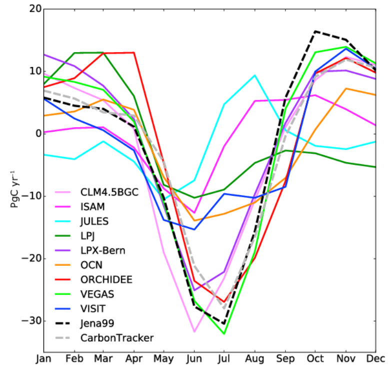
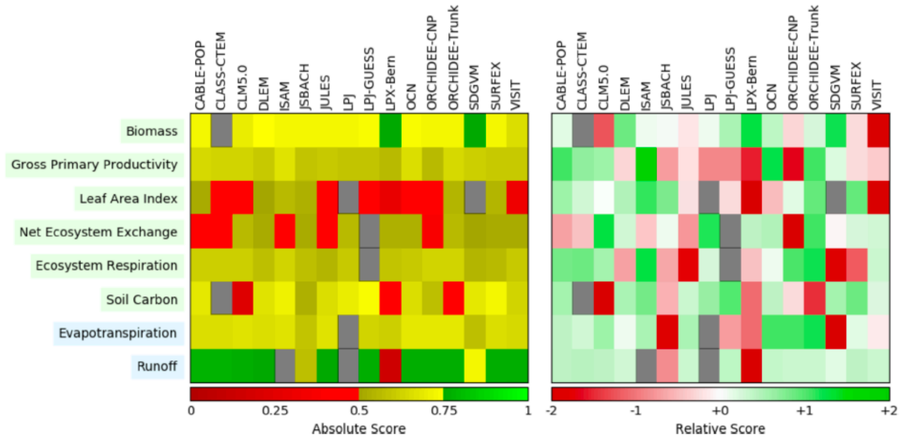
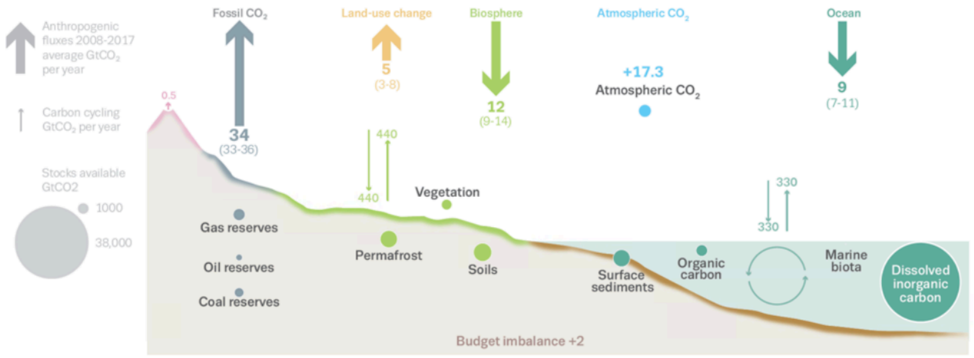
TRENDY Modeling Contribution to the Global Carbon Budget

Ben Poulter, Stephen Sitch, Julia Pongratz, Philippe Ciais, Pierre Friedlingstein & TRENDY modeling teams







Key points

1. Design protocol to estimate land-use & land-cover change emissions for apples-to-apples comparisons, e.g., bookkeeping (UNFCCC) vs land-surface models (IPCC)
2. The TRENDY model intercomparison has evolved to inform the annual Global Carbon Project ‘carbon budget’ activities since 2011
3. Definitions matter, and these drive the complexity of factorial design, e.g., loss of additional sink capacity, legacy fluxes, etc.
4. TRENDY models are not all developed to same state for covering LULCC processes
5. Evaluation of the TRENDY models considers standard benchmarking tools as well as emergent constraints

TRENDY a brief history (2011 to 2018)

The global carbon budget 1959–2011

C. Le Quéré[1], R. J. Andres[2], T. Boden[2], T. Conway[3], R. A. Houghton[4], J. I. House[5], G. Marland[6], G. P. Peters[7], G. R. van der Werf[8], A. Ahlström[9], R. M. Andrew[7], L. Bopp[10], J. G. Canadell[11], P. Ciais[10], S. C. Doney[12], C. Enright[1], P. Friedlingstein[13], C. Huntingford[14], A. K. Jain[15], C. Jourdain[1,*], E. Kato[16], R. F. Keeling[17], K. Klein Goldewijk[18,19,20], S. Levis[21], P. Levy[14], M. Lomas[22], B. Poulter[10], M. R. Raupach[11], J. Schwinger[23,24], S. Sitch[25], B. D. Stocker[26,27], N. Viovy[10], S. Zaehle[28], and N. Zeng[29]

