A topdown and bottomup approach to estimate global carbon cycle

J Jian1,

1 Department of Crop and Soil Environmental Sciences, Virginia Tech, Blacksburg, VA, USA

2 Department of Forest Resources & Environmental Conservation, Virginia Tech, Blacksburg, VA, USA

3 Department of Forest Resources & Environmental Conservation and Department of Horticulture, Virginia Tech, Blacksburg, VA, USA

\*Corresponding Author: Jinshi Jian ([jinshi@vt.edu](mailto:jinshi@vt.edu))

**Inferring Rs from global terrestrial carbon cycle**

Soil respiration (Rs), consists of heterotrophic respiration (Rh) and autotrophic respiration (Ra), is a major part of global carbon cycle. However, it is still difficult to partition Rs into Ra and Rh in global scale. Here, we presented an indirect method to quantify global Ra and Rh. Based on 251estimates, Ito (2011) found that 56.20 Pg C yr-1 (±1.78, 95% confidence interval calculated from the original data) from 1862 to 2011. When substract carbon consumed by herbivores (Doughty & Field, 2010; Whittaker & Likens, 1973), fire (van der Werf *et al.*, 2010; Crutzen & Andreae, 1990; Gerber *et al.*, 2004; Piao *et al.*, 2009; Zaehle *et al.*, 2005; Mieville *et al.*, 2010; Schultz *et al.*, 2008), land sink (Le Quéré et al., 2015), and carbon washed away and released by freshwater (Cole *et al.*, 2007; Bastviken *et al.*, 2011; Deemer *et al.*, 2016) from NPP, global Rh between 1961 and 2014 can be estimated (Rh = NPP - Herbivores - LandSink - Fire - FreshWater). Based on a global analysis of the relationship between the heterotrophic and autotrophic components of soil respiration (Bond-Lamberty, Wang, & Gower, 2004), Ra to Rh ratio (Ra / Rh) was 0.75 (±0.16, recalculated based on original data from (Bond-Lamberty et al., 2004)), and the global Ra can be estimated through equation: Ra = Rh × 0.75.

This conclusion is supported by the Rs estimate that emerges from quantifying Rs from global flux estimates of other components of the terrestrial carbon cycle. To make this comparison, we evaluated two approaches to partitioning the global carbon cycle from known estimates of the various fluxes and calculated the unknowns (Fig.5, Table S1 and S2). Both gross primary production (GPP, the atmospheric carbon that is synthesized into carbohydrates by plants) and net primary production (NPP, the remainder of C after portions are respired by plants (Ra)) are known quantities, where GPP is 120 Pg C yr-1 (Prentice *et al.* (2007)) and NPP is 56.2 Pg C yr-1 (Ito, 2011). In the first approach, from NPP we substracted carbon stored in the land sink (2.10 ±0.28 Pg C; Le Quéré *et al.* (2015)), burned by fire (3.53 Pg), drained and released to the atmosphere by fresh water (1.9 Pg), and consumed by forest and grassland herbivores (2.2 Pg C) (Fig.5a and Table S1). The remainder was the carbon consumed by soil dwelling hetrotrophic respiration [Rh, 46.47 (±2.06) Pg C yr-1], which does not include aboveground hetrotrophic respiration (Fig.5a). Based on a global analysis of the relationship between the Rh and belowground autotrophic (Rab) components of soil respiration (Bond-Lamberty et al., 2004), we used the ratio Rab/Rh = 0.75 (±0.16) to estimate Rab (35.18 ±8.98 Pg C yr-1) (Fig.5a and Table S1). The sum of Rh and Rab equaled an Rs of 81.86±10.55 Pg C yr-1, very close to the SKT\_MS1 estimate for global Rs (80.99 Pg C yr-1). In the second approach to estimating Rs from the carbon cycle, we substracted the Rh calculated above from GPP to estiamte autrotrophic respiration (Ra), which equaled to 63.80 (± 1.78) Pg C yr-1(Fig.5b). Based on known fractions, we estimated C respired by roots (Rroots = 23.37±3.58 Pg C yr-1), stems (Rstem = 16.01±2.91 Pg C yr-1), and leaves (Rleaf = 24.42±3.71 Pg C yr-1) (Fig.5b). The sum of Rroot and Rh was 69.54 (±5.36) Pg C yr-1, very close to the global annual Rs estimats from the SKT\_HYP\_MS1 model (66.62 to 75.75 Pg C yr-1). In sum, global annual mean Rs estimated by partitioning from global carbon flux ranged from 69.54 (±5.36) Pg C yr-1 to 81.65 (±10.55) Pg C yr-1, very close to the global mean Rs estimated based on the SKT\_HYP model (70.85 Pg C yr-1) and SKT model (80.99 Pg C yr-1).

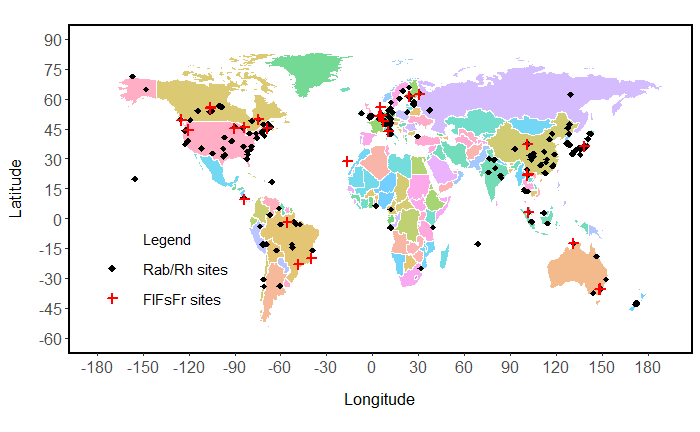


Fig.1 Spatial distribution of Rab/Rh sites from SRDB\_v4 and FlFsFr sites across globe.

