WP3: Verification methods for terrestrial CO2 sources and sinks and carbon stocks

Responsibles:

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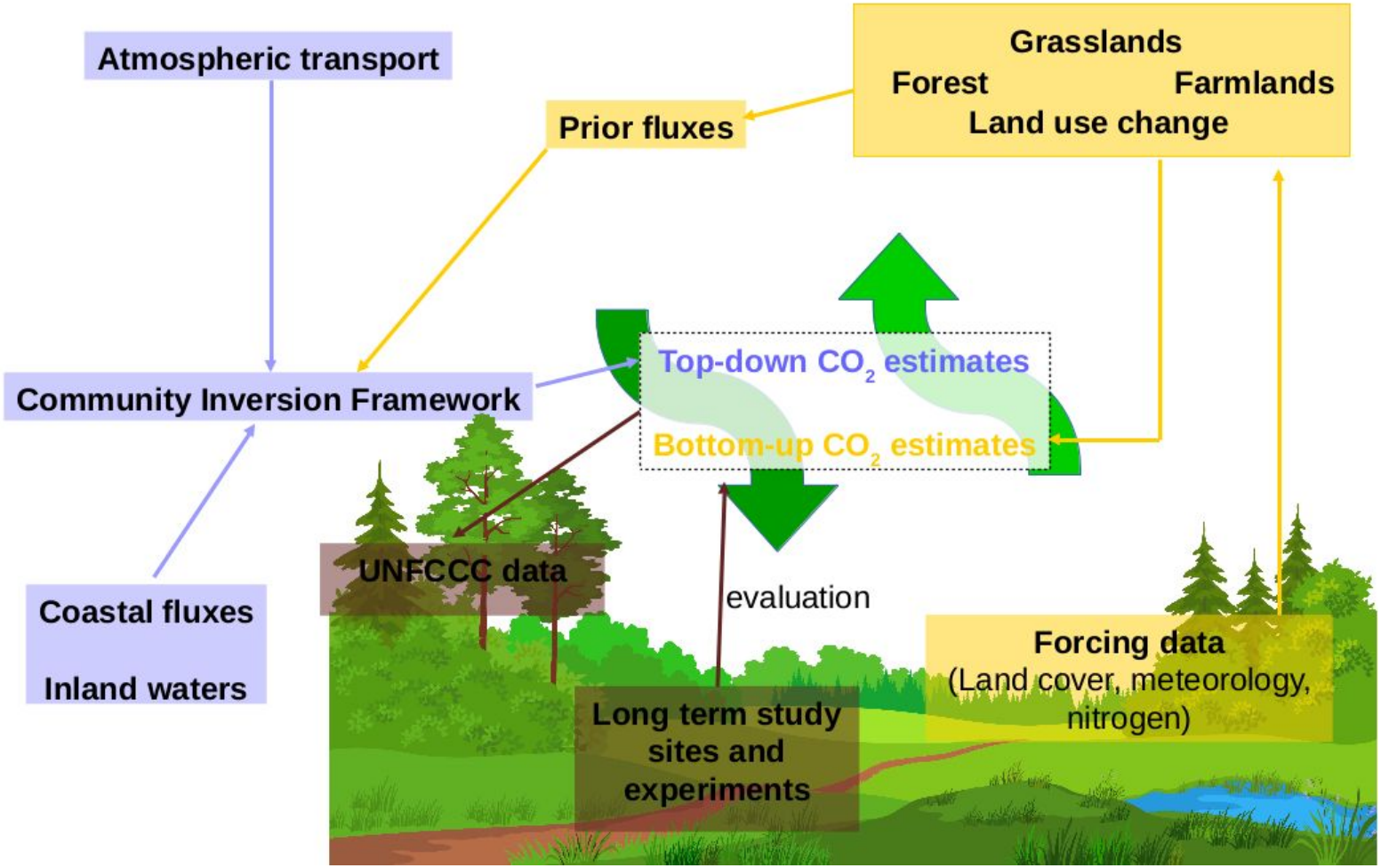
Teleconference

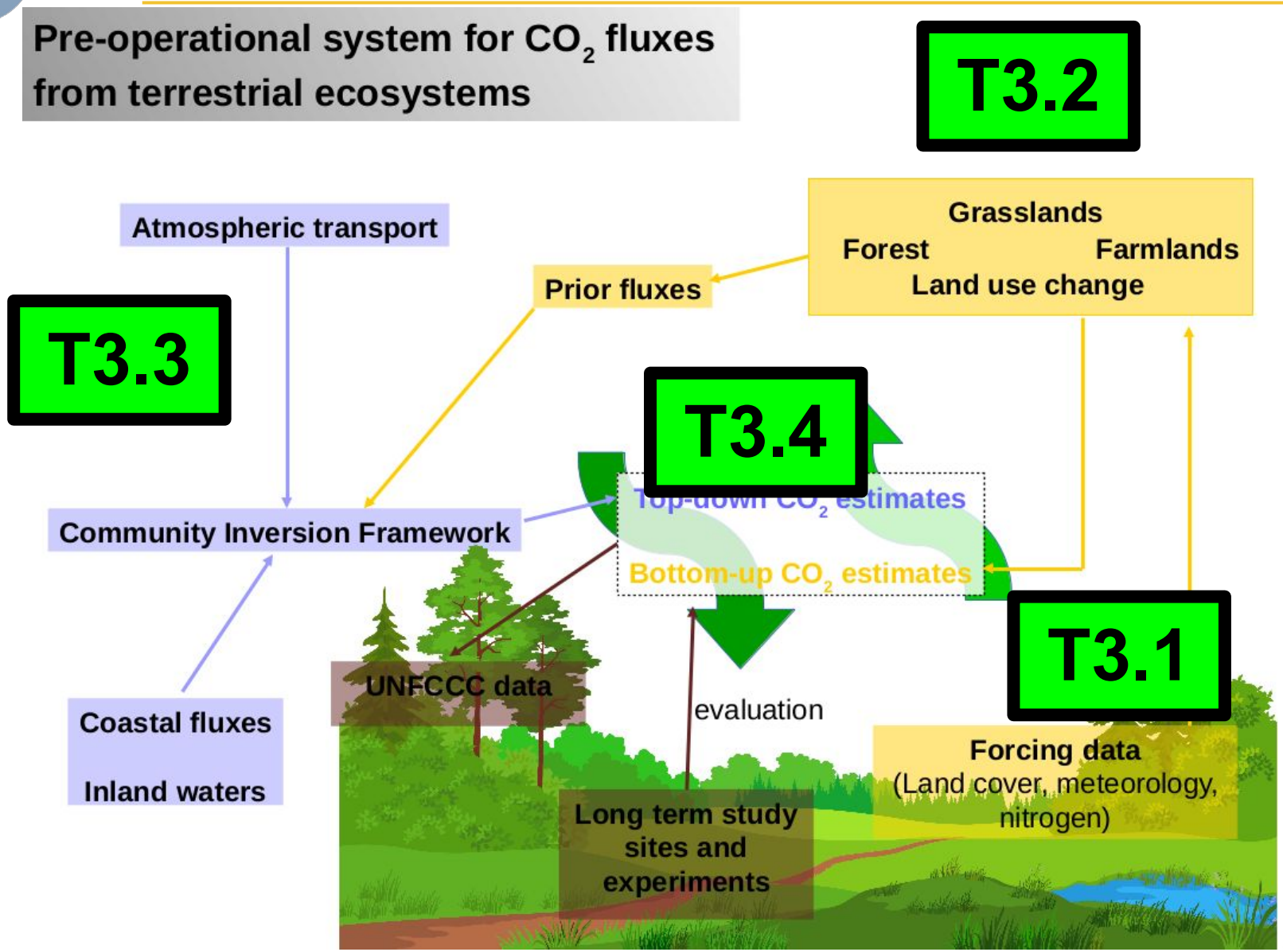
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 776810

WP3 “Pre-operational system”

