Biogeosciences, 21, 5079–5115, 2024
https://doi.org/10.5194/bg-21-5079-2024

Biogeosciences Open Access EGU

Research article

X-BASE: the first terrestrial carbon and water flux products from an extended data-driven scaling framework, FLUXCOM-X

Jacob A. Nelson[1,★], Sophia Walther[1,★], Fabian Gans[1], Basil Kraft[1], Ulrich Weber[1], Kimberly Novick[2], Nina Buchmann[3], Mirco Migliavacca[4], Georg Wohlfahrt[5], Ladislav Šigut[6], Andreas Ibrom[7], Dario Papale[8,9], Mathias Göckede[1], Gregory Duveiller[1], Alexander Knohl[10,11], Lukas Hörtnagl[3], Russell L. Scott[12], Weijie Zhang[1], Zayd Mahmoud Hamdi[1], Markus Reichstein[1,13], Sergio Aranda-Barranco[14,15], Jonas Ardö[16], Maarten Op de Beeck[17,18], Dave Billesbach[19,☆], David Bowling[20], Rosvel Bracho[21], Christian Brümmer[22], Gustau Camps-Valls[23], Shiping Chen[24], Jamie Rose Cleverly[25], Ankur Desai[26], Gang Dong[27], Tarek S. El-Madany[1], Eugenie Susanne Euskirchen[28], Iris Feigenwinter[3], Marta Galvagno[29], Giacomo A. Gerosa[30], Bert Gielen[31], Ignacio Goded[4], Sarah Goslee[32], Christopher Michael Gough[33], Bernard Heinesch[34], Kazuhito Ichii[35], Marcin Antoni Jackowicz-Korczynski[36,37], Anne Klosterhalfen[38], Sara Knox[39,40], Hideki Kobayashi[41], Kukka-Maaria Kohonen[3], Mika Korkiakoski[42], Ivan Mammarella[43], Mana Gharun[44], Riccardo Marzuoli[30], Roser Matamala[45,46,47], Stefan Metzger[48,49], Leonardo Montagnani[50], Giacomo Nicolini[9,58], Thomas O'Halloran[51,52], Jean-Marc Ourcival[53], Matthias Peichl[54], Elise Pendall[55], Borja Ruiz Reverter[56], Marilyn Roland[57], Simone Sabbatini[9,58], Torsten Sachs[59], Marius Schmidt[60], Christopher R. Schwalm[61], Ankit Shekhar[3], Richard Silberstein[62], Maria Lucia Silveira[63], Donatella Spano[64,9], Torbern Tagesson[16,65], Gianluca Tramontana[66], Carlo Trotta[9], Fabio Turco[3], Timo Vesala[67,68], Caroline Vincke[69], Domenico Vitale[70], Enrique R. Vivoni[71,72], Yi Wang[3], William Woodgate[73,74], Enrico A. Yepez[75], Junhui Zhang[76,77], Donatella Zona[78], and Martin Jung[1]

[1]Max Planck Institute for Biogeochemistry, Jena, Germany
[2]O'Neill School of Public and Environmental Affairs, Indiana University – Bloomington, Bloomington, IN 47405, USA
[3]Department of Environmental Systems Science, ETH Zurich, 8092 Zurich, Switzerland
[4]European Commission, Joint Research Centre, Ispra, Varese, Italy
[5]Institut für Ökologie, Universität Innsbruck, Sternwartestr. 15, 6020 Innsbruck, Austria
[6]Department of Matters and Energy Fluxes, Global Change Research Institute CAS, Bělidla 986/4a, CZ-60300 Brno, Czech Republic
[7]Department of Environment and Resource Engineering, Technical University of Denmark (DTU), Bygningstorvet 115, 2800 Kongens Lyngby, Denmark
[8]Research Institute on Terrestrial Ecosystems (IRET), National Research Council (CNR), 00010 Montelibretti, Rome, Italy
[9]CMCC Foundation – Euro-Mediterranean Center on Climate Change, Viterbo, Italy
[10]Bioclimatology, Faculty of Forest Sciences, University of Göttingen, 37077 Göttingen, Germany
[11]Centre of Biodiversity and Sustainable Land Use (CBL), University of Göttingen, 37077 Göttingen, Germany
[12]Southwest Watershed Research Center, USDA-ARS, Tucson, AZ, USA
[13]German Centre for Integrative Biodiversity Research (iDiv) Halle–Jena–Leipzig, Leipzig, Germany
[14]Department of Ecology, University of Granada, Granada, Spain
[15]Andalusian Institute for Earth System Research (CEAMA-IISTA), University of Granada, Granada, Spain
[16]Department of Physical Geography and Ecosystem Science, Lund University, Sölvegatan 12, 223 62 Lund, Sweden
[17]Research Group Plants and Ecosystems, Department of Biology, University of Antwerp, Antwerp, Belgium
[18]ICOS/Ecosystem Thematic Centre
[19]Department of Biological Systems Engineering, School of Natural Resources, University of Nebraska, Lincoln, NE 68583, USA
[20]School of Biological Sciences, University of Utah, Salt Lake City, Utah 84112, USA
[21]School of Forest, Fisheries, and Geomatics Sciences University of Florida, Gainesville, FL 32611, USA
[22]Institute of Climate-Smart Agriculture, Thünen Institute of Climate-Smart Agriculture, Braunschweig, Germany
[23]Image Processing Laboratory (IPL), Universitat de València, Valencia, Spain

Published by Copernicus Publications on behalf of the European Geosciences Union.