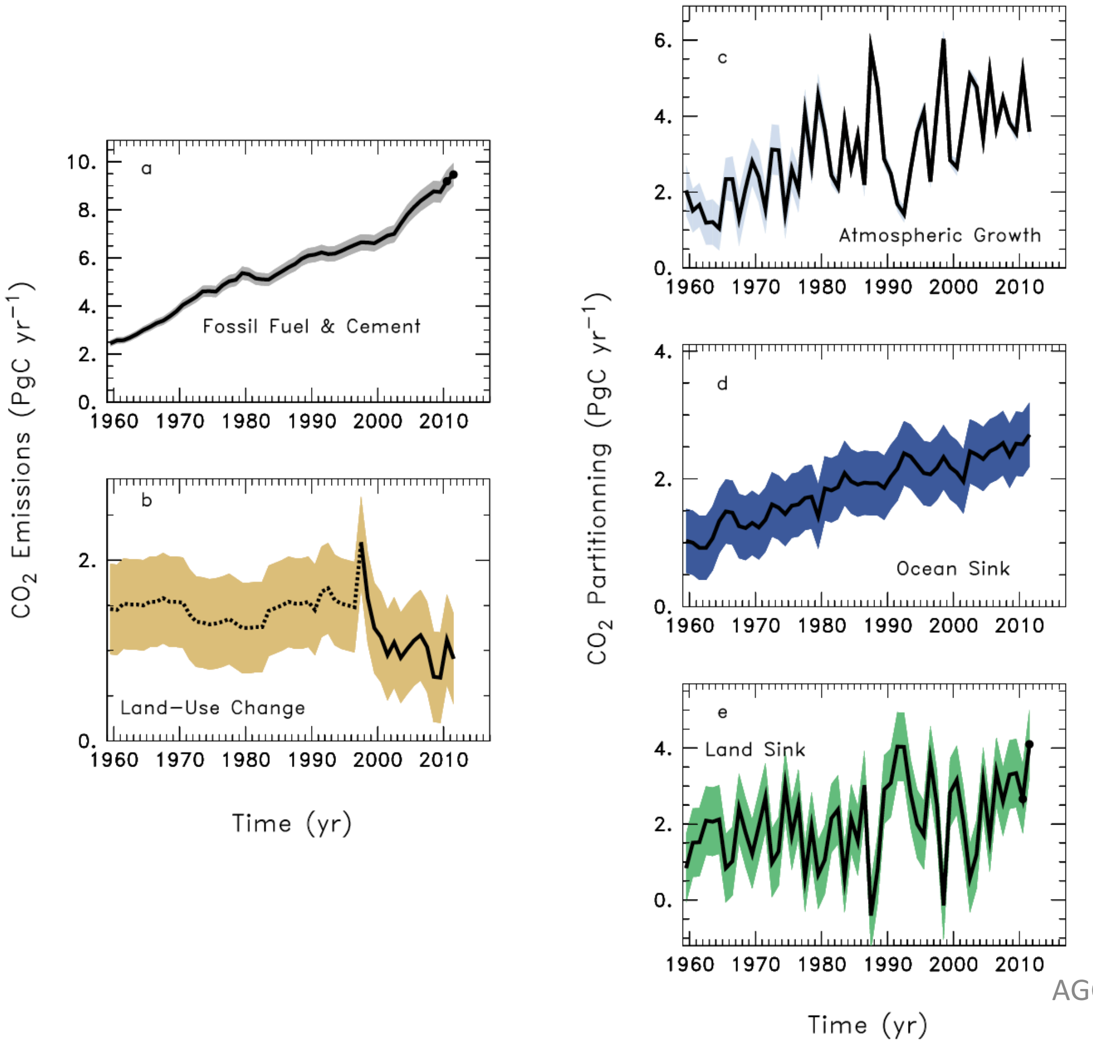
Global Carbon Budget 2018

Corinne Le Quéré[1], Robbie M. Andrew[2], Pierre Friedlingstein[3], Stephen Sitch[4], Judith Hauck[5], Julia Pongratz[6,7], Penelope A. Pickers[8], Jan Ivar Korsbakken[2], Glen P. Peters[2], Josep G. Canadell[9], Almut Arneth[10], Vivek K. Arora[11], Leticia Barbero[12,13], Ana Bastos[6], Laurent Bopp[14], Frédéric Chevallier[15], Louise P. Chini[16], Philippe Ciais[15], Scott C. Doney[17], Thanos Gkritzalis[18], Daniel S. Goll[15], Ian Harris[19], Vanessa Haverd[20], Forrest M. Hoffman[21], Mario Hoppema[5], Richard A. Houghton[22], George Hurtt[16], Tatiana Ilyina[7], Atul K. Jain[23], Truls Johannessen[24], Chris D. Jones[25], Etsushi Kato[26], Ralph F. Keeling[27], Kees Klein Goldewijk[28,29], Peter Landschützer[7], Nathalie Lefèvre[30], Sebastian Lienert[31], Zhu Liu[1,54], Danica Lombardozzi[32], Nicolas Metzl[30], David R. Munro[33], Julia E. M. S. Nabel[7], Shin-ichiro Nakaoka[34], Craig Neill[35,36], Are Olsen[24], Tsueno Ono[38], Prabir Patra[39], Anna Peregon[15], Wouter Peters[40,41], Philippe Peylin[15], Benjamin Pfeil[24,37], Denis Pierrot[12,13], Benjamin Poulter[42], Gregor Rehder[43], Laure Resplandy[44], Eddy Robertson[25], Matthias Rocher[45], Christian Rödenbeck[46], Ute Schuster[4], Jörg Schwinger[37], Roland Séférian[45], Ingunn Skjelvan[37], Tobias Steinhoff[47], Adrienne Sutton[48], Pieter P. Tans[49], Hanqin Tian[50], Bronte Tilbrook[35,36], Francesco N. Tubiello[51], Ingrid T. van der Laan-Luijkx[40], Guido R. van der Werf[52], Nicolas Viovy[15], Anthony P. Walker[53], Andrew J. Wiltshire[25], Rebecca Wright[1,8], Sönke Zaehle[46], and Bo Zheng[15]

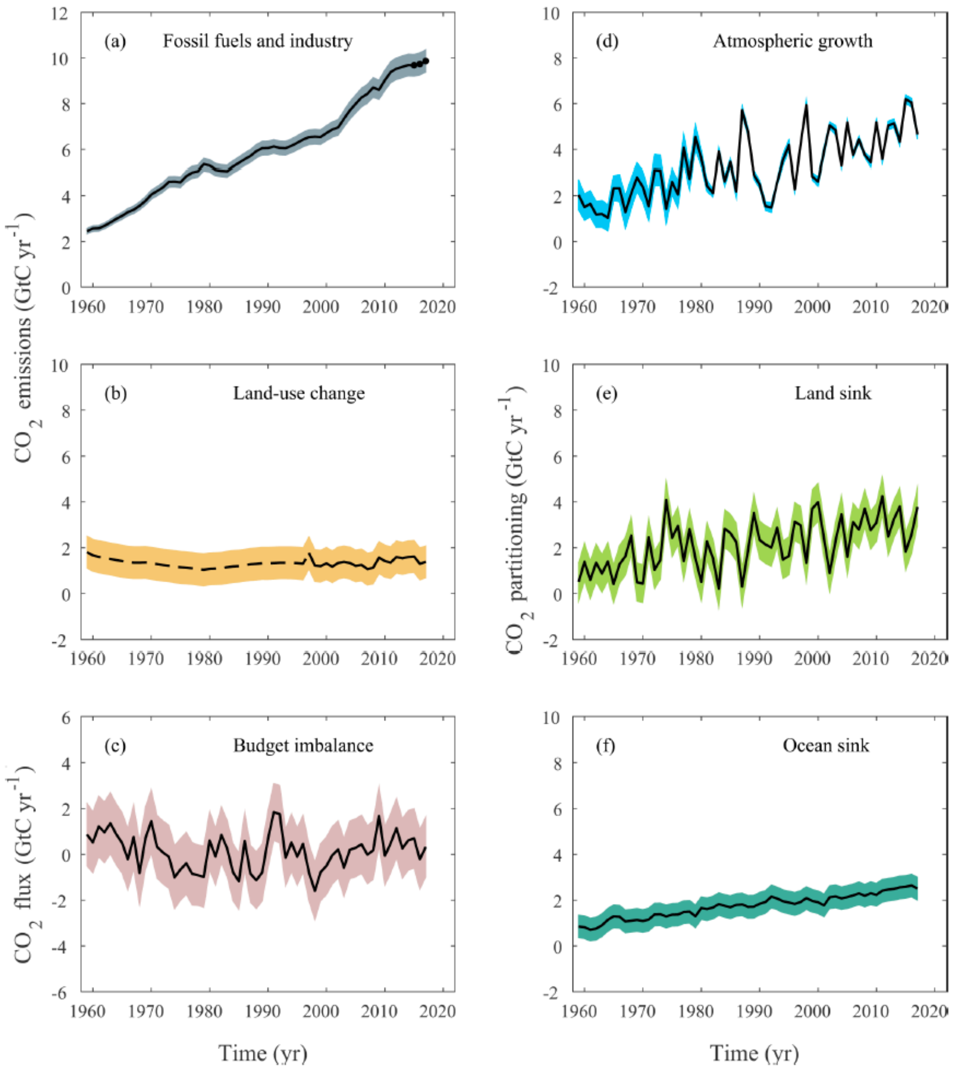
Version	End Year	Models	Drivers	Scenarios	Other notes
V1	2011	9	CRU-NCEPv4 HYDEv3.1 / LUHv1	3; fixed/varying LU-2005	No LULCC >2005 Only 4 LUC models
V2	2012	9		3; LU-1860	HYDEv3.1 trend
V3	2013	10		2;	
V4	2014	10	HYDEv3.2 / LUHv1	2;	
V5	2015	14	LUHv2ext	4; equil. run	Gross transitions Wood harvest
V6	2016	15		4;	Residual sink Budget imbalance
V7	2017	16	CRU-JRA	5; LASC	
V8	2018	14		8; LASC, N-dep.	

TRENDY a brief history (2011 to 2018)

GCP 1959-2011 (Le Quere et al. 2013)



GCP 2018 (Le Quere et al. 2018)



TRENDY v1: Global Carbon Budget 1959-2011

Model name	Reference
Dynamic Global Vegetation Models providing E_{LUC}	
VISIT	Kato et al. (2013) Climate forcing is changed to use CRU TS3.10.01 up to the year 2009
ISAM-HYDE	Jain et al. (2013)
LPJmL	Poulter et al. (2010)
LPJ-Bern	Stocker et al. (2011); Strassmann et al. (2008)
Dynamic Global Vegetation Models providing S_{LAND}	
Community Land Model 4CN	Lawrence et al. (2011)
Hyland	Levy et al. (2004)
JULES	Clark et al. (2011); Cox (2001)
LPJ	Sitch et al. (2003)
LPJ-GUESS	Smith et al. (2001); Ahlström et al. (2012) and references therein
O-CN	Zaehle et al. (2011)
Orchidee	Krinner et al. (2005)
Sheffield-DGVM	Woodward and Lomas (2004)
VEGAS	Zeng et al. (2005)
Ocean Biogeochemistry Models providing S_{OCEAN}	
NEMO-PlankTOM5	Buitenhuis et al. (2010) with no nutrient restoring below the mixed layer depth
LSCE	Aumont and Bopp (2006)
CCSM-BEC	Doney et al. (2009)
MICOM-HAMOCC	Assmann et al. (2010) with updates to the physical model as described in Tjiputra et al. (2013)

Table 2. Comparison of the processes included in the E_{LUC} of the global carbon budget and the DGVMs. See Table 3 for model references.

	CO_2 budget	VISIT	ISAM-HYDE	LPJmL	LPJ-Bern
Deforestation, afforestation, forest regrowth after abandonment of agriculture	yes	yes	yes	yes	yes
Wood harvest and forest degradation	yes	no	yes	no	no
Shifting cultivation	yes	yes	no	no	no
Cropland harvest	yes	no	no	no	yes
Peat fires	from 1997	no	no	no	no
Fire suppression	for US only	no	no	no	no
Management–Climate interactions	from 1997	no	no	no	no
Climate change and variability	no	climate change is present but decadal mean response is used for regrowing uptake	climate variability present but not corresponding to observed years	yes	yes
CO_2 fertilisation	no	yes	yes	yes	yes
Nitrogen dynamics	no	no	yes	no	no

TRENDY v3 to v5

TRENDY v3

	Bookkeeping	CABLE	CLM4.5BGC	ISAM	JULES	LPJ-GUESS	LPJ	LPX	ORCHIDEE	VEGAS	VISIT
Wood harvest and forest degradation[a]	yes	yes	yes	yes	no	no	no	no	no	yes	yes[b]
Shifting cultivation	yes	no	yes	no	no	no	no	no	no[c]	no[d]	yes
Cropland harvest	yes	yes	yes	no	no	yes	no	yes	yes	yes	yes
Peat fires	no	no	yes	no	no	no	no	no	no	no	no
Fire simulation and/or suppression	for US only	no	yes	no	no	yes	yes	yes	no	yes	yes
Climate and variability	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
CO_2 fertilisation	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Carbon–nitrogen interactions, including N deposition	no	yes	yes	yes	no	no	no	yes	no	no	no

[a] Refers to the routine harvest of established managed forests rather than pools of harvested products. [b] Wood stems are harvested according to the land-use data. [c] Models only used to calculate S_{LAND}. [d] Model only used to compare $E_{LUC} + S_{LAND}$ to atmospheric inversions (Fig. 6).