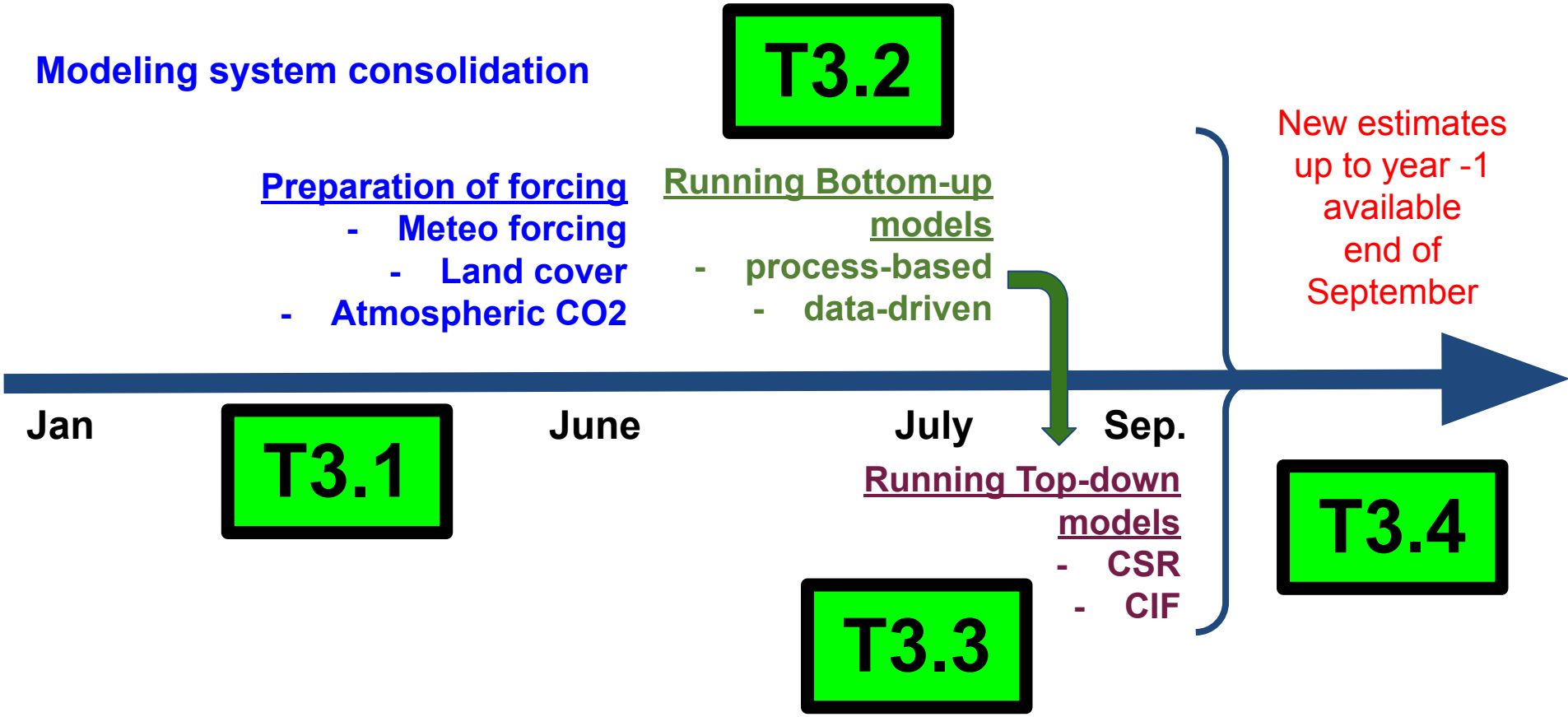
Pre-operational system for CO_2 fluxes from terrestrial ecosystems



WP3 "View from within"



Toward operationalisation



⇒ **New test this summer 2021**

WP3 – Main achievement M19-M36

- **T3.1: UPDATE state-of-the-art driving datasets**
- T3.2: UPDATE the bottom-up budget of terrestrial CO2 fluxes using a few complementary models (statistical or process-based).
- T3.3: UPDATE the Europe-wide inversions of NEE using in situ data of atmospheric CO2 and a high-resolution transport model.
- T3.4: Develop new multi-data model fusion strategies to investigate CO2 budgets and trends; Specific focus on Eastern Europe.

T3.1 Collate state-of-the-art driving data

T3.1 Input data sets

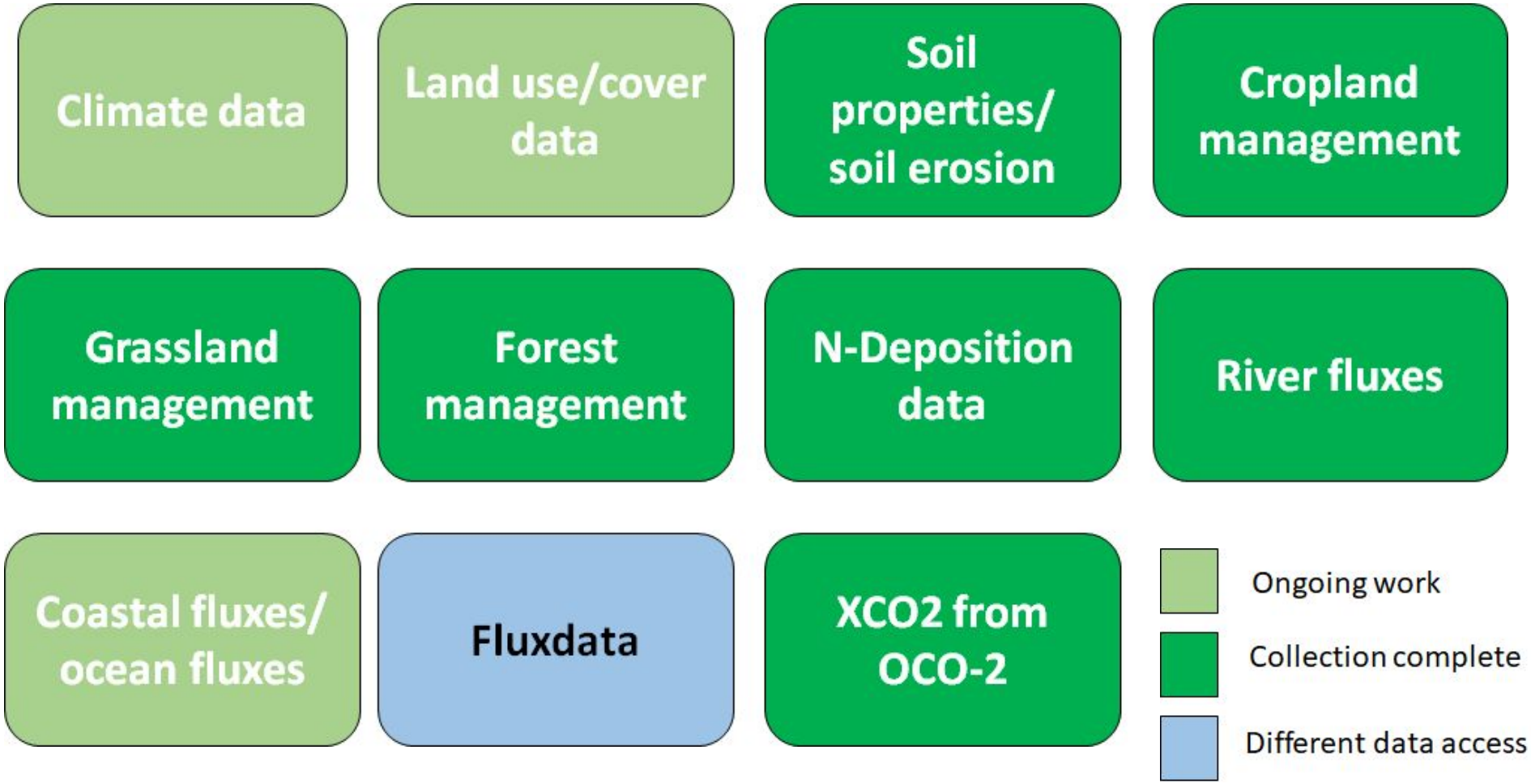
Input for models

Evaluation data

GHG budget component

Data set	Name/ model	Inst.	Coverage	Resolution	Time frame	Contact in the project
Land use	HILDA[3]	KIT	global	1 km	1900-2010	Richard Fuchs[a], Karina Winkler[b]
Biomass	HILDA[3]	WU	global	1 km	1900-2010	Martin Herold[c]
N-Deposition	EMEP model[4]	JRC		1 km	2010	Frank Dentener[d]
Erosion	PESERA[5]	ESDAC	Europe	1 km	2004	Emanuel Lugato[e]
Soil data	LUCAS[6]	ESDAC	Europe	1 km/10 km	2015	Emanuel Lugato[e]
Climate	UERRA[8]	ECMWF	Europe	11 km	1961-2017	Richard Engelen[f]
Flux data	FLUXNET network		global	sites	diverse	Dario Papale, Werner Kutsch
Fertiliser application rates	CAPRI	JRC	Europe	0.25°	2000-2012	Adrain Leip[g]
Crop management timing		UNIABDN	EU28	0.25°	2000-2015	Matthias Kuhnert[h]
Fresh water fluxes		ULB	Europe	0.1°	2016	Ronny Lauerwald[i]
Ocean coastal fluxes		UiB	Northern Europe	0.125°	1997-2016	Are Olsen[j]
Forest management		WU	Europe	0.125°	2000-2015	Mart-Jan Schelhass[k], Gert-Jan Nabuurs[l]
Grassland management		CEA-LSCE	Europe	0.5°	1860-2012	Philippe Ciais[m]
atmospheric CO2	FOCAL[10]	UBremen	global	2 km	2015-2016	Maximilian Reuter[n]