[24]State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, PR China
[25]College of Science and Engineering, James Cook University, Cairns, Queensland, Australia
[26]Department of Atmospheric and Oceanic Sciences, University of Wisconsin – Madison, Madison, WI 53706, USA
[27]School of Life Science, Shanxi University, Taiyuan 030006, China
[28]Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, AK 99775, USA
[29]Environmental Protection Agency of Aosta Valley, Climate Change Unit, ARPA Valle d'Aosta, Italy
[30]Department of Mathematics and Physics, Catholic University of the Sacred Heart, Brescia, Italy
[31]Plants and Ecosystems (PLECO), Department of Biology, University of Antwerp, 2610 Wilrijk, Belgium
[32]Pasture Systems and Watershed Management Research Unit, USDA-ARS, University Park, PA, USA
[33]Department of Biology, Virginia Commonwealth University, Richmond, VA 23284, USA
[34]Terra Teaching and Research Center, University of Liège – Gembloux Agro-Bio Tech, 5030 Gembloux, Belgium
[35]Center for Environmental Remote Sensing (CEReS), Chiba University, 1-33, Yayoi-cho, Inage-ku, Chiba 263-8522, Japan
[36]Department of Ecoscience, Aarhus University, Frederiksborgvej 399, Roskilde 4000, Denmark
[37]Department of Physical Geography and Ecosystem Science, Lund University, Sölvegatan 12, 223 62 Lund, Sweden
[38]Bioclimatology, University of Göttingen, 37077 Göttingen, Germany
[39]Department of Geography, McGill University, Montréal, Canada
[40]Department of Geography, The University of British Columbia, Vancouver, Canada
[41]Institute for Global Change, Japan Agency for Marine-Earth Science and Technology (JAMSTEC), 3173-25 Showa-machi, Yokohama, Kanagawa 236-0001, Japan
[42]Finnish Meteorological Institute, Climate System Research Unit, P.O. Box 503, 00101 Helsinki, Finland
[43]Institute of Atmospheric and Earth System Research/Physics, University of Helsinki, Helsinki, Finland
[44]Institute of Landscape Ecology, University of Münster, Münster, Germany
[45]Environmental Science Division, Argonne National Laboratory, Lemont, IL, USA
[46]University of Chicago Consortium for Advanced Science and Engineering (CASE), Chicago, IL, USA
[47]Northwestern Argonne Institute of Science and Engineering, Evanston, IL, USA
[48]National Ecological Observatory Network, Battelle, 1685 38th Street, Boulder, CO 80301, USA
[49]Department of Atmospheric and Oceanic Sciences, University of Wisconsin – Madison, 1225 W Dayton St, Madison, WI 53711, USA
[50]Free University of Bolzano, Faculty of Agricultural, Environmental and Food Sciences – Universitätsplatz 1 – Piazza Università, 1 39100 Bozen–Bolzano, Italy
[51]Belle W. Baruch Institute of Coastal Ecology and Forest Science, Clemson University, Georgetown, SC, USA
[52]Forestry and Environmental Conservation Department, Clemson University, Clemson, SC, USA
[53]CEFE, Univ Montpellier, CNRS, EPHE, IRD, Montpellier, France
[54]Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, Skogsmarksgränd 17, 901 83, Umeå, Sweden
[55]Hawkesbury Institute for the Environment, Western Sydney University, Penrith 2751, Australia
[56]Departamento de Química e Física, Universidade Federal da Paraíba – Campus II, 58397-000 Areia, Paraíba, Brazil
[57]Plants and Ecosystems, Department of Biology, University of Antwerp, 2610 Wilrijk, Belgium
[58]Department for Innovation in Biological, University of Tuscia, Agro-food and Forest Systems (DIBAF), Viterbo, Italy
[59]GFZ German Research Centre for Geosciences, Potsdam, Germany
[60]Forschungszentrum Jülich, Institute of Bio-and Geosciences: Agrosphere (IBG-3), 52428 Jülich, Germany
[61]Woodwell Climate Research Center: FALMOUTH, MA, US
[62]School of Science, Edith Cowan University, Australia
[63]University of Florida, Range Cattle Research and Education Center, 3401 Experiment Station, Ona, FL 33865, USA
[64]Department of Agriculture Sciences, University of Sassari, Sassari, Italy
[65]Department of Geosciences and Natural Resource Management, University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen, Denmark
[66]TERRASYSTEM Srl Spin-Off Company of the University of Tuscia, 01100 Viterbo, Italy
[67]Institute for Atmospheric and Earth System Research/Physics, Faculty of Science, University of Helsinki, 00014 Helsinki, Finland
[68]Institute for Atmospheric and Earth System Research/Forest Sciences, Faculty of Agriculture and Forestry, University of Helsinki, 00014 Helsinki, Finland
[69]UCLouvain – Earth and Life Institute (ELI) Croix du Sud, 2 bte L7.05.24, de Serres B249, 1348 Louvain-la-Neuve, Belgium