TRENDY v5

	Bookkeeping	CABLE	CLASS-CTEM	CLM	DLEM	ISAM	JSBACH	JULES	LPJ-GUESS	LPJ	LPX-Bern	OCN	ORCHIDEE	SDGVM	VISIT
Processes relevant for E_{LUC}															
Wood harvest and forest degradation[a]	yes					yes		no	no	no		yes			
Shifting cultivation	yes[b]					no		no	no	no		no			
Cropland harvest	yes					yes		no	yes	no		yes			
Peat fires	no					no		no	no	no		no			
Processes also relevant for S_{LAND}															
Fire simulation and/or suppression	for US only	no	yes	yes	yes	no	yes	no	yes	yes	yes	no	no	yes	yes
Climate and variability	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
CO_2 fertilisation	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Carbon–nitrogen interactions, including N deposition	no	yes	no	yes	yes	yes	no	no	yes	no	yes	yes	no	yes[c]	no

[a] Refers to the routine harvest of established managed forests rather than pools of harvested products. [b] Not in the recent update (Houghton and Nassikas, 2016). [c] Very limited. Nitrogen uptake is simulated as a function of soil C, and Vcmax is an empirical function of canopy N. Does not consider N deposition.

TRENDY v7

Table A1. Comparison of the processes included (Y) or not (N) in the bookkeeping and dynamic global vegetation models for their estimates of E_{LUC} and S_{LAND}. See Table 4 for model references. All models include deforestation and forest regrowth after abandonment of agriculture (or from afforestation activities on agricultural land).

	Bookkeeping models		DGVMs															
	H&N2017	BLUE	CABLE-POP	CLASS-CTEM	CLM5.0	DLEM	ISAM	JSBACH	JULES	LPJ-GUESS	LPJ	LPX-Bern	OCN	ORCHIDEE-CNP	ORCHIDEE-Trunk	SDGVM	SURFEX	VISIT
Processes relevant for E_{LUC}																		
Wood harvest and forest degradation[a]	Y	Y	Y	N	Y	Y	Y	Y	N	Y	Y	N[d]	Y	N	Y	N	N	Y
Shifting cultivation/sub-grid-scale transitions	N[b]	Y	Y	N	Y	N	N	Y	N	Y	Y	N[d]	N	N	N	N	N	Y
Cropland harvest (removed, r, or added to litter, l)	Y(r)[h]	Y(r)[h]	Y(r)	Y(l)	Y(r)	Y	Y	Y(r,l)	N	Y(r)	Y(l)	Y(r)	Y(r,l)	Y(r)	Y(r)	Y(r)	N	Y(r)
Peat fires	Y	Y	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N
Fire as a management tool	Y[h]	Y[h]	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
N fertilisation	Y[h]	Y[h]	N	N	Y	Y	Y	N	N	Y	N	Y	Y	Y	N	N	N	N
Tillage	Y[h]	Y[h]	Y	Y[e]	N	N	N	N	N	Y	N	N	N	N	Y[g]	N	N	N
Irrigation	Y[h]	Y[h]	N	N	Y	Y	Y	N	N	Y	N	N	N	N	N	N	Y[g]	N
Wetland drainage	Y[h]	Y[h]	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Erosion	Y[h]	Y[h]	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y
Southeast Asia peat drainage	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Grazing and mowing harvest (removed, r, or added to litter, l)	Y(r)[h]	Y(r)[h]	Y(r)	N	N	N	Y(l)	Y(l)	N	Y(r)	Y(l)	N	Y(r,l)	N	N	N	N	N
Processes relevant also for S_{LAND}																		
Fire simulation	US only	N	N	Y	Y	Y	N	Y	N	Y	Y	Y	N	N	N	Y	Y	Y
Climate and variability	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
CO_2 fertilisation	N[f]	N[f]	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y[e]	Y	Y	Y
Carbon–nitrogen interactions, including N deposition	N[h]	N[h]	Y	N[d]	Y	Y	Y	Y	N	Y	N	Y	Y	Y	N	Y[c]	N[i]	N

[a] Refers to the routine harvest of established managed forests rather than pools of harvested products. [b] No back-and-forth transitions between vegetation types at the country level, but if forest loss based on FRA exceeded agricultural expansion based on the FAO, then this amount of area is interpreted as shifting cultivation. [c] Limited. Nitrogen uptake is simulated as a function of soil C, and photosynthesis is directly related to canopy N. Does not consider N deposition. [d] Although C–N cycle interactions are not represented, the model includes a parameterization of down-regulation of photosynthesis as CO_2 increases to emulate nutrient constraints (Arora et al., 2009). [e] Tillage is represented over croplands by increased soil carbon decomposition rate and reduced humification of litter to soil carbon. [f] Bookkeeping models include the effect of CO_2 fertilisation as captured by observed carbon densities, but not as an effect that is transient in time. [g] A 20 % reduction of active soil organic carbon (SOC) pool turnover time for C_3 crops and 40 % reduction for C_4 crops. [h] Process captured implicitly by use of observed carbon densities. [i] Simple parameterization of nitrogen limitation based on Yin (2002; assessed on FACE experiments).

TRENDY v8 (in process…)

Table 5. Comparison of the processes included in the bookkeeping method and DGVMs in their estimates of ELUC and SLAND. See Table 6 for model references. All models include deforestation and forest

	Bookkeeping	Bookkeepi	CABLE-	CLASS-CTEM	CLM	DLEM	ISAM	JSBACH	JULES	LPJ-GUESS	LPJ	LPX-Bern	OCN	ORCHIDEE	SDGVM	VISIT	ISBA-CT	ORCHIDEE-	ORCHID
Processes relevant for ELUC																			
Wood harvest and forest degradation (a)	yes	yes	yes	no	yes	yes	yes	yes	no	yes	yes	no (d)	yes	yes	no	yes	no	no	no
Shifting cultivation / Subgrid scale transitions	no (b)	yes	yes	no	yes	no	no	yes	no	yes	yes	no (d)	no	no	no	yes	no	no	no
Cropland harvest (removed, r, or added to litter, l)	yes (r) (z)	yes (r) (z)	yes (r)	yes (added to litter)	yes (r	yes	yes	yes (r+l)	no	yes (r)	yes (	yes (r)	yes (r+l)	yes	yes (r)	yes (r)	no	yes	yes (r)
Peat fires	yes	yes	no	no	yes	no	no	no	no	no	no	no	no	no	no	no	no	no	no
fire as a management tool	yes (z)	yes (z)	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
N fertilization	yes (z)	yes (z)	no	no	yes	yes	yes	no	no	yes	no	yes	yes	no	no	no	no	no	yes
tillage	yes (z)	yes (z)	yes	yes (g)	no	no	no	no	no	yes	no	no	no	yes	no	no	no	yes (20% re	no
irrigation	yes (z)	yes (z)	no	no	yes	yes	yes	no	no	yes	no	no	no	no	no	no	yes (h)	no	no
wetland drainage	yes (z)	yes (z)	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
erosion	yes (z)	yes (z)	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	no	no
South East Asia peat drainage	yes	yes	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
Grazing and mowing Harvest (removed, r, or added to litte	yes (r) (z)	yes (r) (z)	yes (r)	no	no	no	yes (l)	yes (l)	no	yes (r)	yes (	no	yes (r+l)	no	no	no	no	no	no
Processes also relevant for SLAND																			
Fire simulation and/or suppression	for US only	no	no	yes	yes	yes	no	yes	no	yes	yes	yes	no	no	yes	yes	yes	yes - not sup	no
Climate and variability	no	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
CO2 fertilisation	no (i)	no (i)	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes - with dc	yes
Carbon-nitrogen interactions, including N deposition	no (z)	no (z)	yes	no (f)	yes	yes	yes	yes	no	yes	no	yes	yes	no	yes (c)	no	yes (e)	no	yes

(z) Process captured implicitly by use of observed carbon densities.

(a) Refers to the routine harvest of established managed forests rather than pools of harvested products.

(b) No back- and forth-transitions between vegetation types at the country-level, but if forest loss based on FRA exceeded agricultural expansion based on FAO, then this amount of area was cleared for cropland and the same amount of area of old croplanc

(c) Limited. Nitrogen uptake is simulated as a function of soil C, and Vcmax is an empirical function of canopy N. Does not consider N deposition.

(d) Available but not active.

(e) Simple parameterization of nitrogen limitation based on Yin 2002 (assessed on FACE experiments)

(f) Although C-N cycle interactions are not represented, the model includes a parameterization of down-reguation of photosynthesis as CO2 increases to emulate nutrient constraints (Arora et al., 2009, https://doi.org/10.1175/2009JCLI3037.1)

(g) Tillage is represented over croplands by increased soil carbon decomposition rate and reduced humification of litter to soil carbon.