**3.3.** **Global carbon cycle and soil respiration**

Here we conducted a summary analysis of global terrestrial carbon cycling to evaluate which estimate from the models close to the real global mean annual soil respiration. Soil respiration consumed the photosynthetic carbon assimilation which was fixed by plant, or called gross primary production (GPP). Plant autotrophic respiration (including fraction of leaf respiration (Fl), fraction of stem respiration (Fs) and fraction of root respiration (Fr)) consumed part of GPP, the left part was called net primary productivity (NPP). Part of NPP consumed by heterotrophic respiration (Rh), other part of NPP was consumed by herbivores, burned by fire or becomes long term carbon storage (carbon sink), and the sum of leaf respiration (Fl) and heterotrophic respiration (Rh) is soil respiration. Theoretically, if we know the pathway of each part of global annual GPP, we can estimate global mean annual soil respiration.

In order to identify the magnitude of global mean annual GPP, we collected 35 literatures reported GPP from 1975 to 2011, the 35 reported GPP range from 71.73 to 183.39 Pg (table 3). The average GPP was 123.55 Pg, which was close to IPCC’s estimation (120 Pg, 3rd assessment). When the lowest estimation (71.73 Pg) and the highest estimation (183.39 Pg) was excluded, the GPP estimations range from 97 to 160.95 Pg (figure 3), and the average was 123.31 Pg.

|  |  |
| --- | --- |
| E:\VT\MyResearch\17.SRDB\GlobalRsProject1\R\GPPHist.jpg | E:\VT\MyResearch\17.SRDB\GlobalRsProject1\R\GPPTimeTrend.jpg |
| Fig.3 Histogram of the 33 estimates (the highest and lowest GPP estimation were excluded) of gross primary production (a) and temporal change of gross primary production (b). | |

Table 1. Summary of published values on global carbon consumed by fire, herbivores animals and carbon sink by terrestrial ecosystem. Mean (± 95% confidence interval, if available) for each item was obtained or calculated based on data from the paper. N/A means data not available. Rab stands for belowground autotrophic respiration, Rh stands for heterotrophic respiration.

|  |  |  |  |
| --- | --- | --- | --- |
| **Item** | **Period** | **Amount (Pg)** | **Reference** |
| NPP (56.20) | 1862-2011 | 56.20 (± 1.78) | (Ito, 2011) |
| Herbivores consumed  (2.20) | N/A | 1.40 (± 0.20) | (Doughty & Field, 2010) |
| N/A | 3.00 | (Whittaker & Likens, 1973) |
| Fire consumed carbon  (3.53) | 1997-2009 | 2.00 | (van der Werf et al., 2010) |
| 1960s | 3.50 (± 1.50) | (Crutzen & Andreae, 1990) |
| N/A | 7.30 | (Gerber et al., 2004) |
| 1901-2002 | 4.00 | (Piao et al., 2009) |
| 1980-2000 | 5.10 | (Zaehle et al., 2005) |
| 1920-1970 | 2.02 | (Mieville et al., 2010) |
| 1970-2010 | 2.71 | (Mieville et al., 2010) |
| 1900-2000 | 3.02 (± 0.30) | (Mouillot, Narasimha, Balkanski, Lamarque, & Field, 2006) |
| 1960-2000 | 2.08 | (Schultz et al., 2008) |
| Land sink carbon (2.10) | 1959-2014 | (2.10± 0.28) | (Le Quéré et al., 2015) |
| Carbon washed away by fresh water (1.90) | N/A | 1.90 | (Cole et al., 2007) |
| N/A | 1.70 | (Bastviken et al., 2011) |
| N/A | 2.10 | (Deemer et al., 2016) |
| Rab / Rh | 1983-2004 | 0.75 (± 0.16) | (Bond-Lamberty et al., 2004) |