[70]Department of Methods and Models for Economics, Territory and Finance (MEMOTEF), Sapienza University of Rome, Via del Castro Laurenziano, 9, 00161 Rome, Italy
[71]School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ, USA
[72]Center for Hydrologic Innovations, Arizona State University, Tempe, AZ, USA
[73]School of the Environment, The University of Queensland, St Lucia 4072, Queensland, Australia
[74]CSIRO, Space and Astronomy, Kensington, 6151, WA, Australia
[75]Instituto Tecnológico de Sonora, 5 de Febrero 818 Sur, Col. Centro, Cd. Obregon, Sonora, 85000, Mexico
[76]School of Life Sciences, Qufu Normal University, Qufu 273165, Shandong, China
[77]Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China
[78]Department Biology, San Diego State University, San Diego, CA 92182, USA
☆retired
★These authors contributed equally to this work.

Correspondence: Jacob A. Nelson (jnelson@bgc-jena.mpg.de) and Sophia Walther (swalth@bgc-jena.mpg.de)

Received: 18 January 2024 – Discussion started: 7 February 2024
Revised: 1 August 2024 – Accepted: 2 August 2024 – Published: 18 November 2024

Abstract. Mapping in situ eddy covariance measurements of terrestrial land–atmosphere fluxes to the globe is a key method for diagnosing the Earth system from a data-driven perspective. We describe the first global products (called X-BASE) from a newly implemented upscaling framework, FLUXCOM-X, representing an advancement from the previous generation of FLUXCOM products in terms of flexibility and technical capabilities. The X-BASE products are comprised of estimates of CO_2 net ecosystem exchange (NEE), gross primary productivity (GPP), evapotranspiration (ET), and for the first time a novel, fully data-driven global transpiration product (ET_T), at high spatial (0.05°) and temporal (hourly) resolution. X-BASE estimates the global NEE at $-5.75 \pm 0.33\,\mathrm{Pg\,C\,yr^{-1}}$ for the period 2001–2020, showing a much higher consistency with independent atmospheric carbon cycle constraints compared to the previous versions of FLUXCOM. The improvement of global NEE was likely only possible thanks to the international effort to increase the precision and consistency of eddy covariance collection and processing pipelines, as well as to the extension of the measurements to more site years resulting in a wider coverage of bioclimatic conditions. However, X-BASE global net ecosystem exchange shows a very low interannual variability, which is common to state-of-the-art data-driven flux products and remains a scientific challenge. With $125 \pm 2.1\,\mathrm{Pg\,C\,yr^{-1}}$ for the same period, X-BASE GPP is slightly higher than previous FLUXCOM estimates, mostly in temperate and boreal areas. X-BASE evapotranspiration amounts to $74.7 \times 10^3 \pm 0.9 \times 10^3\,\mathrm{km^3}$ globally for the years 2001–2020 but exceeds precipitation in many dry areas, likely indicating overestimation in these regions. On average 57 % of evapotranspiration is estimated to be transpiration, in good agreement with isotope-based approaches, but higher than estimates from many land surface models. Despite considerable improvements to the previous upscaling products, many further opportunities for development exist. Pathways of exploration include methodological choices in the selection and processing of eddy covariance and satellite observations, their ingestion into the framework, and the configuration of machine learning methods. For this, the new FLUXCOM-X framework was specifically designed to have the necessary flexibility to experiment, diagnose, and converge to more accurate global flux estimates.

1 Introduction

Energy, water, and carbon exchange between terrestrial surfaces and the atmosphere are key components of the Earth system and impact ecosystems, ecosystem services, weather, climate, and water availability. The exchange (or flux) can be directly observed using eddy covariance (EC) measurement systems (Baldocchi, 2019), which are installed on towers overlooking the ecosystem of interest. The EC stations typically represent an area of a few hundred square meters to a square kilometer. One key advantage of the EC methodology is the ability to provide near-continuous measurements with some records now exceeding 20 years (Pastorello et al., 2020), allowing for examination of flux variations from the order of 30 min to decades. EC systems also provide a unique perspective on the magnitude, temporal variability, and environmental sensitivity of ecosystem CO_2 uptake, water use, and local climate regulation (Baldocchi, 2019; Musavi et al., 2017; Bao et al., 2022). However, while many of the most pressing scientific knowledge gaps surrounding the delicate land carbon balance and the water cycle require spatially and temporally resolved flux patterns at continental to global scales, EC observations are confined to individual locations in space and limited periods in time (Kumar et al., 2016; Pa-