TRENDY v7

	Mean ($GtC\,yr^{-1}$) $\pm 1\sigma$						
	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009	2008–2017	2017
Land-use change emissions (E_{LUC})							
Bookkeeping methods	1.5 ± 0.7	1.2 ± 0.7	1.2 ± 0.7	1.4 ± 0.7	1.3 ± 0.7	1.5 ± 0.7	1.4 ± 0.7
DGVMs	1.5 ± 0.7	1.4 ± 0.7	1.5 ± 0.7	1.3 ± 0.6	1.4 ± 0.6	1.9 ± 0.6	2.0 ± 0.7

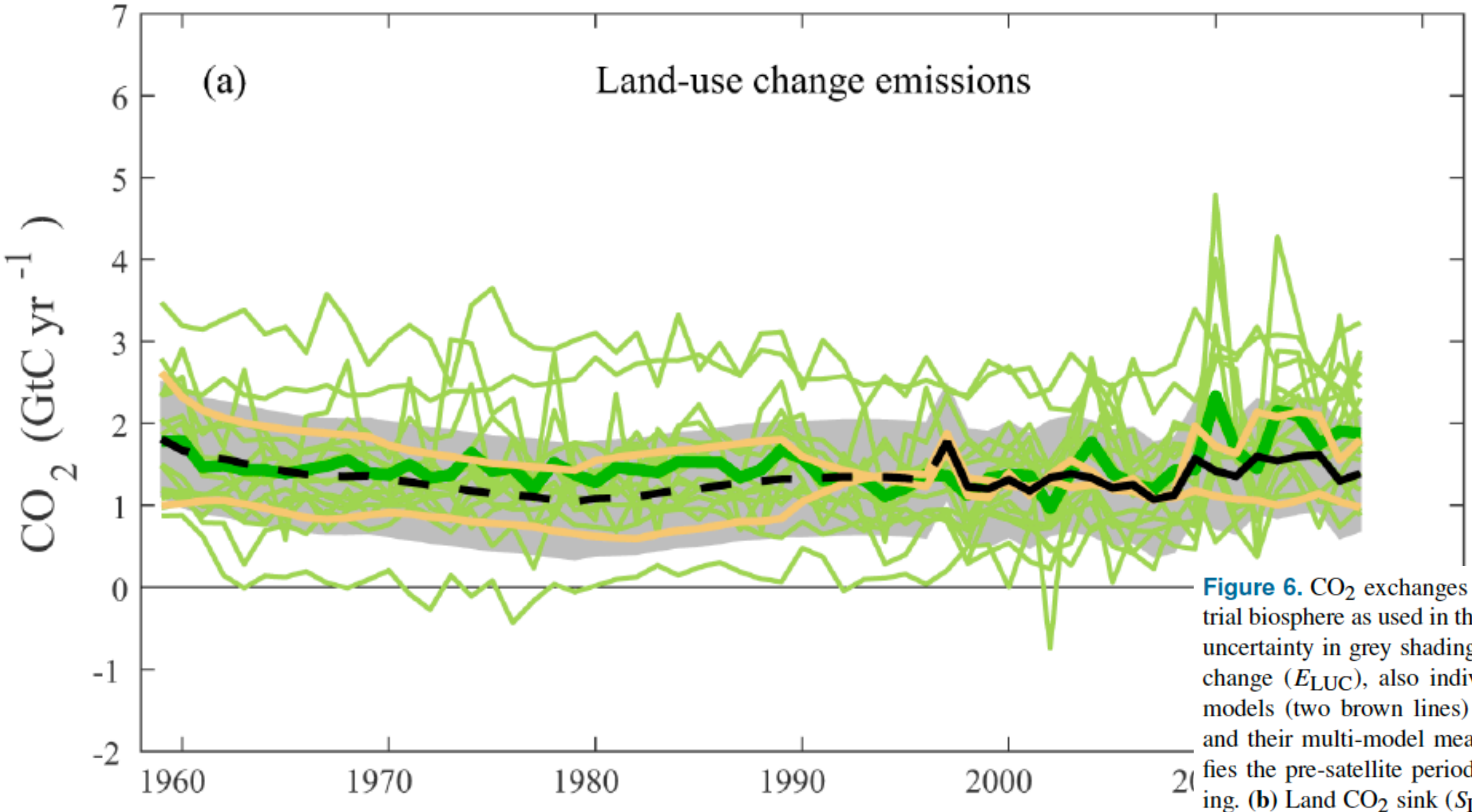
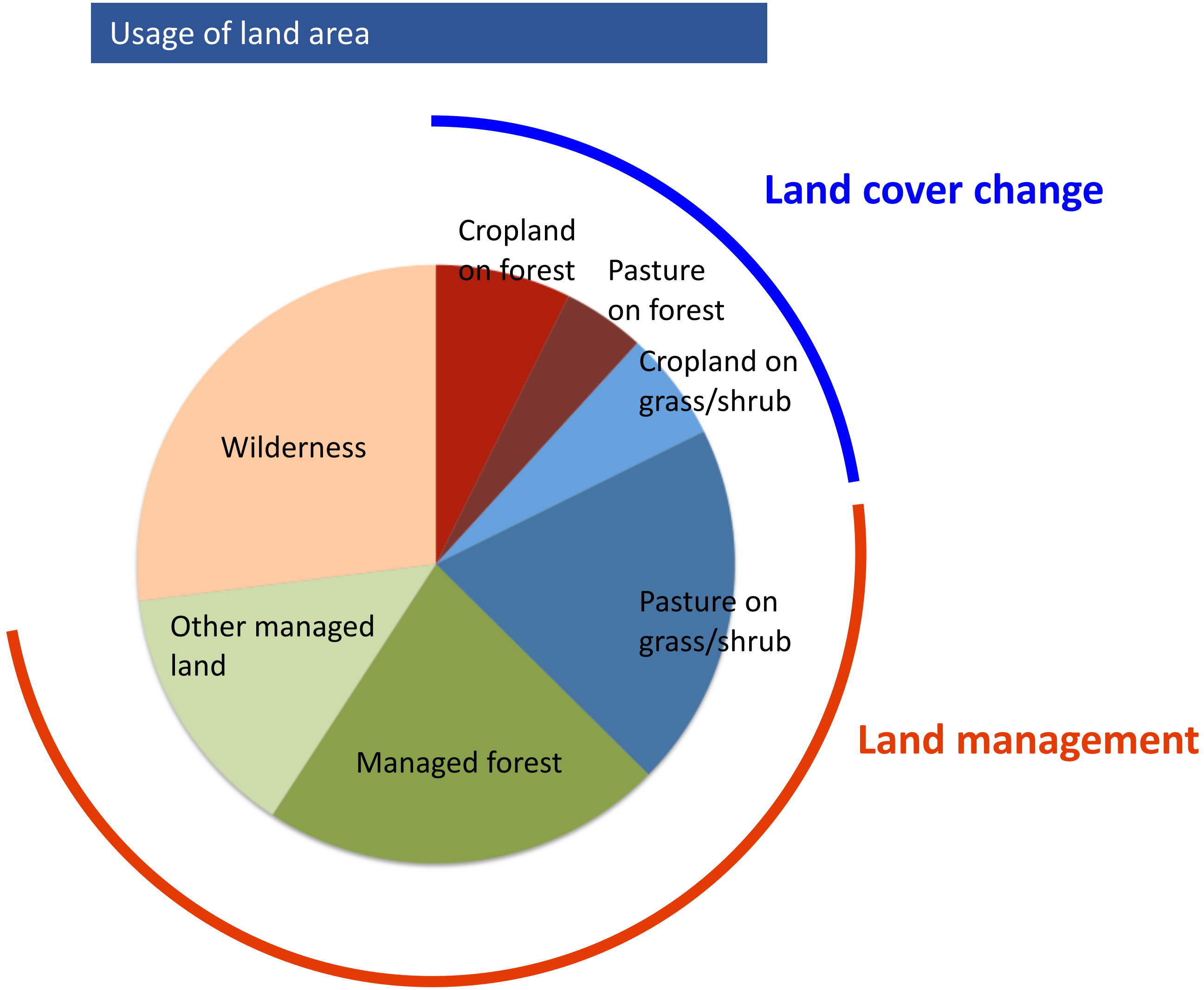


Figure 6. CO_2 exchanges between the atmosphere and the terrestrial biosphere as used in the global carbon budget (black with $\pm 1\sigma$ uncertainty in grey shading), for **(a)** CO_2 emissions from land-use change (E_{LUC}), also individually showing the two bookkeeping models (two brown lines) and the DGVM model results (green) and their multi-model mean (dark green). The dashed line identifies the pre-satellite period before the inclusion of peatland burning. **(b)** Land CO_2 sink (S_{LAND}) with individual DGVMs (green); **(c)** total land CO_2 fluxes **(b–a)** with individual DGVMs (green) and their multi-model mean (dark green).