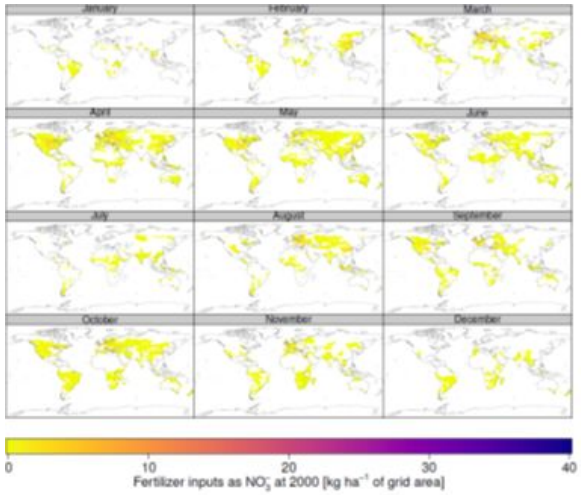
T3.1 Collate state-of-the-art driving data



T3.1 Collate state-of-the-art driving data

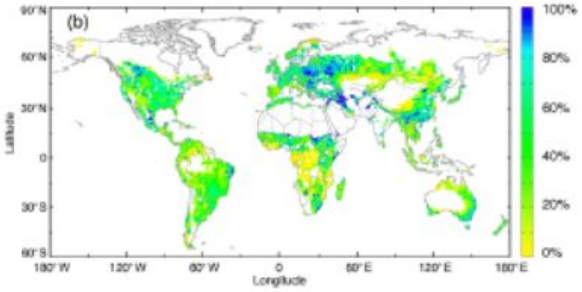
Management data for different land use were collected and provided

Cropland management management



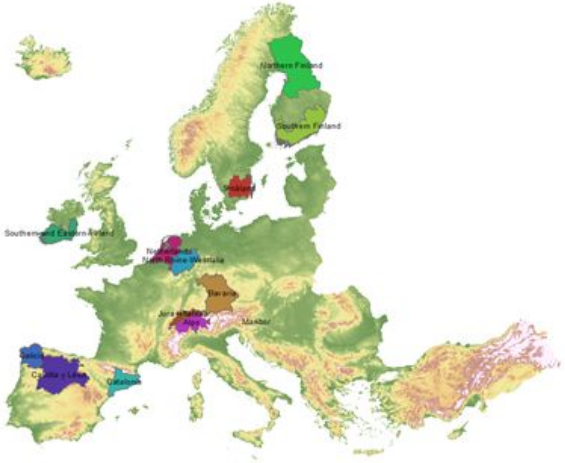
Nishina et al., 2016

Grassland management



Chang et al., 2016

Forest



Schelhaas et al., 2018

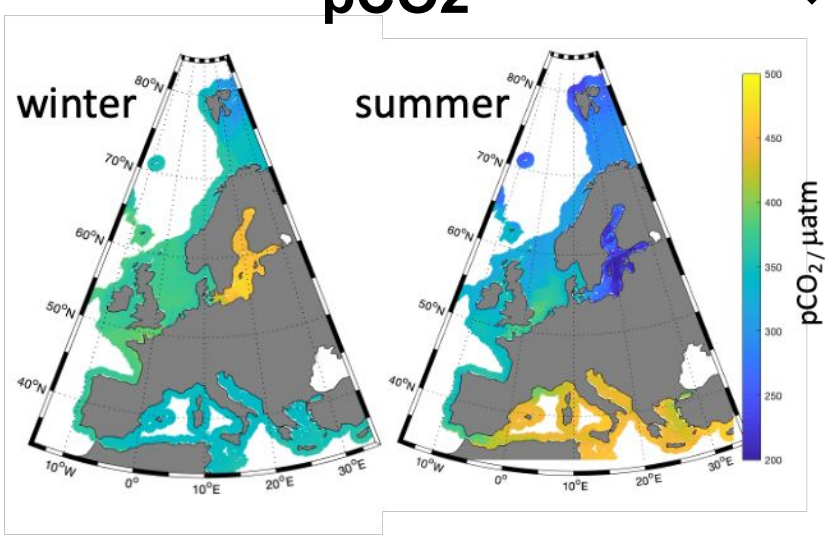
T3.1 Collate state-of-the-art driving data

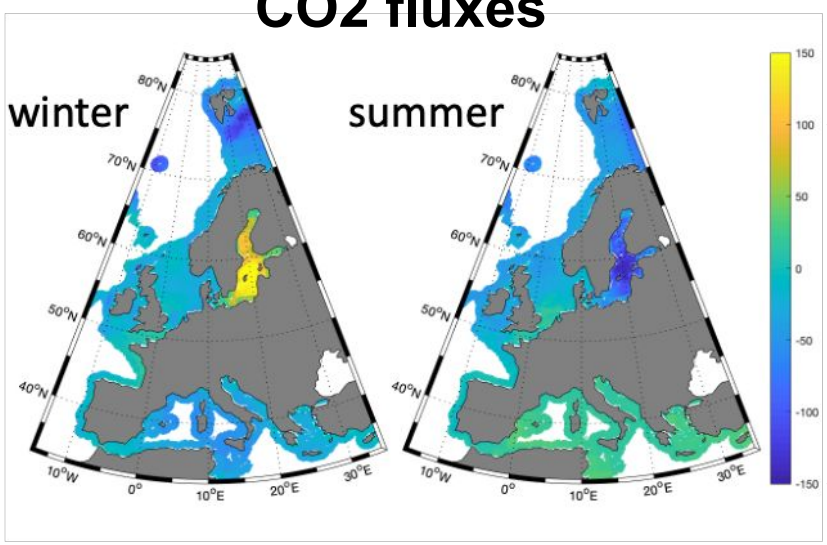
Coastal ocean fluxes

- Based on surface ocean pCO2 measurements: data driven approach to map observed pCO2 data with a set of predictors (e.g. SST, chlorophyl, Mixed layer depth)
- Differents statistical models (Random Forest (Becker et al, in prep), Multi-Linear Regression (Becker et al, 2021))
- 1998 - 2019, monthly pCO2, daily air-sea fluxes; 0.125° resolution

⇒ CO2 fluxes estimated from pCO2

pCO2 ⇒ **CO2 fluxes**





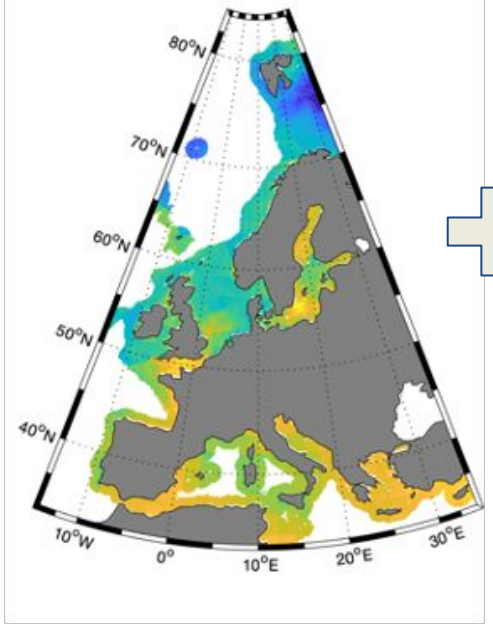
T3.1 Collate state-of-the-art driving data

Coastal ocean fluxes

- Merging the coastal ocean fluxes with open ocean fluxes
- Choosing the coastal product where it is available
- Combined product covering 2020 will be available in early August

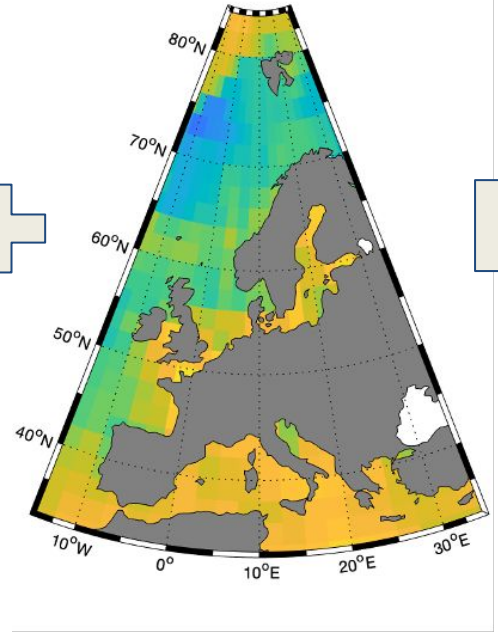
Coastal fluxes, RF

(Becker et al., in prep)