Table 4. Summary of global GPP (units: Pg) estimates

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Period** | **GPP (Pg)** | **Trend**  **(Pg yr-1)** | **Reference** | **Notes** |
| 1975 | 71.73 |  | (Box, 1978) | Converted from dry matter |
| 1990-1999 | 120.00 |  | (Ciais et al., 1997) |  |
| 1991 | 133.10 |  | (Ruimy, Dedieu, & Saugier, 1996) | Temperature data was 1991 |
| 1995 | 113.00 |  | (Thompson & Randerson, 1999) |  |
| 1965-1994 | 114.7 |  | (Kucharik, Foley, & Delire, 2000) |  |
| 2000 | 183.39 |  | (Knorr & Heimann, 2001) |  |
| 1953-1999 | 121.5 |  | (AKIHIKO Ito, 2003) |  |
| 1993 | 153.48 |  | (Still, Berry, Collatz, & DeFries, 2003) |  |
| 1961-1998 | 124.70 |  | (Akihiko Ito & OIKAWA, 2004) |  |
| 1990-1999 | 118.00 |  | (Woodward & Lomas, 2004) |  |
| 1971-2000 | 124.60 | 0.44 | (Akihiko Ito, 2005) |  |
| 1997-1999 | 137.40 |  | (Krinner et al., 2005) |  |
| 1980-2000 | 135.70 |  | (Rayner et al., 2005) |  |
| 1992-1999 | 160.95 |  | (Takahiro Sasai, Ichii, Yamaguchi, & Nemani, 2005) | Estimated from figure 3 |
| 1965-2000 | 122.00 |  | (Zeng, Mariotti, & Wetzel, 2005) |  |
| 2001-2003 | 109.29 |  | (Zhao, Heinsch, Nemani, & Running, 2005) |  |
| 1982-2001 | 112.13 | 0.28 | (A Ito & Sasai, 2006) | Average of six estimations |
| 1900-2000 | 125.00 | 0.14 | (R. M. Law, Kowalczyk, & WANGs, 2006) |  |
| 2001-2003 | 113.67 |  | (Zhao, Running, & Nemani, 2006) | Average of ten estimations |
| 2000-2001 | 132.25 |  | (Demarty et al., 2007) | Average of two estimations |
| 2001-2004 | 131.50 |  | (T. Sasai, Okamoto, Hiyama, & Yamaguchi, 2007) |  |
| 2001 | 97.00 |  | (Thornton & Zimmermann, 2007) | Average of D0, D1and P1 |
| 1981-2004 | 124.00 |  | (Qian, Joseph, & Zeng, 2008) |  |
| 2000 | 118.00 |  | (Jacobson & Streets, 2009) |  |
| 2000-2003 | 110.00 |  | (Yangjian Zhang, Xu, Chen, & Adams, 2009) |  |
| 1980-2000 | 139.7 | 0.27 | (Arora et al., 2009) | Exclude data of 1850s |
| 1986-2002 | 129.00 |  | (Alton, 2011) | P-fixed |
| 2001 | 120.00 |  | (Prentice et al., 2007) | IPCC |
| 2000-2011 | 107.00 |  | (Yebra, Van Dijk, Leuning, & Guerschman, 2015) |  |
| 2001-2003 | 118.00 |  | (Ryu et al., 2011) |  |
| 1982-2004 | 117.00 |  | (Bonan et al., 2011) |  |
| 1998-2005 | 123.00 |  | (Beer et al., 2010) |  |
| 1992-2008 | 119.00 |  | (Jung et al., 2011) |  |
| 2000-2003 | 110.50 |  | (Yuan et al., 2010) |  |
| 1970-2000 | 134.00 |  | (Gerber et al., 2004) |  |
| 2000 | 141 |  | (Raddatz et al., 2007) | Figure 7 |
| 2010 | 147.5 |  | (Raddatz et al., 2007) | Figure 7 |
| 1997-2010 | 119 | 0.0181 | (Anav et al., 2015) | Table 3 |
| 1997-2010 | 112 | 0.005 | (Anav et al., 2015) | Table 3 |
| 1997-2010 | 148 | 0.078 | (Anav et al., 2015) | Table 3 |
| 1997-2010 | 147 | 0.417 | (Anav et al., 2015) | Table 3 |
| 1997-2010 | 130 | 0.353 | (Anav et al., 2015) | Table 3 |
| 1997-2010 | 131 | 0.262 | (Anav et al., 2015) | Table 3 |
| 1997-2010 | 149 | 0.621 | (Anav et al., 2015) | Table 3 |
| 1997-2010 | 140 | 0.598 | (Anav et al., 2015) | Table 3 |
| 1997-2010 | 153 | 0.508 | (Anav et al., 2015) | Table 3 |
| 1997-2010 | 169 | 0.454 | (Anav et al., 2015) | Table 3 |
| 2000-2010 | 117 | 0.41 | (M. Chen et al., 2017) | ENSEMBLE |
| 2000-2010 | 112 | 0.28 | (M. Chen et al., 2017) | MODIS |
| 1980-2009 | 162.5 |  | (Welp et al., 2011) | The global damping time constant method |
| **1950-2010** | **128.05** | **0.32** |  | **Average** |

Fig. 1 Terrestrial carbon cycling pathway. Solid filled boxes denote the values are mean (± 95% confidence interval) of data collected from the literature. The dashed boxes denote calculated values. All units are Pg C yr-1. Abbreviations used are as follows: Gross Primary Production (GPP) was from (Prentice et al., 2007), Net Primary Production (NPP), autotrophic respiration (Ra), belowground autotrophic respiration (Rab), root respiration (Rroot), stem respiration (Rstem), leaf respiration (Rleaf), belowground heterotrophic respiration (Rh), and Soil respiration (Rs). Calculation in panel (a): Rh =NPP - Herbivores - Land Sink - Fire - Freshwater. Calculation in panel (b): Ra = GPP - NPP, Rroot = Ra × proportion of Rroot to Ra (0.37), Rstem = Ra × proportion of Rstem to Ra (0.25), Rleaf = Ra × proportion of Rleaf to Ra (0.38). For details and references about each carbon component, please see supplemental material Table S1 and Table S2.

Table 1. Summary of published values on global carbon consumed by fire, herbivores animals and carbon sink by terrestrial ecosystem. Mean (± 95% confidence interval, if available) for each item was obtained or calculated based on data from the paper. N/A means data not available. Rab stands for belowground autotrophic respiration, Rh stands for heterotrophic respiration.

|  |  |  |  |
| --- | --- | --- | --- |
| **Item** | **Period** | **Amount (Pg)** | **Reference** |
| NPP (56.20) | 1862-2011 | 56.20 (± 1.78) | (AKIHIKO Ito, 2011) |
| Herbivores consumed  (2.20) | N/A | 1.40 (± 0.20) | (Doughty & Field, 2010) |
| N/A | 3.00 | (Whittaker & Likens, 1973) |
| Fire consumed carbon  (3.53) | 1997-2009 | 2.00 | (van der Werf et al., 2010) |
| 1960s | 3.50 (± 1.50) | (Crutzen & Andreae, 1990) |
| N/A | 7.30 | (Gerber et al., 2004) |
| 1901-2002 | 4.00 | (Piao et al., 2009) |
| 1980-2000 | 5.10 | (Zaehle et al., 2005) |
| 1920-1970 | 2.02 | (Mieville et al., 2010) |
| 1970-2010 | 2.71 | (Mieville et al., 2010) |
| 1900-2000 | 3.02 (± 0.30) | (Mouillot, Narasimha, Balkanski, Lamarque, & Field, 2006) |
| 1960-2000 | 2.08 | (Schultz et al., 2008) |
| Land sink carbon (2.10) | 1959-2014 | (2.10± 0.28) | (Le Quéré et al., 2015) |
| Carbon washed away by fresh water (1.90) | N/A | 1.90 | (Cole et al., 2007) |
| N/A | 1.70 | (Bastviken et al., 2011) |
| N/A | 2.10 | (Deemer et al., 2016) |
| Rab / Rh | 1983-2004 | 0.75 (± 0.16) | (Bond-Lamberty et al., 2004) |