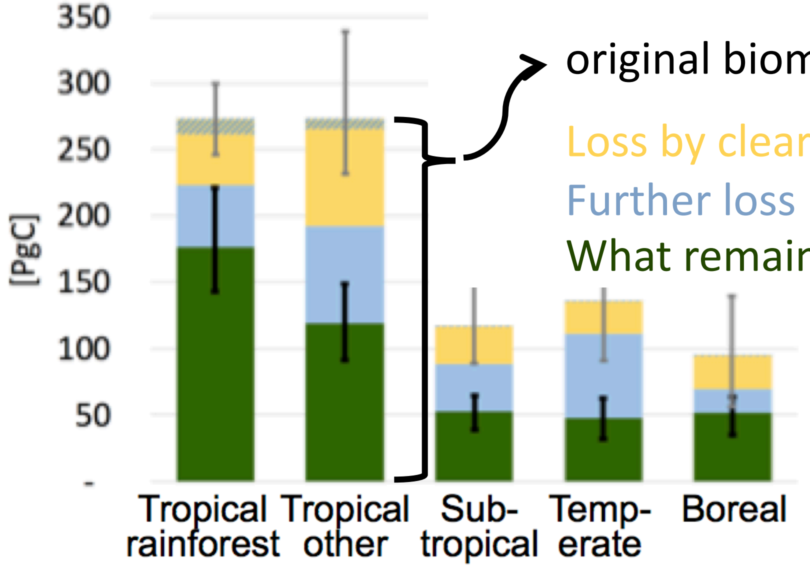
Role of land management

¾ of the Earth's land surface is under management



numbers from Luyssaert. Pongratz et al, *Nature Climate Change,* 2014

Half of the vegetation biomass has been removed by humans
Half of that by land management



original biomass

Loss by clearing of natural vegetation

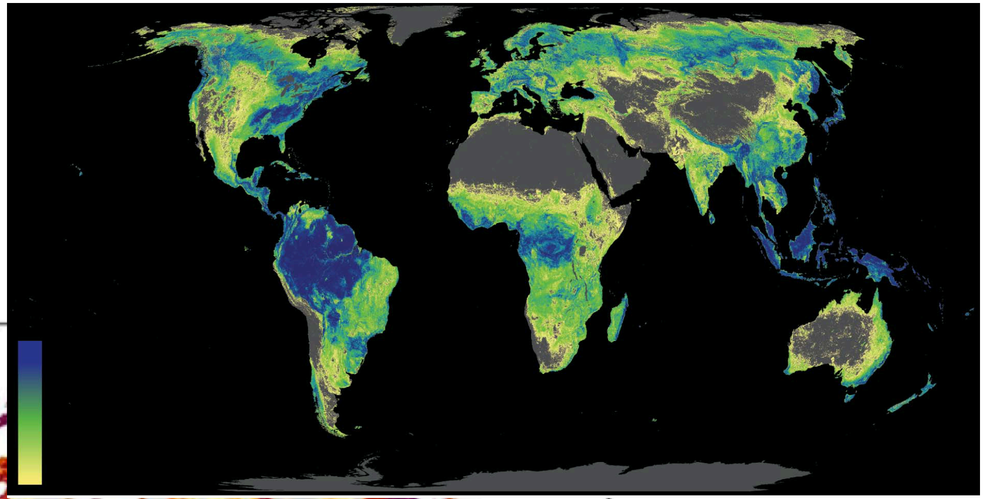
Further loss by management

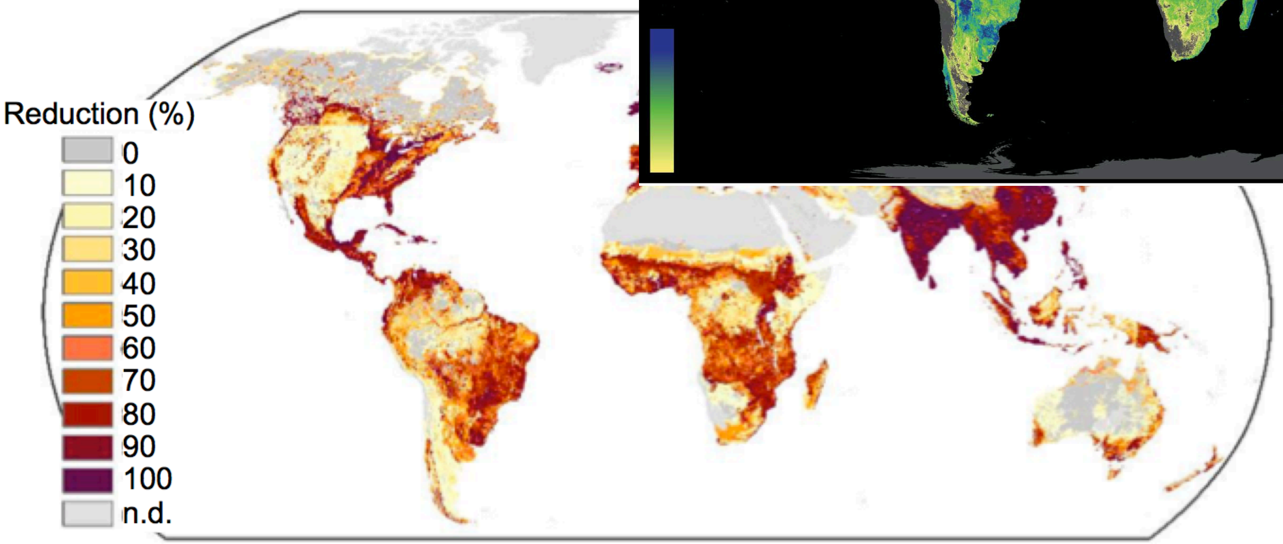
What remains

RESTORATION ECOLOGY

The global tree restoration potential

Jean-Francois Bastin[1]*, Yelena Finegold[2], Claude Garcia[3,4], Danilo Mollicone[2], Marcelo Rezende[2], Devin Routh[1], Constantin M. Zohner[1], Thomas W. Crowther[1]





Remote sensing
+
inventories

Erb et al, *Nature,* 2017; Pongratz et al, *Global Change Biol., 2017*

Consequences of missing LULCC processes

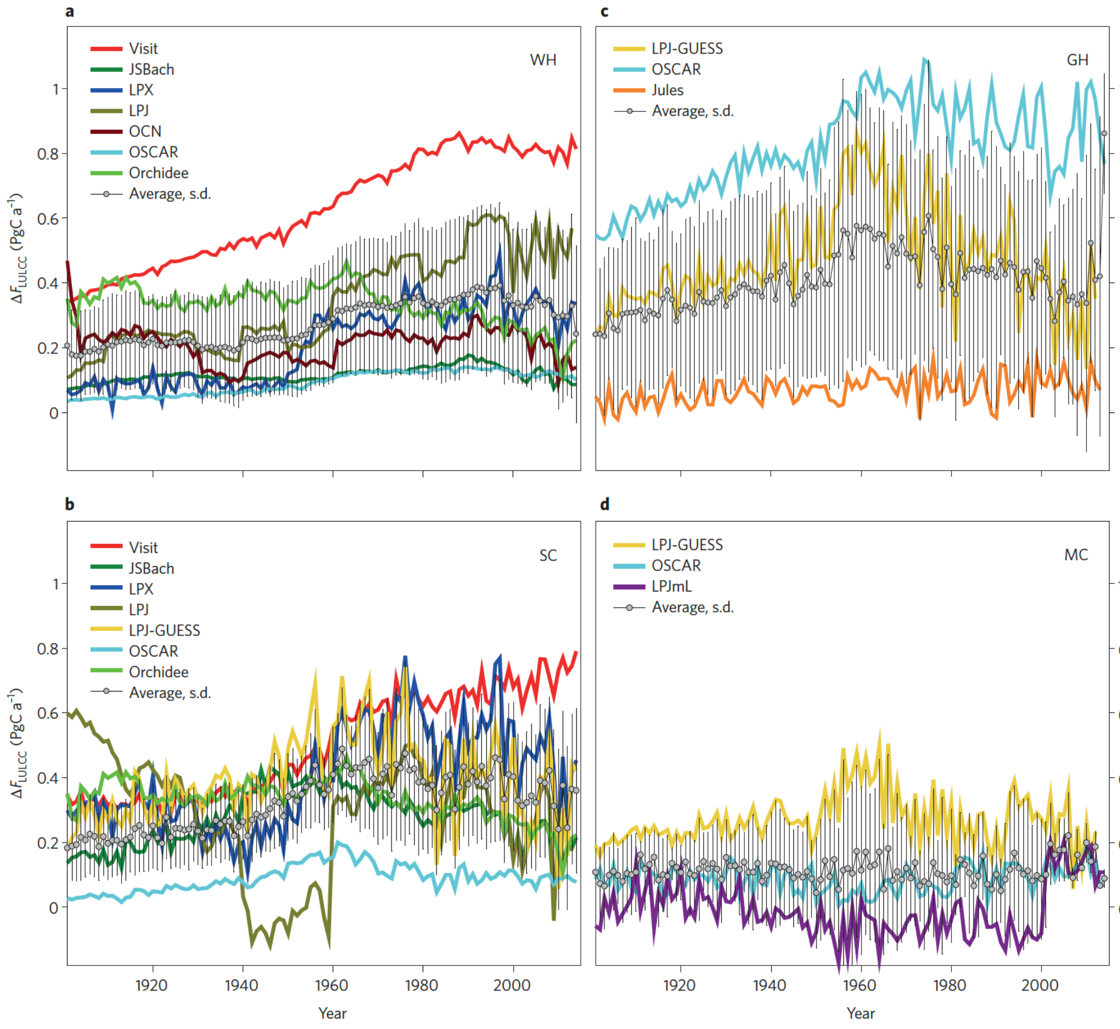
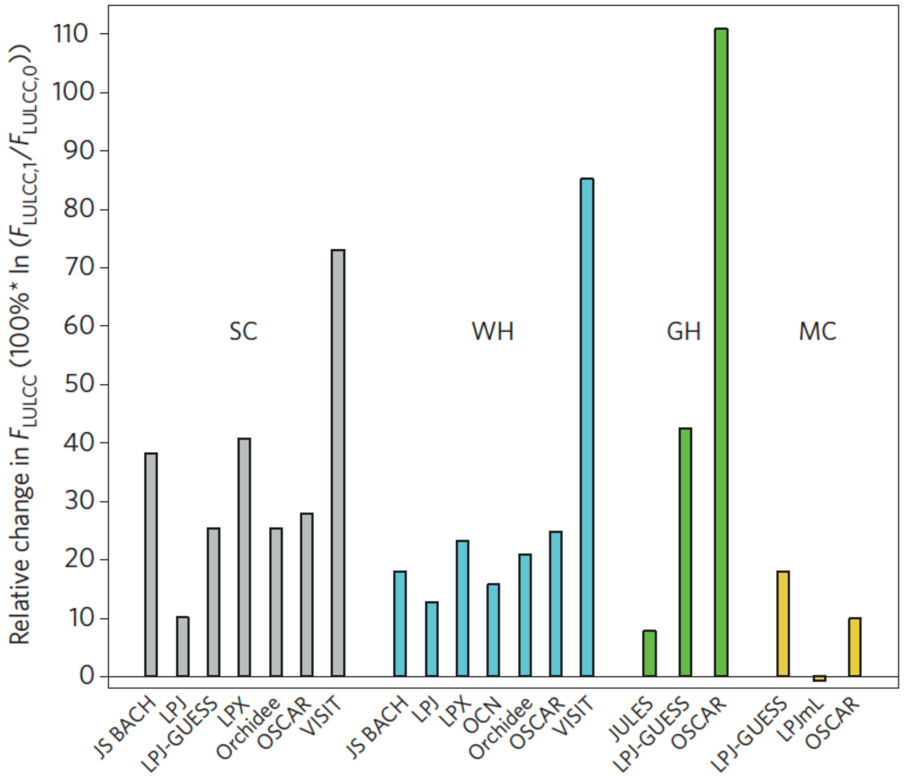