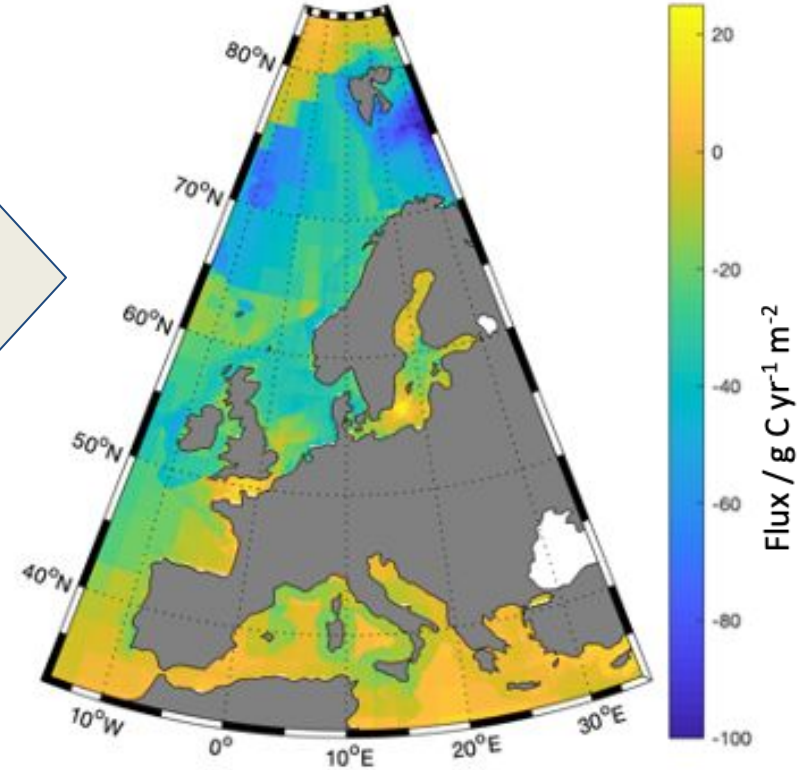


Open ocean fluxes

(Rödenbeck et al., 2014)



Combined product



Average fluxes for 2019

Lateral fluxes

Lateral C fluxes and associated CO_2 emissions from inland waters

H. Zhang, C. Gommet, G. Laruelle, R. Lauerwald, P. Ciais and P. Regnier (ULB, Belgium & IPSL-LSCE, France)

CO2 evasion from European inland waters using an empirical model (based on GLORICH observational data)

0.1° x 0.1° climatology (mean over the last 3 decades)

Key Limitations

- No temporality (seasonal & IAV)
- No linkage with terrestrial C leaching (DOC + POC + CO2)

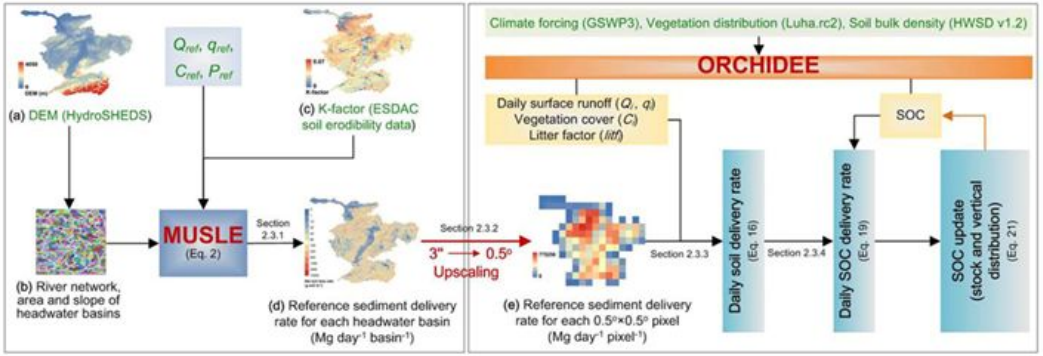
Petrescu et al., ESSD, 2021

Lateral fluxes

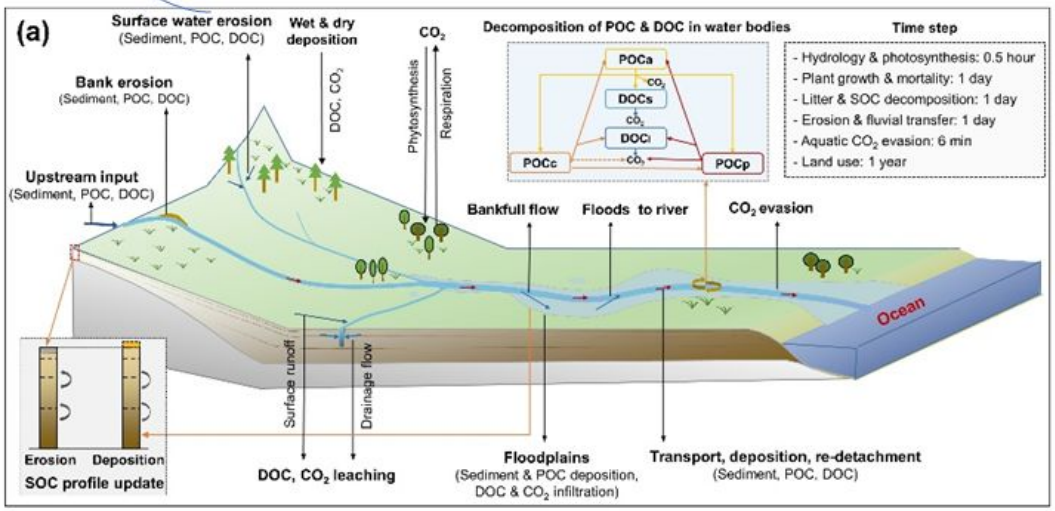
Lateral redistribution of carbon in Europe using a land surface model (ORCHIDEE-$C_{lateral}$)

- Numerically efficient erosion scheme based on MUSLE
- High spatial-resolution scheme (3')
- « Smart » upscaling strategy (0.5°)

Erosion scheme in ORCHIDEE-$C_{lateral}$



ORCHIDEE-$C_{lateral}$



Zhang et al., JAIMES, 2020

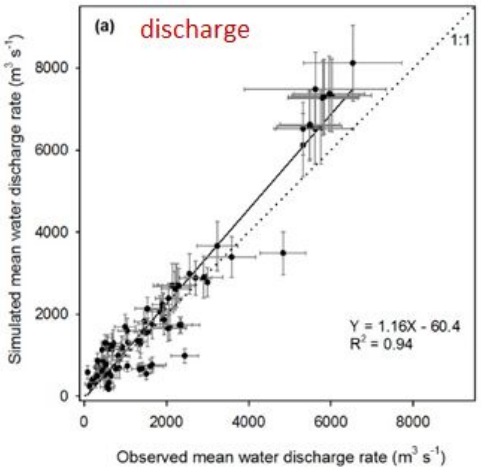
- Terrestrial fluxes
- Soil erosion
- Soil DOC, CO2 leaching
- Riverine transport
- POC sedimentation & OC decomposition
- River CO2 outgassing

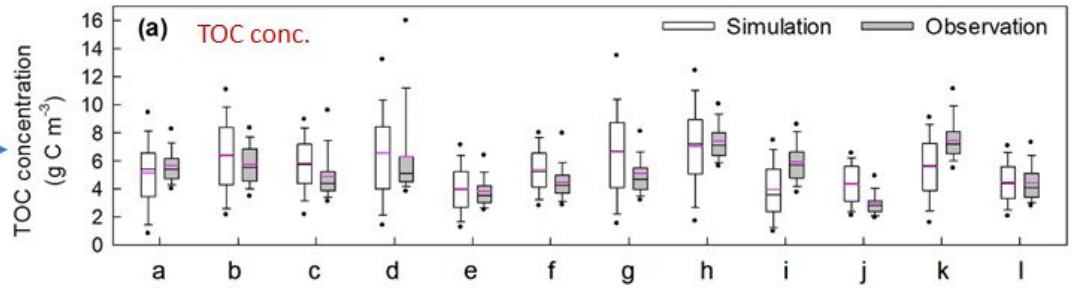
- **Impact of lateral C fluxes on soil C stocks**

Zhang et al., in prep.