Table 2 Summary of papers separate leaf respiration fraction (Fl), stem respiration fraction (Fs) and root respiration fraction (Fr). N/A means data not available.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Fl** **(**%) | **Fs (**%) | **Fr (**%) | **Vegetation type** | **Reference** |
| 50.00 | N/A | N/A | Tropical forest | (Allen & Lemon, 1976) |
| 53.00 | 35.00 | 12.00 | Tropical forest | (Yoda, 1983) |
| 55.00 | N/A | N/A | Warm-temperate forest | (Yoda, 1978) |
| 28.00 | 26.00 | 46.00 | Temperate deciduous forest | (Edwards, Shugart, McLaughlin, Harris, & Reichle, 1981) |
| 33.50 | 39.40 | 29.00 | Pinus radiata trees | (Michael G Ryan, Hubbard, Pongracic, Raison, & Murtrie, 1996) |
| 31.60 | 39.40 | 29.00 | Forest in northern Manitob, Canada | (M. G. Ryan, Lavigne, & Gower, 1997) |
| 43.17 | 34.53 | 22.30 | Forest in Central Saskatchewa, Canada | (M. G. Ryan et al., 1997) |
| 32.92 | 13.60 | 53.48† | Pine forest | (B. E. Law, Ryan, & Anthoni, 1999) |
|  | | 24.92 | Crop | (Suleau et al., 2011) |
|  | | 46.70 | Young Beech forest | (Granier et al., 2000) |
| 23.30 | 6.70 | 70.00 | Tropical savanna | (X. Chen, Hutley, & Eamus, 2003) |
| 24.40 | 18.28 | 57.32† | Deciduous forest | (Bolstad, Davis, Martin, Cook, & Wang, 2004) |
| 31.27 | 26.01 | 42.72 | Hardwood forest | (Curtis et al., 2005) |
|  | | 29.01 | Spruce-dominated forest | (Davidson, Richardson, Savage, & Hollinger, 2006) |
|  | | 34.78 | Temperate forest | (Nagy, Janssens, Curiel Yuste, Carrara, & Ceulemans, 2006) |
|  | | 49.04 | Rain forest | (Yiping Zhang et al., 2006) |
|  | | 36.43† | Douglas Fir | (Jassal et al., 2007) |
| 46.22 | 17.07 | 36.71† | Scots Pine | (Zha, Xing, Wang, Kellomaki, & Barr, 2007) |
| 38.10 | 26.33 | 35.57 | Eucalyptus forest | (Keith et al., 2009) |
| 41.49 | 12.04 | 46.47† | Scots pine forest | (Kolari et al., 2009) |
| 50.51 | 21.21 | 28.28 | Amazonian forests | (Malhi et al., 2009) |
| 24.86 | 25.15 | 49.99 | Pine forest | (Wieser et al., 2009) |
|  | | 36.21 | Alpine meadow | (P. Zhang, Tang, Hirota, Yamamoto, & Mariko, 2009) |
| 50.00 | 15.45 | 34.55 | Black spruce forest | (Hermle, Lavigne, Bernier, Bergeron, & Paré, 2010) |
| 22.96 | 34.31 | 42.73† | Brazil Eucalyptus | (Michael G. Ryan et al., 2010) |
| 55.52 | 19.42 | 25.06 | Rain forest | (Tan et al., 2010) |
|  | | 23.55 | Maize | (Jans et al., 2010) |
| 30.70 | 43.15 | 26.15† | Eucalyptus plantation | (Campoe, Stape, Laclau, Marsden, & Nouvellon, 2012) |
|  | | 24.00† | Mediterranean pine forest | (Matteucci et al., 2015) |
| **38.27****(±2.54)** | **25.10(****±2.49)** | **36.63(±2.48)** | **Average** |  |

Label † means that root respiration was estimated from model: RA0.5 = -7.97 + 0.93Rs0.5 (units: g c m-2 yr-1). (Bond-Lamberty et al., 2004).

**References:**

Allen, L. H., & Lemon, E. R. (1976). Carbon dioxide exchange and turbulence in a Costa Rican tropical rain forest. In J. . Monteith (Ed.), *Vegetation and the Atmosphere* (Vol. 2, pp. 265–308). Lendon: Academic Press.

Alton, P. B. (2011). How useful are plant functional types in global simulations of the carbon, water, and energy cycles? *Journal of Geophysical Research: Biogeosciences*, *116*(1), 1–14. https://doi.org/10.1029/2010JG001430

Anav, A., Friedlingstein, P., Beer, C., Ciais, P., Harper, A., Jones, C., … Zhao, M. (2015). Reviews of Geophysics primary production : A review. *Reviews of Geophysics*, *53*, 785–818. https://doi.org/10.1002/2015RG000483.Received

Arora, V. K., Boer, G. J., Christian, J. R., Curry, C. L., Denman, K. L., Zahariev, K., … Lee, W. G. (2009). The Effect of terrestrial photosynthesis down regulation on the twentieth-century carbon budget simulated with the CCCma Earth System Model. *Journal of Climate*, *22*(22), 6066–6088. https://doi.org/10.1175/2009JCLI3037.1

Bastviken, D., Tranvik, L. J., Downing, J., Crill, J. a, M, P., & Enrich-prast, A. (2011). Freshwater methane emissions offset the continental carbon sink. *Science*, *331*(6013), 50. https://doi.org/10.1126/science.1196808

Beer, C., Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., … Papale, D. (2010). Terrestrial Gross Carbon Dioxide Uptake: Global Distribution and Covariation with Climate. *Sicence*, *329*(August), 834–839.