Figure 1 | Difference in LULCC emission flux (ΔF_{LULCC}) due to individual processes. a, Wood harvesting. **b**, Shifting cultivation. **c**, Grazing and crop harvesting (using the grass functional type). **d**, Full crop representation. Coloured lines represent different models, grey symbols and hairlines are average ±1 standard deviation.



Historical carbon dioxide emissions caused by land-use changes are possibly larger than assumed

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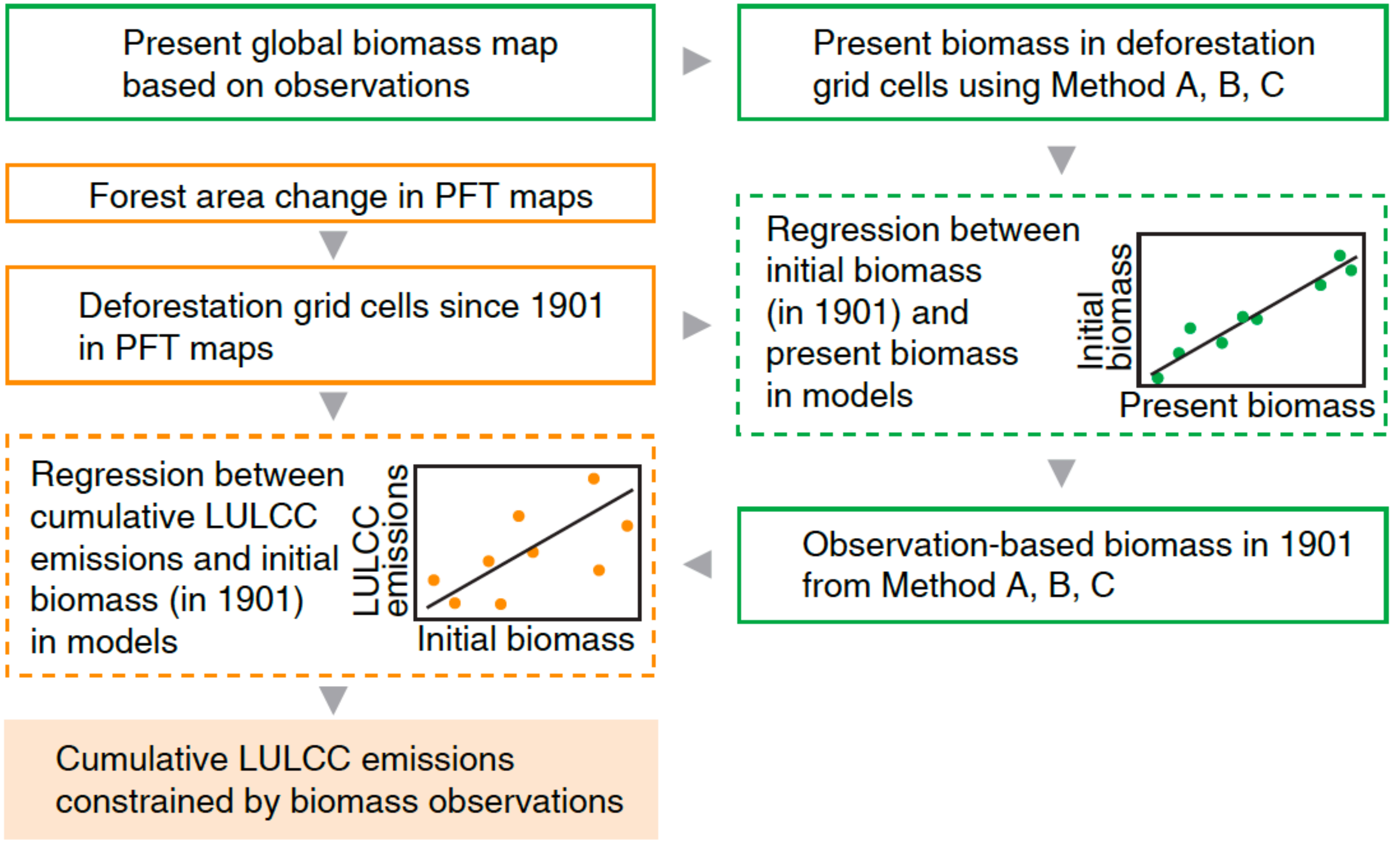
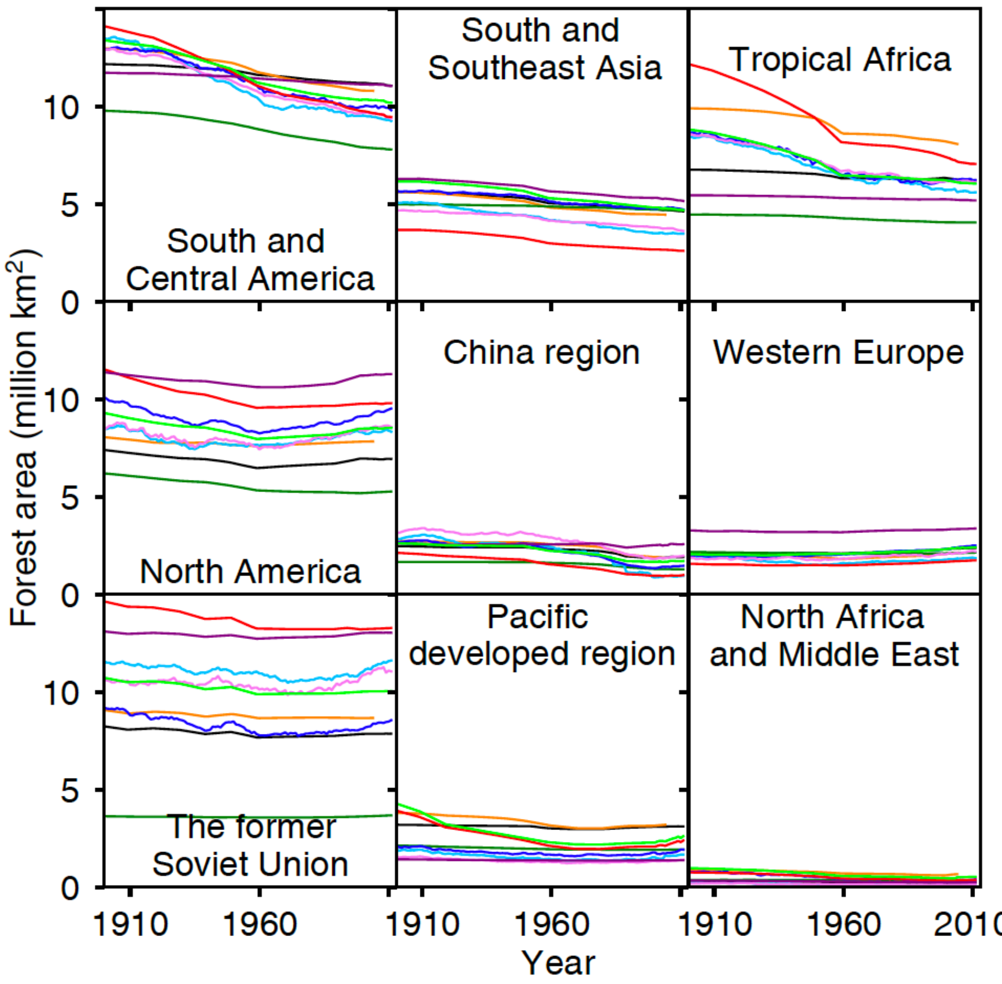
Benchmarking of TRENDY models