Lateral fluxes

Lateral fluxes with ORCHIDEE-$C_{lateral}$

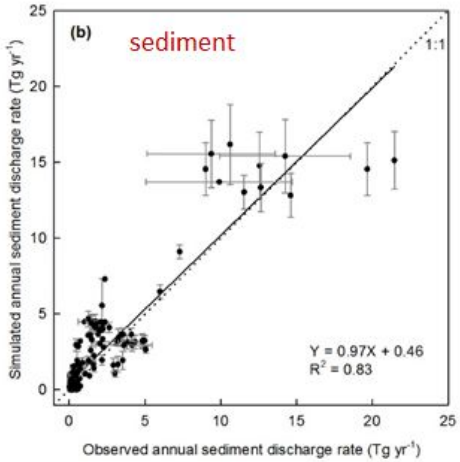


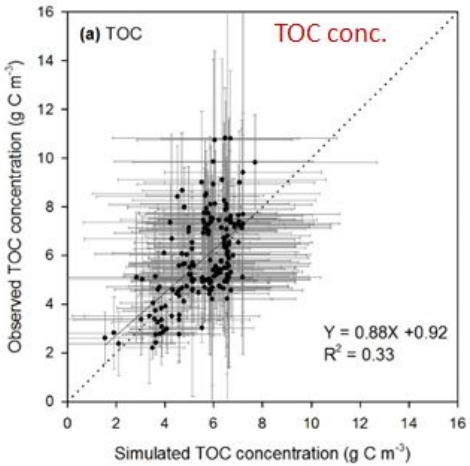


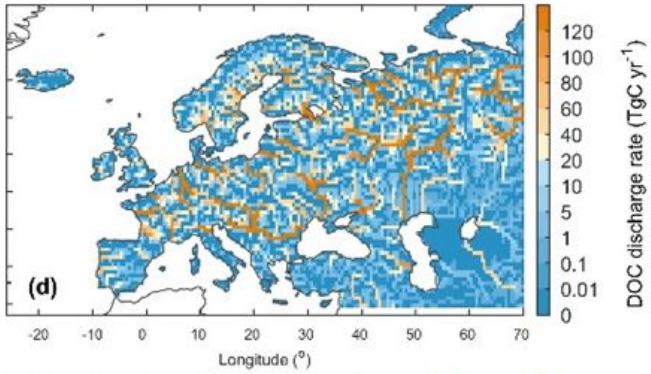
12 catchments (time)

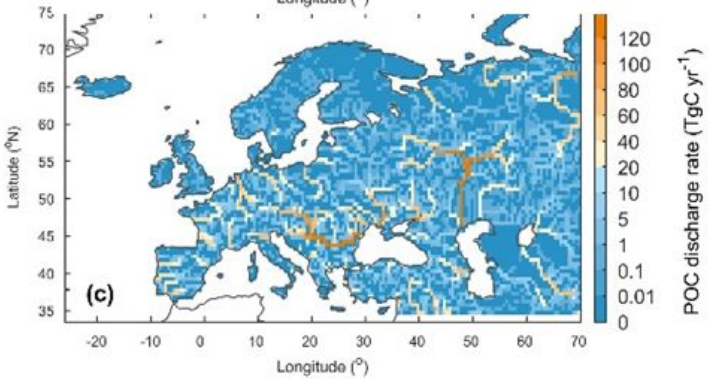
57 catchments (space)

Zhang et al., in prep.









Lateral fluxes

River CO_2 evasion with ORCHIDEE-$C_{lateral}$

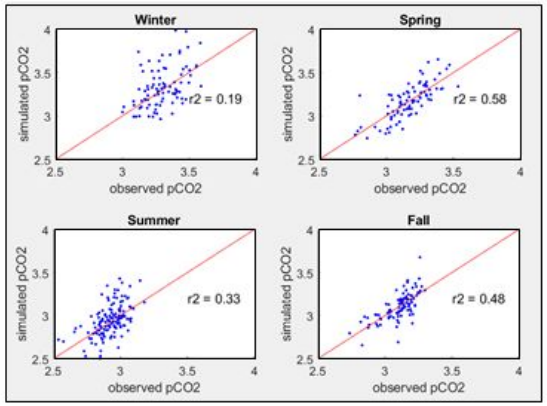
Mean flux from observed climatology

Seasonal variability and IAV from ORCHIDEE-$C_{lateral}$

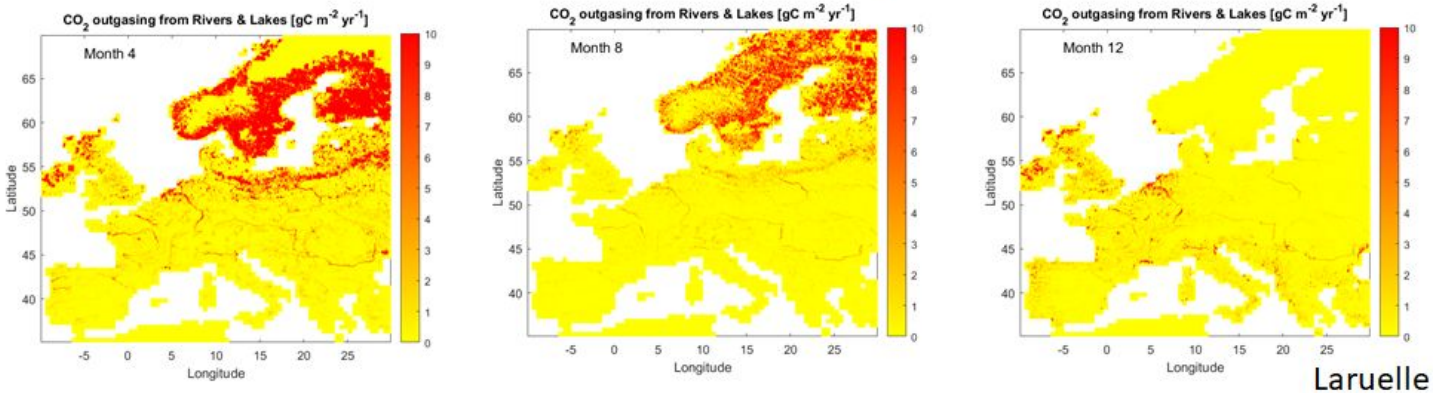
Lake CO_2 evasion from observations

Seasonal variability from upgraded empirical model

Multiple Linear Regressions to predict pCO_2 from predictors (Temperature, Surface, Altitude, Latitude)



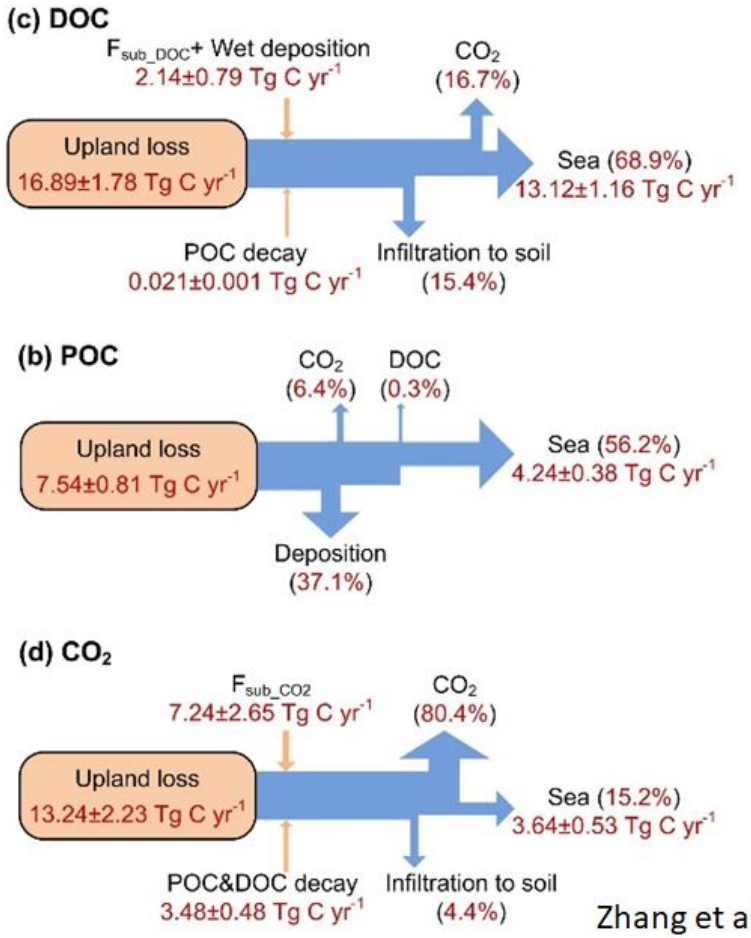
Seasonally-resolved inland water CO_2 evasion from Europe



Laruelle et al., in prep.