Bolstad, P. V, Davis, K. J., Martin, J., Cook, B. D., & Wang, W. (2004). Component and whole-system respiration fluxes in northern deciduous forests. *Tree Physiology*, *24*(5), 493–504. https://doi.org/10.1093/treephys/24.5.493

Bonan, G. B., Lawrence, P. J., Oleson, K. W., Levis, S., Jung, M., Reichstein, M., … Swenson, S. C. (2011). Improving canopy processes in the Community Land Model version 4 (CLM4) using global flux fields empirically inferred from FLUXNET data. *Journal of Geophysical Research*, *116*(G2), 1–22. https://doi.org/10.1029/2010JG001593

Bond-Lamberty, B., Wang, C., & Gower, S. T. (2004). A global relationship between the heterotrophic and autotrophic components of soil respiration? *Global Change Biology*, *10*(10), 1756–1766. https://doi.org/10.1111/j.1365-2486.2004.00816.x

Box, E. (1978). Geographical dimensions of terrestrial net and gross primary productivity. *Radiation and Environmental Biophysics*, *15*(4), 305–322. https://doi.org/10.1007/BF01323458

Campoe, O. C., Stape, J. L., Laclau, J. P., Marsden, C., & Nouvellon, Y. (2012). Stand-level patterns of carbon fluxes and partitioning in a Eucalyptus grandis plantation across a gradient of productivity, in Sao Paulo State, Brazil. *Tree Physiology*, *32*(6), 696–706. https://doi.org/10.1093/treephys/tps038

Chen, M., Raﬁque, R., Asrar, G. R., Bond-Lamberty, B., Ciais, P., Zhao, F., … Hickler, T. (2017). Regional contribution to variability and trends of global gross primary productivity. *Environmental Research Letters*, *12*(10), 105005. https://doi.org/10.1088/1748-9326/aa8978

Chen, X., Hutley, L. B., & Eamus, D. (2003). Carbon balance of a tropical savanna of northern Australia. *Oecologia*, *137*(3), 405–416. https://doi.org/10.1007/s00442-003-1358-5

Ciais, P., Denning, A. S., Tans, P. P., Berry, J. A., Randall, D. A., Collatz, G. J., … Heimann, M. (1997). A three-dimensional synthesis study of 18O in atmospheric COz. *JOURNAL OF GEOPHYSICAL RESEARCH*, *102*, 5857–5872.

Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., … Melack, J. (2007). Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. *Ecosystems*, *10*(1), 171–184. https://doi.org/10.1007/s10021-006-9013-8

Crutzen, P., & Andreae, M. O. (1990). Biomass burning in the tropics: Impact on atmospheric chemistry and biogeochemical cycles. *Science*, *250*(4988), 1669–1678.

Curtis, P. S., Vogel, C. S., Gough, C. M., Schmid, H. P., Su, H. B., & Bovard, B. D. (2005). Respiratory carbon losses and the carbon-use efficiency of a northern hardwood forest, 1999-2003. *New Phytologist*, *167*(2), 437–456. https://doi.org/10.1111/j.1469-8137.2005.01438.x

Davidson, E. A., Richardson, A. D., Savage, K. E., & Hollinger, D. Y. (2006). A distinct seasonal pattern of the ratio of soil respiration to total ecosystem respiration in a spruce-dominated forest. *Global Change Biology*, *12*(2), 230–239. https://doi.org/10.1111/j.1365-2486.2005.01062.x

Deemer, B. R., Harrison, J. A., Li, S., Beaulieu, J. J., DelSontro, T., Barros, N., … Proof, B. P.--uncorrected. (2016). Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis. *BioScience*, *XX*(X), biw117. https://doi.org/10.1093/biosci/biw117

Demarty, J., Chevallier, F., Friend, A. D., Viovy, N., Piao, S., & Ciais, P. (2007). Assimilation of global MODIS leaf area index retrievals within a terrestrial biosphere model. *Geophysical Research Letters*, *34*(15), 1–6. https://doi.org/10.1029/2007GL030014

Doughty, C. E., & Field, C. B. (2010). Agricultural net primary production in relation to that liberated by the extinction of Pleistocene mega-herbivores: an estimate of agricultural carrying capacity? *Environmental Research Letters*, *5*(4), 044001. https://doi.org/10.1088/1748-9326/5/4/044001

Edwards, N. T., Shugart, H. H., McLaughlin, S. B., Harris, W. F., & Reichle, D. E. (1981). Carbon metabolism in terrestrial ecosystems. In D. E. Reichle (Ed.), *Dynamic Properties of Forest Ecosystems* (pp. 499–536). Cambridge: Cambridge Univ. Press.

Gerber, S., Joos, F., & Prentice, C. (2004). Sensitivity of a dynamic global vegetation model to climate and atmospheric CO2. *Global Change Biology*, *10*, 1223–1239. https://doi.org/10.1111/j.1365-2486.2004.00807.x

Granier, A., Ceschia, E., Damesin, C., Dufrêne, E., Epron, D., Gross, P., … Saugier, B. (2000). The carbon balance of a young beech forest. *Functional Ecology*, *14*(3), 2000.

Hermle, S., Lavigne, M. B., Bernier, P. Y., Bergeron, O., & Paré, D. (2010). Component respiration, ecosystem respiration and net primary production of a mature black spruce forest in northern Quebec. *Tree Physiology*, *30*(4), 527–540. https://doi.org/10.1093/treephys/tpq002

Ito, A. (2003). A global-scale simulation of the CO2 exchange between the atmosphere and the terrestrial biosphere with a mechanistic model including stable carbon isotopes , 1953 – 1999. *Tellus*, *55*(B), 596–612.