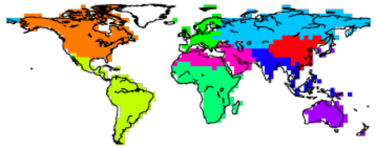
Land-use and land-cover change carbon emissions between 1901 and 2012 constrained by biomass observations

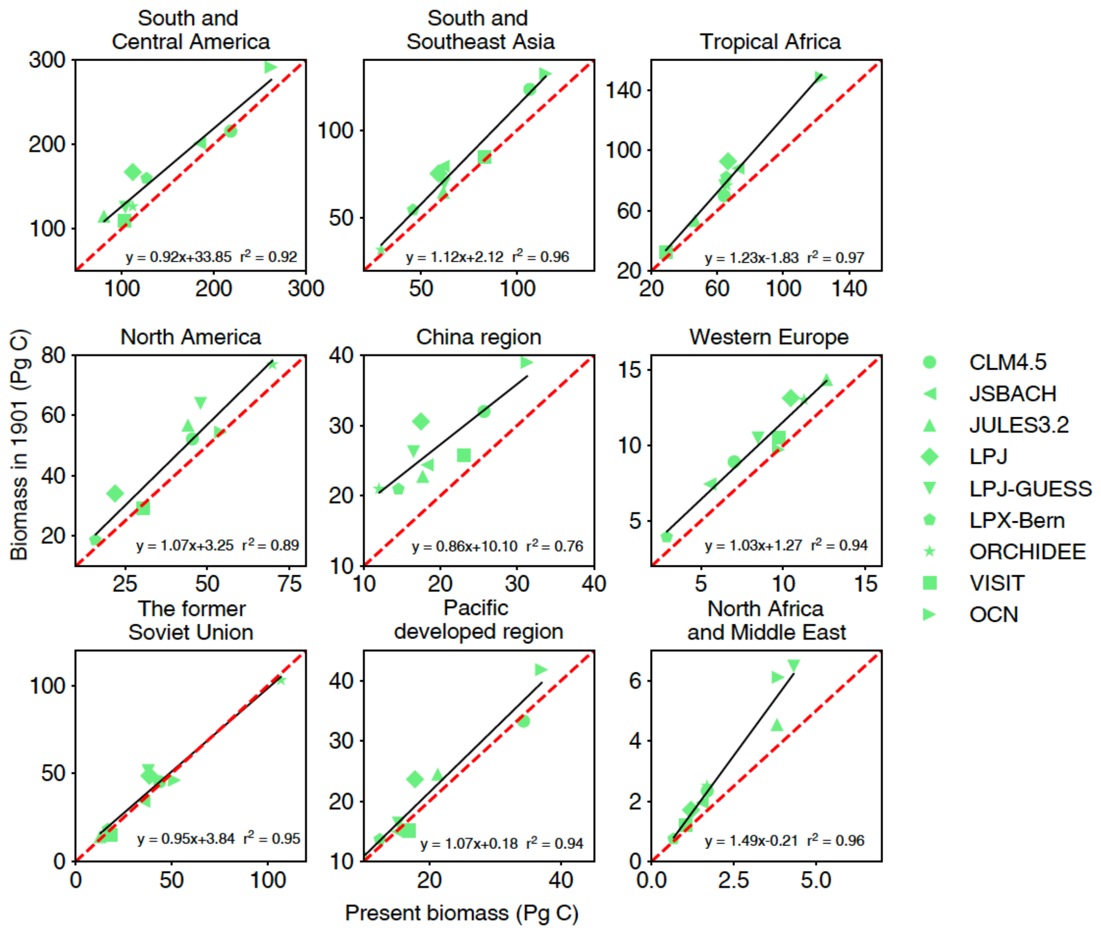
Wei Li[1], Philippe Ciais[1], Shushi Peng[1,2], Ch
Almut Arneth[5], Valerio Avitabile[6], Nuno Ca
Y. Liu[12], Julia E.M.S. Nabel[13], Yude Pan[14],
Maurizio Santoro[17], Stephen Sitch[18], Benja
Rasoul Yousefpour[13,a], and Sönke Zaehle[7]



