so relatively small biases can significantly alter simulated fluxes for a much smaller model domain like ours and (2) air masses enter our model domain usually from the Pacific Ocean, where observations are sparse and biases therefore are likely to occur. Our CarbonTracker-based boundary CO_2 concentrations for the west coast of the United States are constrained by flask samples from the North–South series of NOAA buoys in the North Pacific (Masarie and Tans, 1995). However, there typically remains a slight overprediction of concentrations at those sites (A. Jacobson, NOAA, personal communication, 2010).

As noted, our CO_2 monitoring station on top of Mary's Peak in the Coast Range of western Oregon suggested a high bias in CarbonTracker-prescribed concentrations and we corrected for that bias in our inversion. Accordingly, background concentrations used in the top-down model are constrained by local observations, and there should not be a significant systematic bias in the simulations. However, we examined the sensitivity of our inversion-based flux estimates to the magnitude of this correction (Göckede et al. 2010b) and found it to be quite high (3 TgC yr^{-1} less NEP per 0.1 ppm downward correction), thus future refinements in the correction procedure might alter the results. We have also performed sensitivity tests with regard to bias in the magnitude of the prescribed fossil fuel sources (Göckede et al., 2010b) but found a low sensitivity in that case, which can be attributed to the rather low population density (and hence emissions) for Oregon as a whole.

4.3. *Comparisons across scaling approaches*

In our study region, we have four quasi-independent approaches to estimating NEP (Table 3). The top-down approach indicates a larger sink for both forests and the entire land base than the bottom-up approach, the inventory change approach, or the CarbonTracker estimate. In principle, the top-down and bottom-up approaches should yield similar flux estimates. Nevertheless, previous comparisons, including studies in Europe (Janssens et al., 2003), North America (Fan et al., 1998; Pacala et al., 2001) and China (Piao et al., 2009), have generally found—as was the case in this study—higher NEP sink estimates in the case of the top-down approach. Despite ten years of close attention to this difference, there is not yet an agreed upon explanation for its recurrence (e.g. Stephens et al., 2007).

The CarbonTracker carbon sinks are generally quite low relative to the other approaches. However, because there are no concentration sampling stations in our domain that were used in the CarbonTracker analysis, flux estimates are not substantively constrained locally. Reported CarbonTracker flux uncertainties are of about the same magnitude as the fluxes themselves in our region (CarbonTracker, 2010). The North America inversion of Schuh et al. (2010) indicated higher sinks in the Pacific Northwest than did the CarbonTracker inversion, possibly because it used grid cell specific corrections to the priors rather than the cover type specific corrections in CarbonTracker that are associated with larger geographic areas.

Our bottom-up approach supported NEP estimates intermediate between the estimates from our top-down approach and from the CarbonTracker inversion, and estimates for forestland NEP close to the forest inventory-based estimates. Biome-BGC accounted for crop harvest and forest harvest removals, which have previously been evoked as a possible cause of NEP underestimation in bottom-up modelling approaches (Janssens et al., 2003). Indeed, a key strength of the bottom-up scaling approach for regional NEP is in its use of a carbon cycle process model that is sufficiently complex to capture the ecophysiological and disturbance-related phenomena that directly determine carbon sources and sinks. In addition, the simulation of both carbon stocks and fluxes offers many opportunities for model calibration and validation (Law et al., 2006). Computing power is now such that these models can be run over regional domains at resolutions that reflect the actual heterogeneity of land cover and disturbance history. Limitations of the bottom-up approach are associated with the data demands in terms of model inputs, and the large number of model parameters—including stratification by cover type and ecozone—that must be specified. The combination of many inputs and model parameters (each with their own uncertainty), and significant computational requirements for model spin-up, makes it difficult to specify overall uncertainty on bottom-up regional flux estimates except in the context of intermodel comparisons (e.g. Wang et al., 2010). Additional observational constraints such as satellite-based leaf area index, soil carbon inventories, and a wider array of flux tower observations are beginning to be employed in uncertainty assessments (Randerson et al., 2009).

The top-down approach yielded the highest NEP sink estimates. It operates with a much simpler surface flux model but provides additional constraints on flux estimates in the form of the flux tower NEE observations used to optimize the prior parameters, the satellite FPAR, and observations of CO_2 concentrations. In our study, the posterior NEP sink for 2007 was 21% lower than the prior NEP sink, which would indicate a possible NEP sink overestimate in the reference tower data (consistent with a much lower biometric NEP compared to tower NEP as was found at one of our tower reference sites, see Thomas et al., 2009). A key benefit of the top down approach is that because of the simplicity of the surface flux model (making it computationally tractable), comprehensive uncertainty analyses can be undertaken.

The large difference between the top-down and bottom-up approaches in the sensitivity of mean NEP to interannual variation in climate appears to be related to differences in how they simulate the water balance. Evapotranspiration in Biome-BGC is the sum of transpiration, soil evaporation and canopy interception. Soil water holding capacity is a function of soil texture and depth to bedrock, derived from soil characterization mapping efforts.

It is apparent in Fig. 11 that the soil dried out appreciably sooner in a drier than a wetter year in the Biome-BGC simulations, which explained a reduced GPP, R_e and NEP. In the top-down approach, ET is based on a water use efficiency (mm gC^{-1}) that was held constant across space and time, and the soil water holding capacity was held constant across space. We used 200 mm as was suggested in Turner et al. (2006) and Nightengale et al. (2007) but if that estimate is biased high it could desensitize the simulations to drought effects. In future applications, soil water holding capacity will be mapped using the same soil maps of texture and soil depth as are used in the bottom-up analysis, and WUE will be parametrized at the level of plant functional types based on the expanding availability of ET observations at eddy covariance sites. We have also begun exploring multiyear and multisite parameter optimizations (Turner et al., 2009).

As far as future work with the inversion set up here, several possible limitations have been noted, specifically a bias in the simulated (WRF) mixing layer heights, a bias in the prescribed boundary inflow CO_2 concentrations, or a bias in the prescribed fossil fuel CO_2 sources. Further investigation of these issues would involve profiling radar or aircraft campaigns to evaluate WRF boundary layer height simulations, longer-term comparisons of observed and prescribed boundary inflow concentrations, and continued refinement of fossil fuel source characterization (Dolman et al., 2009).

Future comparisons would also benefit from better compatibility in the datasets used in the two approaches. There may be differences in the degree to which DAYMET and WRF captured the interannual variation in climate. Intercomparisons among climatologies are beginning to be made in our region and show significant differences in some cases (Daly et al., 2008).

5. Conclusions

Spatially and temporally explicit maps of carbon flux between the land and atmosphere are of interest from both a science and a policy perspective. Forest and cropland inventory data, bottom-up modelling, and top-down inverse modelling offer different strengths and weaknesses relative to examining terrestrial carbon flux at the regional scale. Our bottom-up approach employed a process model that simulated both carbon pools and fluxes, thus offering opportunities for model parameter optimization and validation using forest inventory data. However, the model complexity also limits our ability to specify uncertainty on regional flux estimates. Our top-down approach employed a much simpler flux model but was subject to additional uncertainties associated with CO_2 boundary conditions and the effectiveness of the site water balance simulation. All scaling approaches indicated a land base sink, but relatively high carbon sinks were estimated with the regional top-down approach. There was coherence among the approaches with regard to the seasonal cycle and geographic pattern in NEP, as well as lower NEP in the dry year. The variations in the flux estimates and the wide array of sources of uncertainty reinforce the desirability of multiple constraint approaches to evaluation of regional trace gas budgets (Heimann et al., 2008; NRC, 2010).

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