Ito, A. (2005). Climate-related uncertainties in projections of the twenty-first century terrestrial carbon budget: Off-line model experiments using IPCC greenhouse-gas scenarios and AOGCM climate projections. *Climate Dynamics*, *24*(5), 435–448. https://doi.org/10.1007/s00382-004-0489-7

Ito, A. (2011). A historical meta-analysis of global terrestrial net primary productivity: are estimates converging? *Global Change Biology*, *17*(10), 3161–3175. https://doi.org/10.1111/j.1365-2486.2011.02450.x

Ito, A., & OIKAWA, A. (2004). Global Mapping of Terrestrial Primary Productivity and Light-Use Efficiency with a Process-Based Model. In M. Shiyomi, H.Kawahata, H. Koizumi, A. Tsuda, & Y. Awaya (Eds.), *Global Environmental Change in the Ocean and on Land* (pp. 343–358). Tokyo.

Ito, A., & Sasai, T. (2006). A comparison of simulation results from two terrestrial carbon cycle models using three climate data sets. *Tellus Series B-Chemical and Physical Meteorology*, *58*(5), 513–522. https://doi.org/10.1111/j.1600-0889.2006.00208.x

Jacobson, M. Z., & Streets, D. G. (2009). Influence of future anthropogenic emissions on climate, natural emissions, and air quality. *Journal of Geophysical Research Atmospheres*, *114*(8), 1–21. https://doi.org/10.1029/2008JD011476

Jans, W. W. P., Jacobs, C. M. J., Kruijt, B., Elbers, J. A., Barendse, S., & Moors, E. J. (2010). Carbon exchange of a maize (Zea mays L.) crop: Influence of phenology. *Agriculture, Ecosystems and Environment*, *139*(3), 316–324. https://doi.org/10.1016/j.agee.2010.06.008

Jassal, R. S., Black, T. A., Cai, T., Morgenstern, K., Li, Z., Gaumont-Guay, D., & Nesic, Z. (2007). Components of ecosystem respiration and an estimate of net primary productivity of an intermediate-aged Douglas-fir stand. *Agricultural and Forest Meteorology*, *144*(1–2), 44–57. https://doi.org/10.1016/j.agrformet.2007.01.011

Jung, M., Reichstein, M., Margolis, H. A., Cescatti, A., Richardson, A. D., Arain, M. A., … Williams, C. (2011). Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations. *Journal of Geophysical Research: Biogeosciences*, *116*(3), 1–16. https://doi.org/10.1029/2010JG001566

Keith, H., Leuning, R., Jacobsen, K. L., Cleugh, H. A., van Gorsel, E., Raison, R. J., … Keitel, C. (2009). Multiple measurements constrain estimates of net carbon exchange by a Eucalyptus forest. *Agricultural and Forest Meteorology*, *149*(3–4), 535–558. https://doi.org/10.1016/j.agrformet.2008.10.002

Knorr, W., & Heimann, M. (2001). Uncertainties in global terrestrial biosphere modeling, part I: a comprehensive sensitivity analysis with a new photosynthesis and energy balance scheme. *Global Biogeochemical Cycles*, *15*(1), 207–225. https://doi.org/10.1029/1998GB001059

Kolari, P., Kulmala, L., Pumpanen, J., Launiainen, S., Ilvesniemi, H., Hari, P., & Nikinmaa, E. (2009). CO 2 exchange and component CO 2 fl uxes of a boreal Scots pine forest. *Boreal Environment Research*, *14*(August), 761–783.

Krinner, G., Viovy, N., de Noblet-Ducoudré, N., Ogée, J., Polcher, J., Friedlingstein, P., … Prentice, I. C. (2005). A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system. *Global Biogeochemical Cycles*, *19*(1), 1–33. https://doi.org/10.1029/2003GB002199

Kucharik, C. J., Foley, J. A., & Delire, C. (2000). Testing the performance of a dynamic global ecosystem model: Water balance, carbon balance, and vegetation structure. *Global Biogeochemical Cycles*, *14*(3), 795–825.

Law, B. E., Ryan, M. G., & Anthoni, P. M. (1999). Seasonal and annual respiration of a ponderosa pin ecosystem. *Global Change Biology*, *5*, 169–182.

Law, R. M., Kowalczyk, E. a., & WANGs, Y.-P. (2006). Using atmospheric CO 2 data to assess a simplified carbon-climate simulation for the 20th century. *Tellus B*, *58*(5), 427–437. https://doi.org/10.1111/j.1600-0889.2006.00198.x

Le Quéré, C., Moriarty, R., Andrew, R. M., Canadell, J. G., Sitch, S., Korsbakken, J. I., … Boden, T. A. (2015). Global carbon budget 2015. *Earth System Science Data*, *7*(2), 349–396.