Lateral fluxes

To conclude: European land-river C budget with lateral fluxes



Zhang et al., in prep.

Lateral C loss: 47 (38+7) Tg C y^{-1}

Export to sea: 21 Tg C yr^{-1}

CO2 evasion: 19.5 Tg C yr^{-1}

IW sequestration: 6.5 Tg C y^{-1}

Next steps

- IAV of lateral C fluxes
- Impact of lateral C fluxes on terrestrial C sink
- Impact of lateral C fluxes on coastal ocean (TBD)

WP3 – Main achievement M19-M36

- T3.1: UPDATE state-of-the-art driving datasets
- **T3.2: UPDATE the <u>bottom-up</u> budget of terrestrial CO2 fluxes using a few complementary models (statistical or process-based).**
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T3.2 Bottom up budget of CO2 fluxes

APPROACHES

Process-based models	Data - driven Models	Bookkeeping approach
ORCHIDEE	*FluxCom*	*BLUE*
EFISCEN-space	*EFISCEN*	
G4M	*CBM*	
EPIC *DAYCENT*		
ECOSSE		

Ecosystems

- ALL
- Forest
- Crop
- Grass

All — Vegetation — Soil

Compartment

T3.2 Bottom up budget of CO2 fluxes

APPROACHES

Process-based models | Data - driven Models | Bookkeeping approach

Ecosystems

ALL

Forest

Crop

Grass

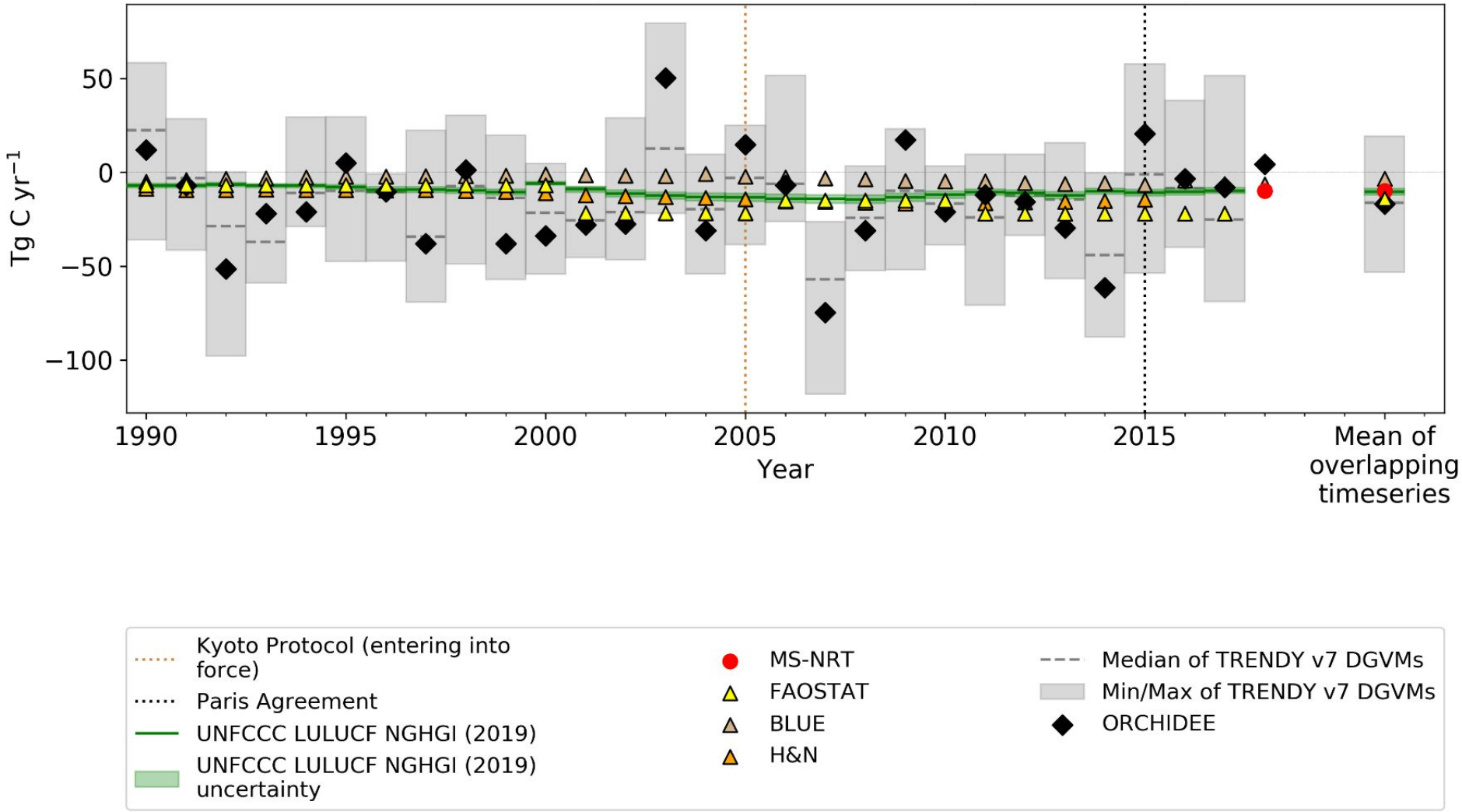
- Benefit from all approaches
- **Open to more land surface model (from TRENDY experiment)**
- To estimate model uncertainties

All | Vegetation | Soil

Compartment

T3.2 Analysis of the drivers of CO2 fluxes

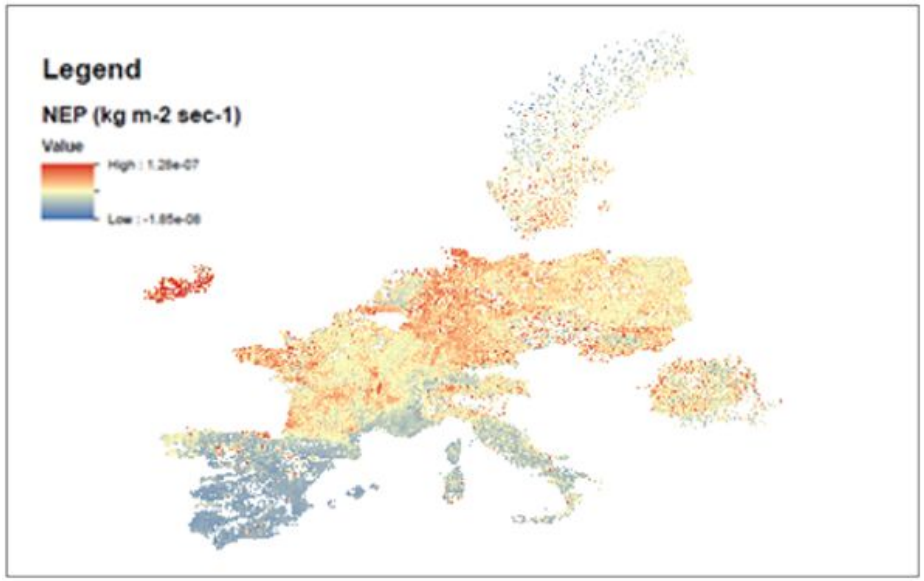
LULUCF - FRANCE

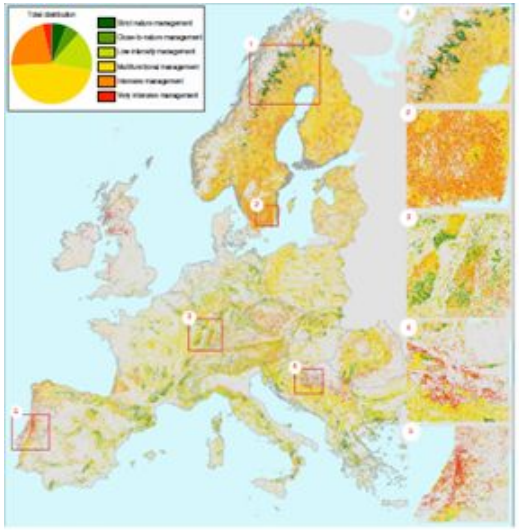


T3.2 Data-driven: Forestry by EFISCEN Space (WUR)