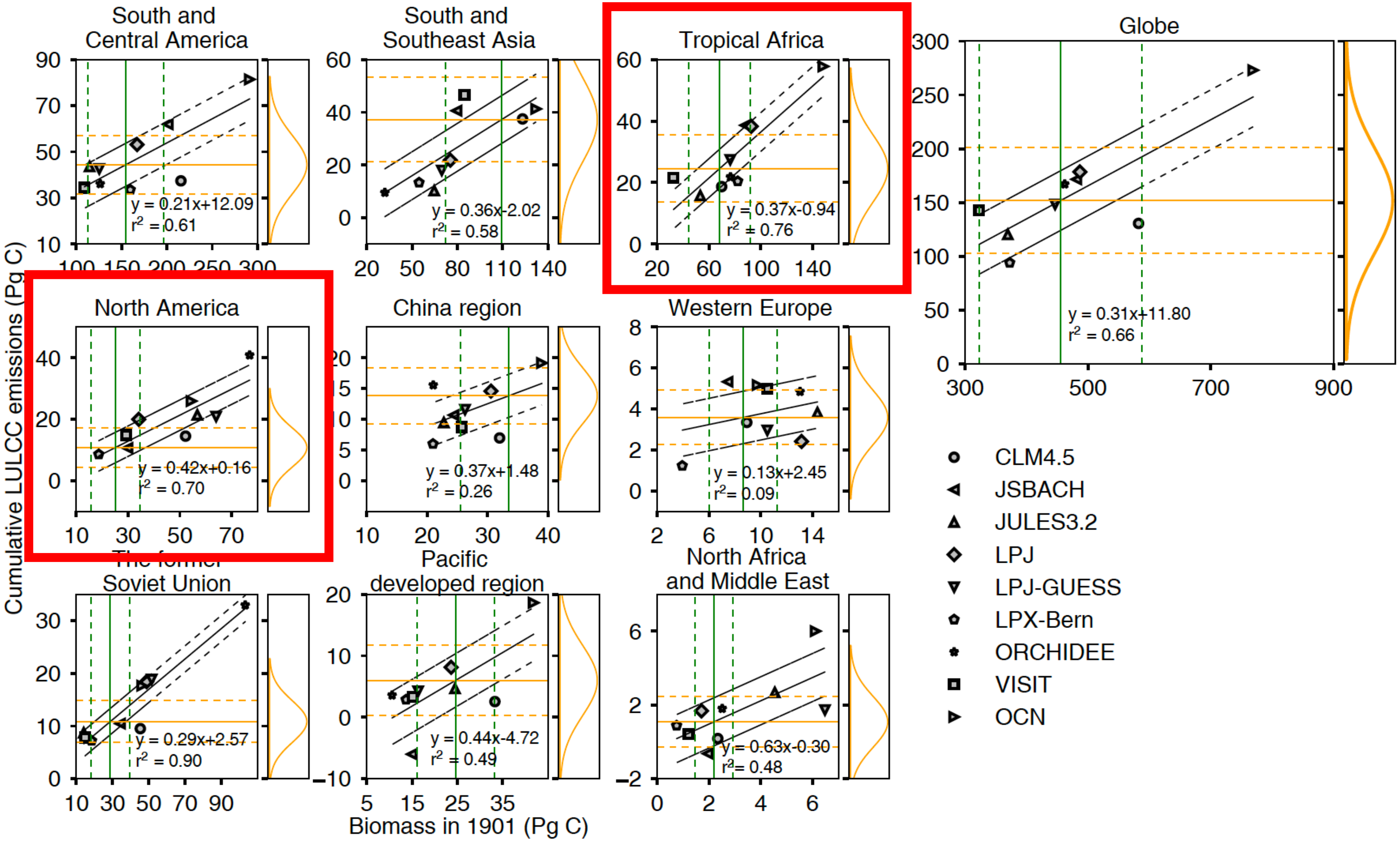
Benchmarking of TRENDY models



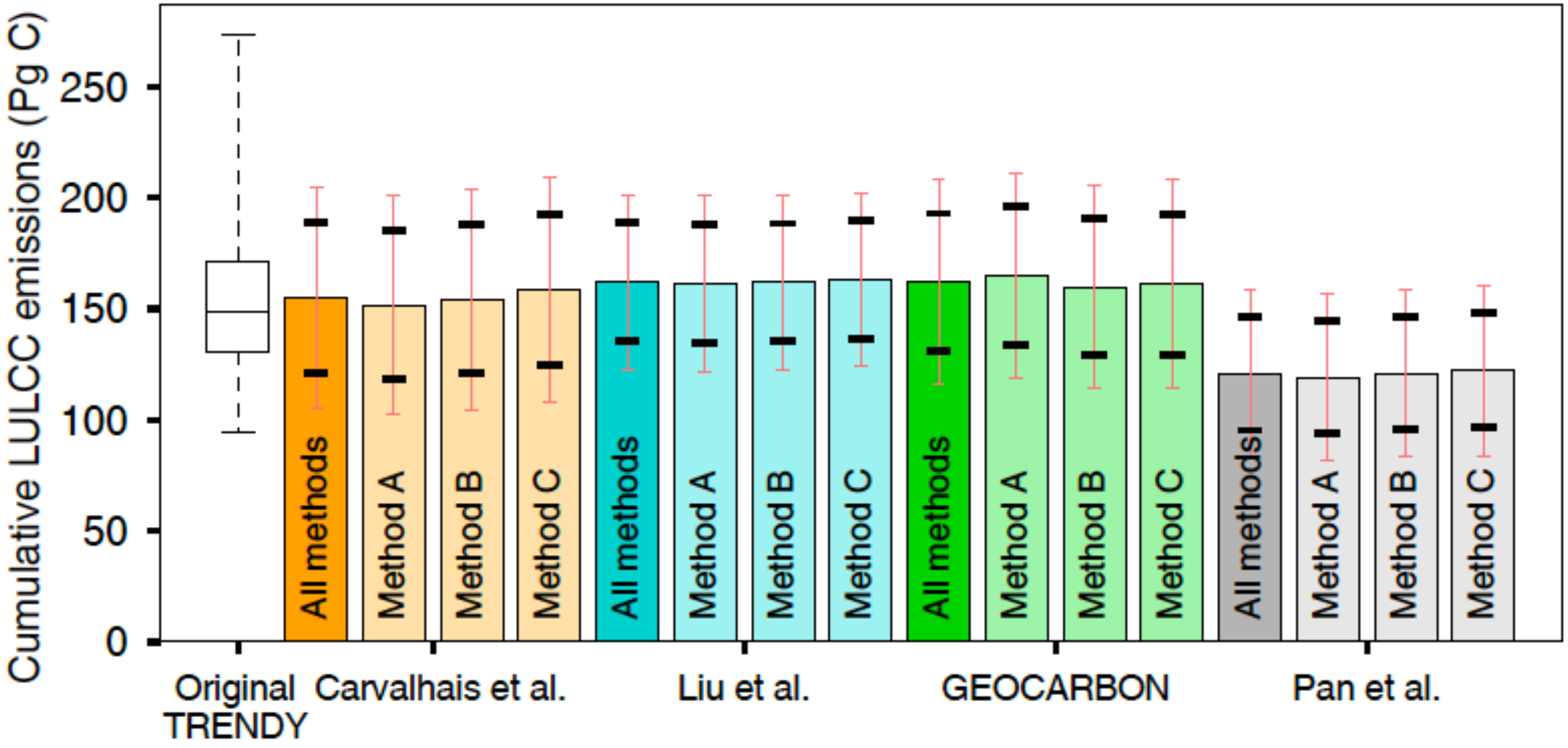




Benchmarking of TRENDY models

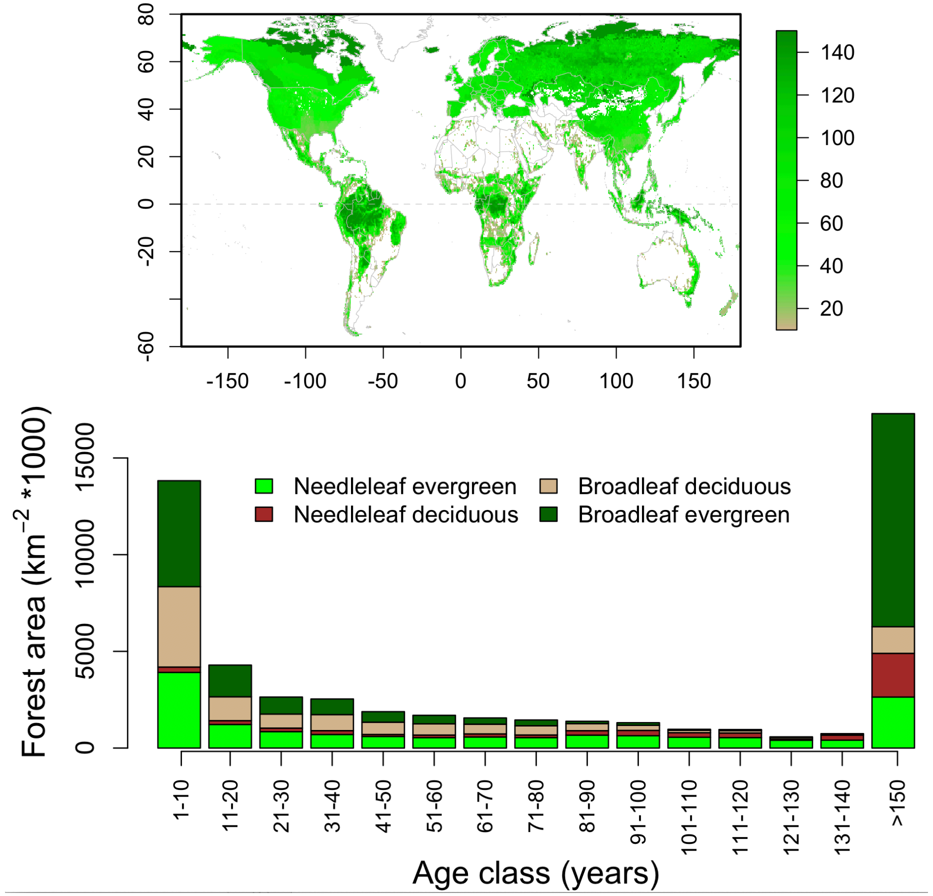


Benchmarking of TRENDY models

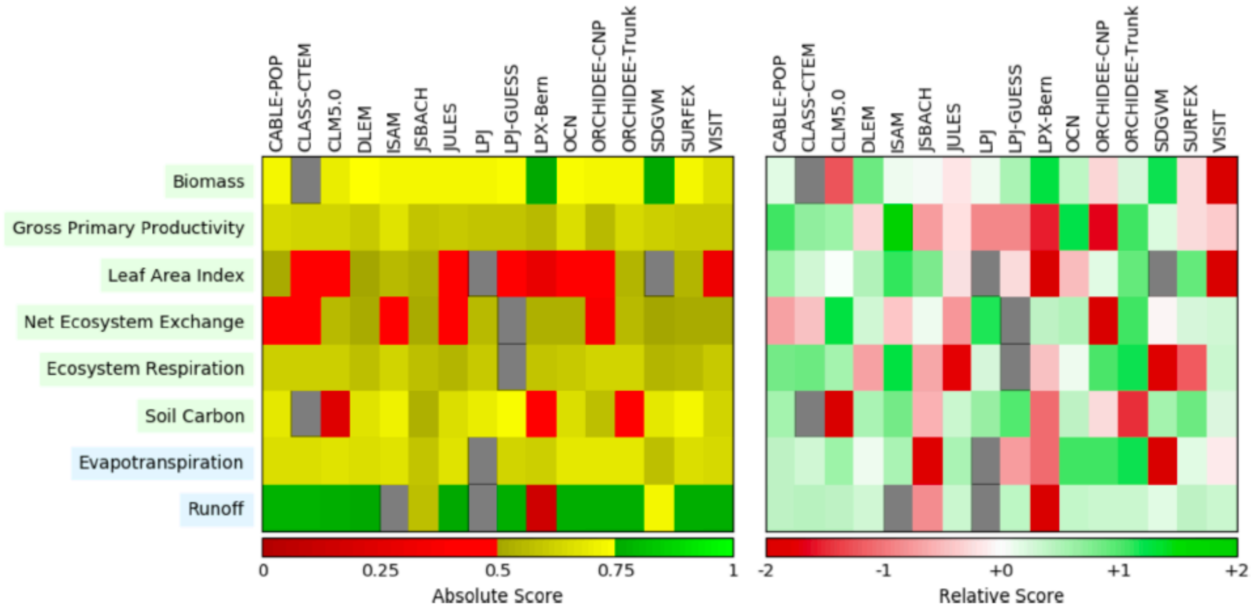


Additional benchmarks of LULCC

Global Forest Age Database (GFAD)



iLAMB



Le Quere et al. (2018)

Key points

1. Design protocol to estimate land-use & land-cover change emissions for apples-to-apples comparisons, e.g., bookkeeping (UNFCCC) vs land-surface models (IPCC)
2. The TRENDY model intercomparison has evolved to inform the annual Global Carbon Project 'carbon budget' activities since 2011
3. Definitions matter, and these drive the complexity of factorial design, e.g., loss of additional sink capacity, legacy fluxes, etc.
4. TRENDY models are not all developed to same state for covering LULCC processes
5. Evaluation of the TRENDY models considers standard benchmarking tools as well as emergent constraints