Malhi, Y., Aragao, L. E. O. C., Metcalfe, D. B., Paiva, R., Quesada, C. A., Almeida, S., … Teixeira, L. M. (2009). Comprehensive assessment of carbon productivity, allocation and storage in three Amazonian forests. *Global Change Biology*, *15*(5), 1255–1274. https://doi.org/10.1111/j.1365-2486.2008.01780.x

Matteucci, M., Gruening, C., Goded Ballarin, I., Seufert, G., Cescatti, A., Ballarin, I. G., … Cescatti, A. (2015). Components, drivers and temporal dynamics of ecosystem respiration in a Mediterranean pine forest. *Soil Biology and Biochemistry*, *88*, 224–235. https://doi.org/10.1016/j.soilbio.2015.05.017

Mieville, A., Granier, C., Liousse, C., Guillaume, B., Mouillot, F., Lamarque, J. F., … Pétron, G. (2010). Emissions of gases and particles from biomass burning during the 20th century using satellite data and an historical reconstruction. *Atmospheric Environment*, *44*(11), 1469–1477. https://doi.org/10.1016/j.atmosenv.2010.01.011

Mouillot, F., Narasimha, A., Balkanski, Y., Lamarque, J.-F., & Field, C. B. (2006). Global carbon emissions from biomass burning in the 20th century. *Geophysical Research Letters*, *33*(1), 2–5. https://doi.org/10.1029/2005GL024707

Nagy, M. T., Janssens, I. A., Curiel Yuste, J., Carrara, A., & Ceulemans, R. (2006). Footprint-adjusted net ecosystem CO2 exchange and carbon balance components of a temperate forest. *Agricultural and Forest Meteorology*, *139*(3–4), 344–360. https://doi.org/10.1016/j.agrformet.2006.08.012

Piao, S., Ciais, P., Friedlingstein, P., De Noblet-Ducoudré, N., Cadule, P., Viovy, N., & Wang, T. (2009). Spatiotemporal patterns of terrestrial carbon cycle during the 20th century. *Global Biogeochemical Cycles*, *23*(4), 1–16. https://doi.org/10.1029/2008GB003339

Prentice, I. C., Farquhar, G. D., Fasham, M. J. R., Goulden, M. L., Heimann, M., Jaramillo, V. J., … Wallace, D. W. R. (2007). The Carbon Cycle and Atmospheric Carbon Dioxide. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, … H. L. Miller (Eds.), *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007* (pp. 183–287). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Qian, H., Joseph, R., & Zeng, N. (2008). Response of the terrestrial carbon cycle to the El Nino-Southern Oscillation. *Tellus Series B-Chemical and Physical Meteorology*, *60*(4), 537–550. https://doi.org/10.1111/j.1600-0889.2008.00360.x

Raddatz, T. J., Reick, C. H., Knorr, W., Kattge, J., Roeckner, E., Schnur, R., … Jungclaus, J. (2007). Will the tropical land biosphere dominate the climate-carbon cycle feedback during the twenty-first century? *Climate Dynamics*, *29*(6), 565–574. https://doi.org/10.1007/s00382-007-0247-8

Rayner, P. J., Scholze, M., Knorr, W., Kaminski, T., Giering, R., & Widmann, H. (2005). Two decades of terrestrial carbon fluxes from a carbon cycle data assimilation system (CCDAS). *Global Biogeochemical Cycles*, *19*(2), GB2026. https://doi.org/10.1029/2004GB002254

Ruimy, A., Dedieu, G., & Saugier, B. (1996). TURC: A diagnostic model of continental gross primary productivity and net primary productivity. *Global Biogeochemical Cycles*, *10*(2), 269–285. https://doi.org/10.1029/96GB00349

Ryan, M. G., Hubbard, R. M., Pongracic, S., Raison, R. J., & Murtrie, R. E. M. C. (1996). Foliage, fine-root, woody-tissue and stand respiration in Relation To Nitrogen Status. *Tree Physiology*, *16*, 333–343.

Ryan, M. G., Lavigne, M. B., & Gower, S. T. (1997). Annual carbon cost of autotrophic respiration in boreal forest ecosystems in relation to species and climate. *Journal of Geophysical Research*, *102*(D24), 28871–28883. https://doi.org/10.1029/97JD01236

Ryan, M. G., Stape, J. L., Binkley, D., Fonseca, S., Loos, R. A., Takahashi, E. N., … Silva, G. G. C. (2010). Factors controlling Eucalyptus productivity: How water availability and stand structure alter production and carbon allocation. *Forest Ecology and Management*, *259*(9), 1695–1703. https://doi.org/10.1016/j.foreco.2010.01.013

Ryu, Y., Baldocchi, D. D., Kobayashi, H., Van Ingen, C., Li, J., Black, T. A., … Roupsard, O. (2011). Integration of MODIS land and atmosphere products with a coupled-process model to estimate gross primary productivity and evapotranspiration from 1 km to global scales. *Global Biogeochemical Cycles*, *25*(4), 1–24. https://doi.org/10.1029/2011GB004053

Sasai, T., Ichii, K., Yamaguchi, Y., & Nemani, R. (2005). Simulating terrestrial carbon fluxes using the new biosphere model “biosphere model integrating eco-physiological and mechanistic approaches using satellite data” (BEAMS). *Journal of Geophysical Research*, *110*, 1–18. https://doi.org/10.1029/2005JG000045

Sasai, T., Okamoto, K., Hiyama, T., & Yamaguchi, Y. (2007). Comparing terrestrial carbon fluxes from the scale of a flux tower to the global scale. *Ecological Modelling*, *208*(2–4), 135–144. https://doi.org/10.1016/j.ecolmodel.2007.05.014

Schultz, M. G., Heil, A., Hoelzemann, J. J., Spessa, A., Thonicke, K., Goldammer, J. G., … van Het Bolscher, M. (2008). Global wildland fire emissions from 1960 to 2000. *Global Biogeochemical Cycles*, *22*(2), 1–17. https://doi.org/10.1029/2007GB003031

Still, C. J., Berry, J. A., Collatz, G. J., & DeFries, R. S. (2003). Global distribution of C 3 and C 4 vegetation: Carbon cycle implications. *Global Biogeochemical Cycles*, *17*(1), 6-1-6–14. https://doi.org/10.1029/2001GB001807

Suleau, M., Moureaux, C., Dufranne, D., Buysse, P., Bodson, B., Destain, J.-P. P., … Aubinet, M. (2011). Respiration of three Belgian crops: Partitioning of total ecosystem respiration in its heterotrophic, above- and below-ground autotrophic components. *Agricultural and Forest Meteorology*, *151*(5), 633–643. https://doi.org/10.1016/j.agrformet.2011.01.012