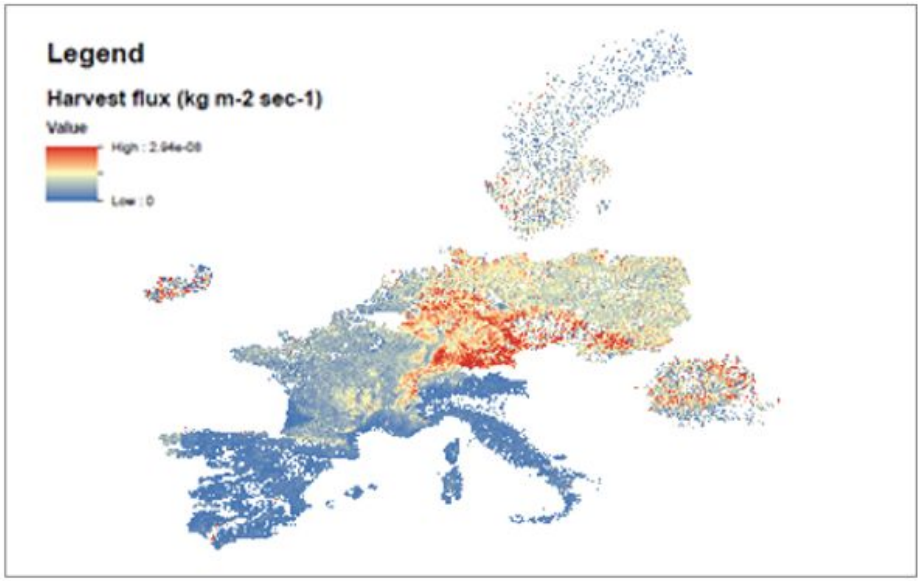
- EFISCEN Space model initialised on NFI plot data for 12 countries
- Individual tree
- Climate sensitive growth functions
- Harvest patterns derived from repeated observations on NFI plots, for different management intensity classes
- Providing NEP, NBP and harvest flux

Fully new approach for bottom up medium resolution forest carbon flux



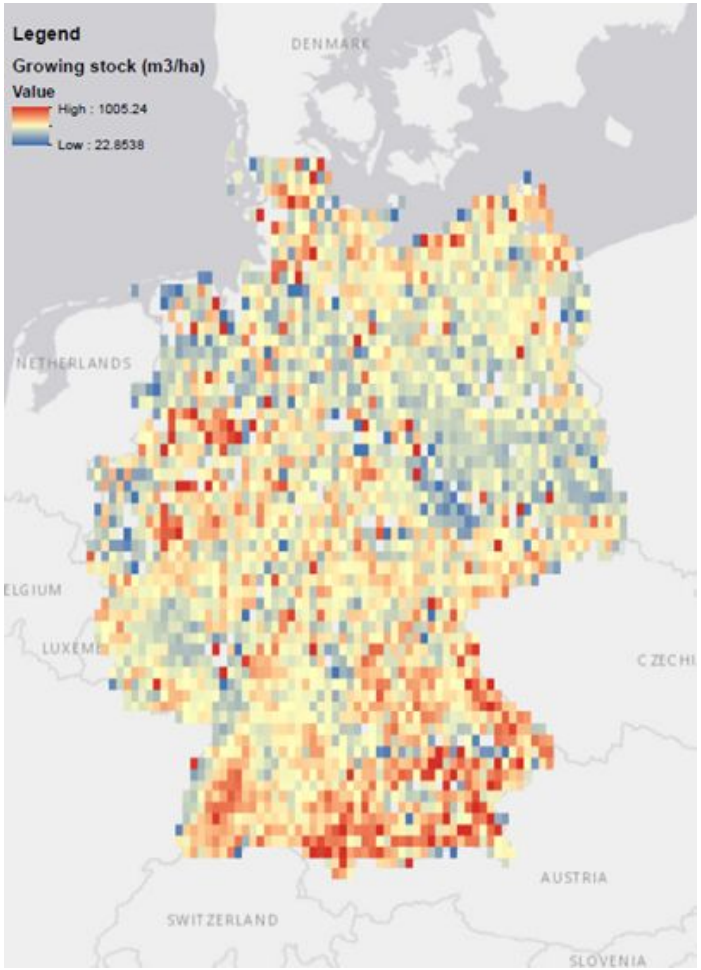


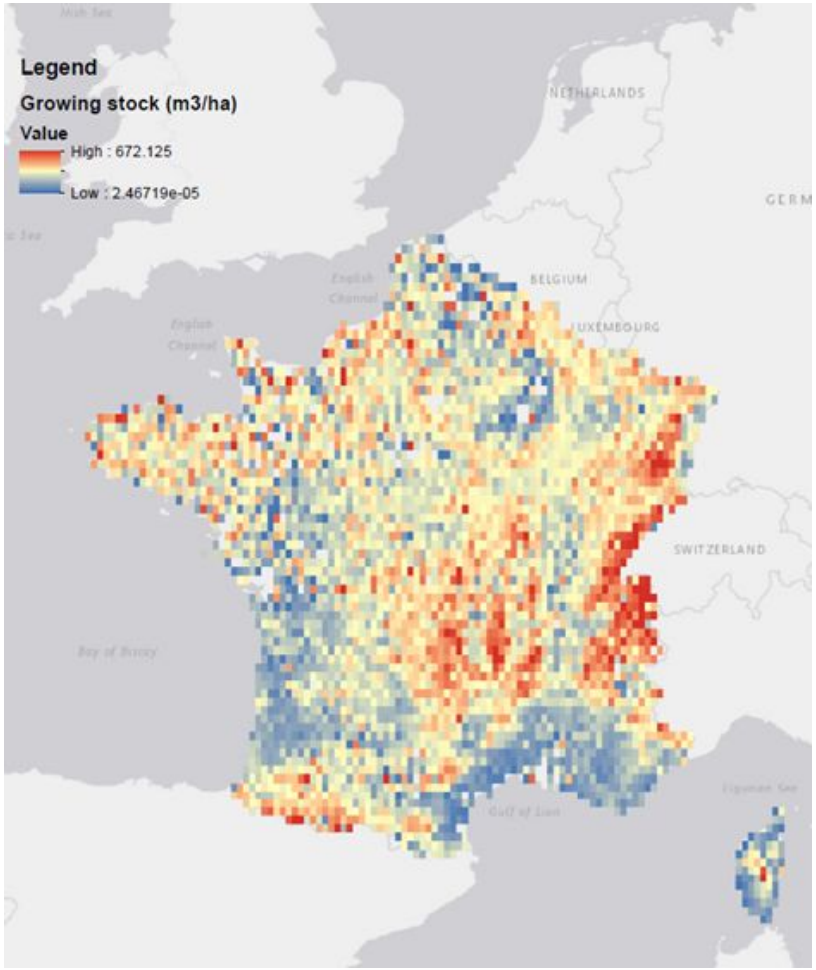
Harvest intensity (Nabuurs et al. 2019)



EFISCEN Space (WUR)