Tan, Z., Zhang, Y., Yu, G., Sha, L., Tang, J., Deng, X., & Song, Q. (2010). Carbon balance of a primary tropical seasonal rain forest. *Journal of Geophysical Research Atmospheres*, *115*(13), 1–17. https://doi.org/10.1029/2009JD012913

Thompson, M. V., & Randerson, J. T. (1999). Impulse response functions of terrestrial carbon cycle models: Method and application. *Global Change Biology*, *5*(4), 371–394. https://doi.org/10.1046/j.1365-2486.1999.00235.x

Thornton, P. E., & Zimmermann, N. E. (2007). An improved canopy integration scheme for a Land Surface Model with prognostic canopy structure. *Journal of Climate*, *20*(15), 3902–3923. https://doi.org/10.1175/JCLI4222.1

van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., … van Leeuwen, T. T. (2010). Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). *Atmospheric Chemistry and Physics*, *10*(23), 11707–11735. https://doi.org/10.5194/acp-10-11707-2010

Welp, L. R., Keeling, R. F., Meijer, H. A. J., Bollenbacher, A. F., Piper, S. C., Yoshimura, K., … Wahlen, M. (2011). Interannual variability in the oxygen isotopes of atmospheric CO 2 driven by El Niño. *Nature*, *477*(7366), 579–582. https://doi.org/10.1038/nature10421

Whittaker, R. H., & Likens, G. E. (1973). Carbon in the biota. In G. M. Woodwell & E. V Pecan (Eds.), *Carbon and biosphere* (pp. 281–302). U.S.: National Technical Information Service.

Wieser, G., Gruber, A., Bahn, M., Catal, E., Carrillo, E., Jimnez, M. S., & Morales, D. (2009). Respiratory fluxes in a Canary Islands pine forest. *Tree Physiology*, *29*(3), 457–466. https://doi.org/10.1093/treephys/tpp008

Woodward, F. I., & Lomas, M. R. (2004). Vegetation dynamics--simulating responses to climatic change. *Biological Reviews*, *79*(3), 643–670. https://doi.org/10.1017/s1464793103006419

Yebra, M., Van Dijk, A. I. J. M. J. M., Leuning, R., & Guerschman, J. P. (2015). Global vegetation gross primary production estimation using satellite-derived light-use efficiency and canopy conductance. *Remote Sensing of Environment*, *163*, 206–216. https://doi.org/10.1016/j.rse.2015.03.016

Yoda, K. (1978). Estimation of community respiration. In K. Kira, Y. Ono, & T. Hosokawa (Eds.), *Biological Production in a Warm Temperate Evergreen Oak Forest of Japan* (Vol. 18, pp. 112–131). Tokyo: Univ. Tokyo Press.

Yoda, K. (1983). Community respiration in a lowland rain forest in Pasoh, peninsular Malaysia. *Ecol*, *33*, 183–197.

Yuan, W., Liu, S., Yu, G., Bonnefond, J. M., Chen, J., Davis, K., … Verma, S. B. (2010). Global estimates of evapotranspiration and gross primary production based on MODIS and global meteorology data. *Remote Sensing of Environment*, *114*(7), 1416–1431. https://doi.org/10.1016/j.rse.2010.01.022

Zaehle, S., Sitch, S., Smith, B., & Hatterman, F. (2005). Effects of parameter uncertainties on the modeling of terrestrial biosphere dynamics. *Global Biogeochemical Cycles*, *19*(3), 1–16. https://doi.org/10.1029/2004GB002395

Zeng, N., Mariotti, A., & Wetzel, P. (2005). Terrestrial mechanisms of interannual CO2 variability. *Global Biogeochemical Cycles*, *19*(1), 1–15. https://doi.org/10.1029/2004GB002273

Zha, T., Xing, Z., Wang, K. Y., Kellomaki, S., & Barr, A. G. (2007). Total and component carbon fluxes of a scots pine ecosystem from chamber measurements and eddy covariance. *Annals of Botany*, *99*(2), 345–353. https://doi.org/10.1093/aob/mcl266

Zhang, P., Tang, Y., Hirota, M., Yamamoto, A., & Mariko, S. (2009). Use of a regression method to partition sources of ecosystem respiration in an alpine meadow. *Soil Biology and Biochemistry*, *41*(4), 663–670. https://doi.org/10.1016/j.soilbio.2008.12.026

Zhang, Y., Sha, L., Yu, G., Song, Q., Tang, J., Yang, X., … Sun, X. (2006). Annual variation of carbon flux and impact factors in the tropical seasonal rain forest of Xishuangbanna, SW China. *Science in China, Series D: Earth Sciences*, *49*(SUPPL. 2), 150–162. https://doi.org/10.1007/s11430-006-8150-4

Zhang, Y., Xu, M., Chen, H., & Adams, J. (2009). Global pattern of NPP to GPP ratio derived from MODIS data: Effects of ecosystem type, geographical location and climate. *Global Ecology and Biogeography*, *18*(3), 280–290. https://doi.org/10.1111/j.1466-8238.2008.00442.x

Zhao, M., Heinsch, F. A., Nemani, R. R., & Running, S. W. (2005). Improvements of the MODIS terrestrial gross and net primary production global data set. *Remote Sensing of Environment*, *95*(2), 164–176. https://doi.org/10.1016/j.rse.2004.12.011

Zhao, M., Running, S. W., & Nemani, R. R. (2006). Sensitivity of Moderate Resolution Imaging Spectroradiometer (MODIS) terrestrial primary production to the accuracy of meteorological reanalyses. *Journal of Geophysical Research: Biogeosciences*, *111*(1), 1–13. https://doi.org/10.1029/2004JG000004