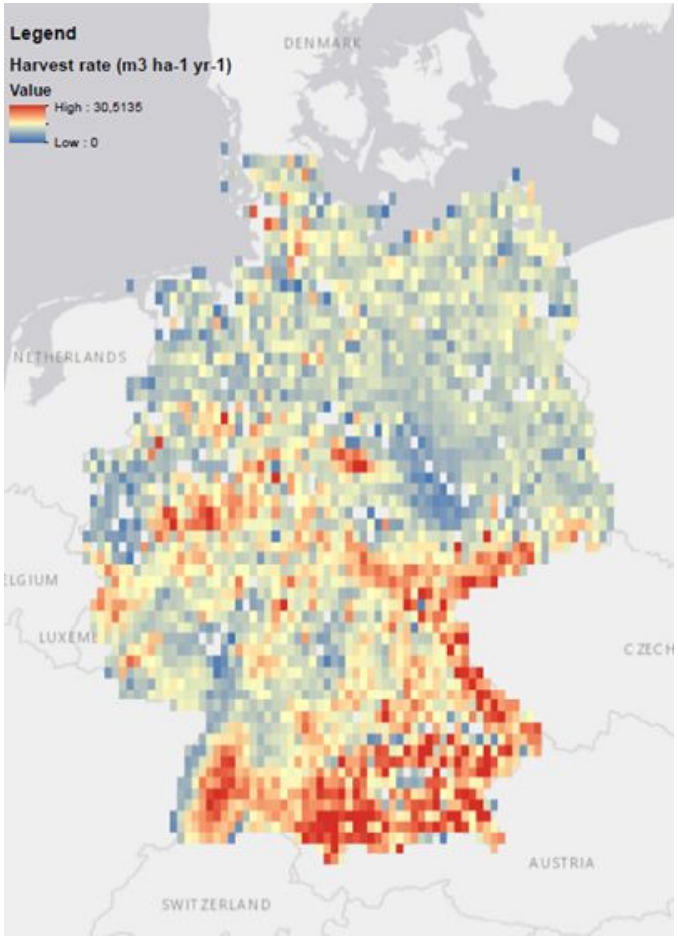
Growing stock

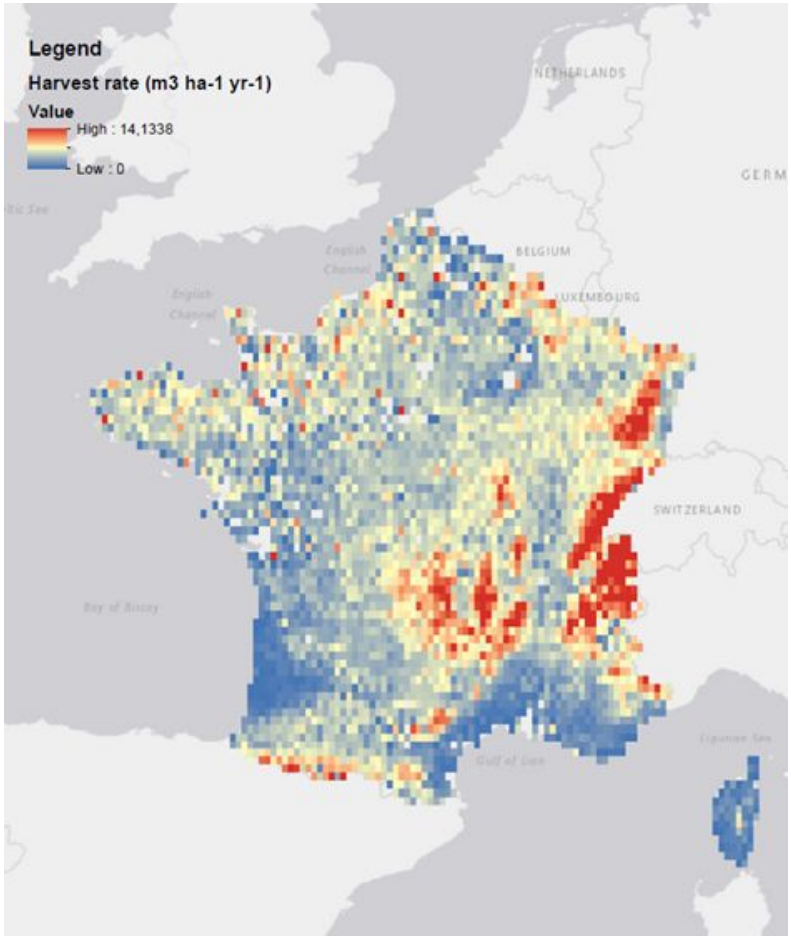




EFISCEN Space (WUR)

Harvest rate





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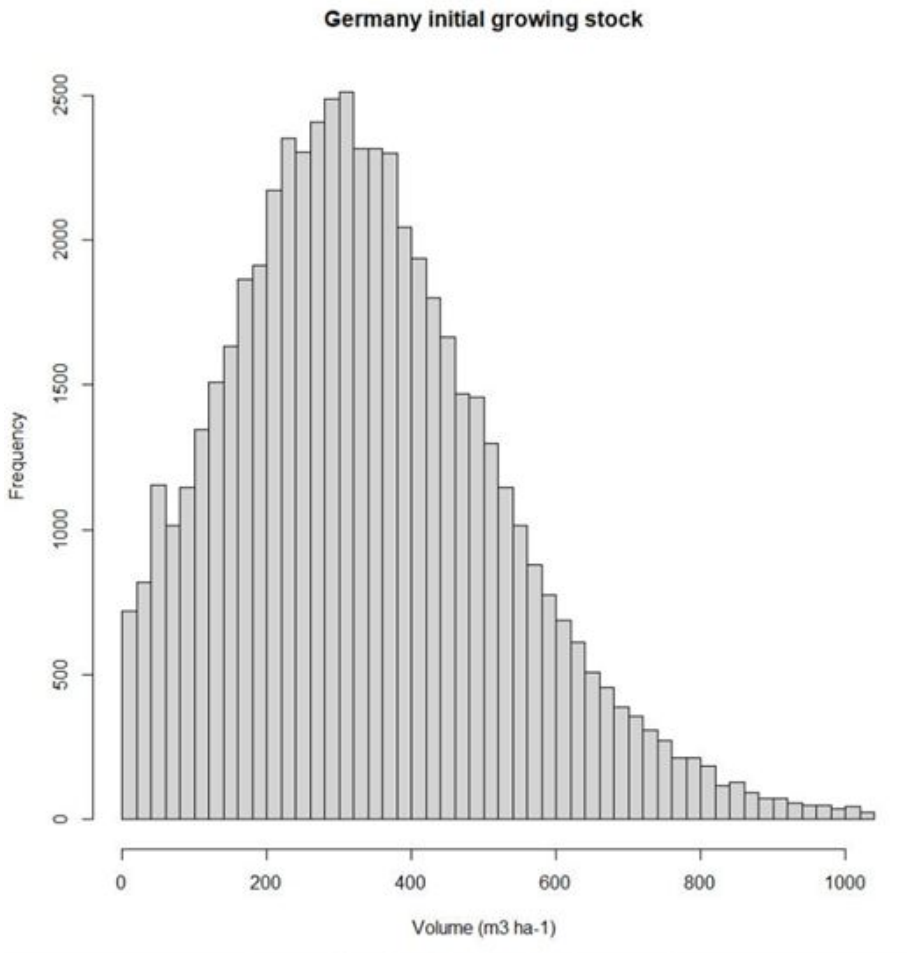
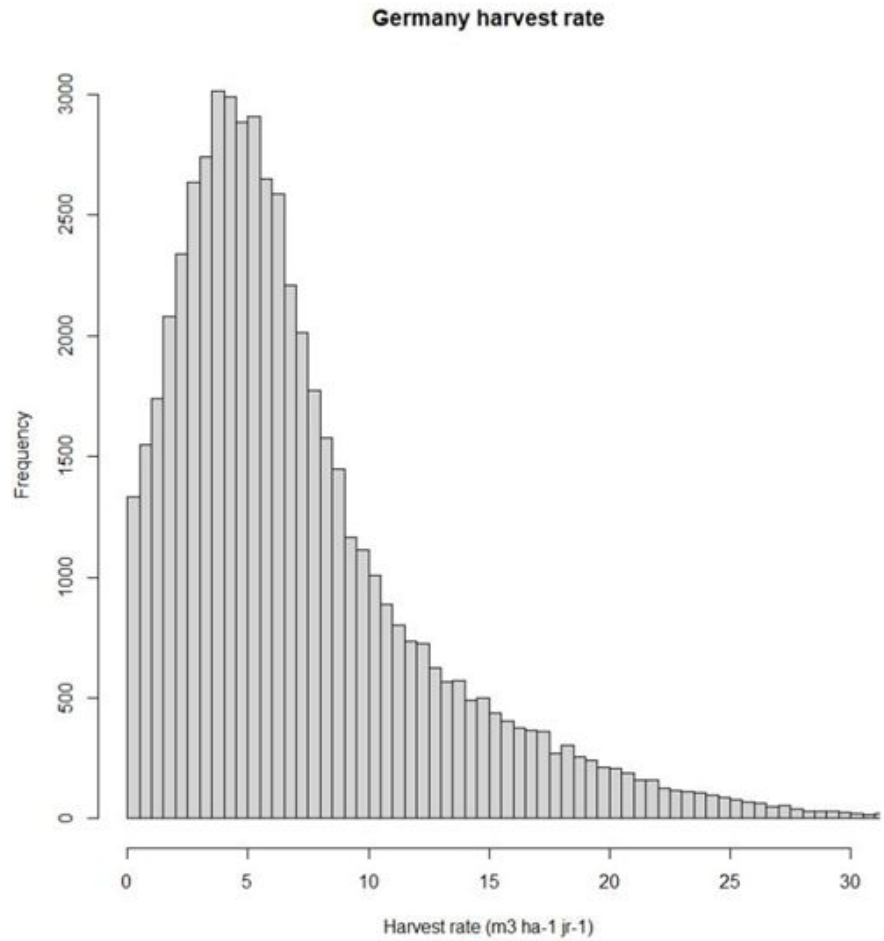
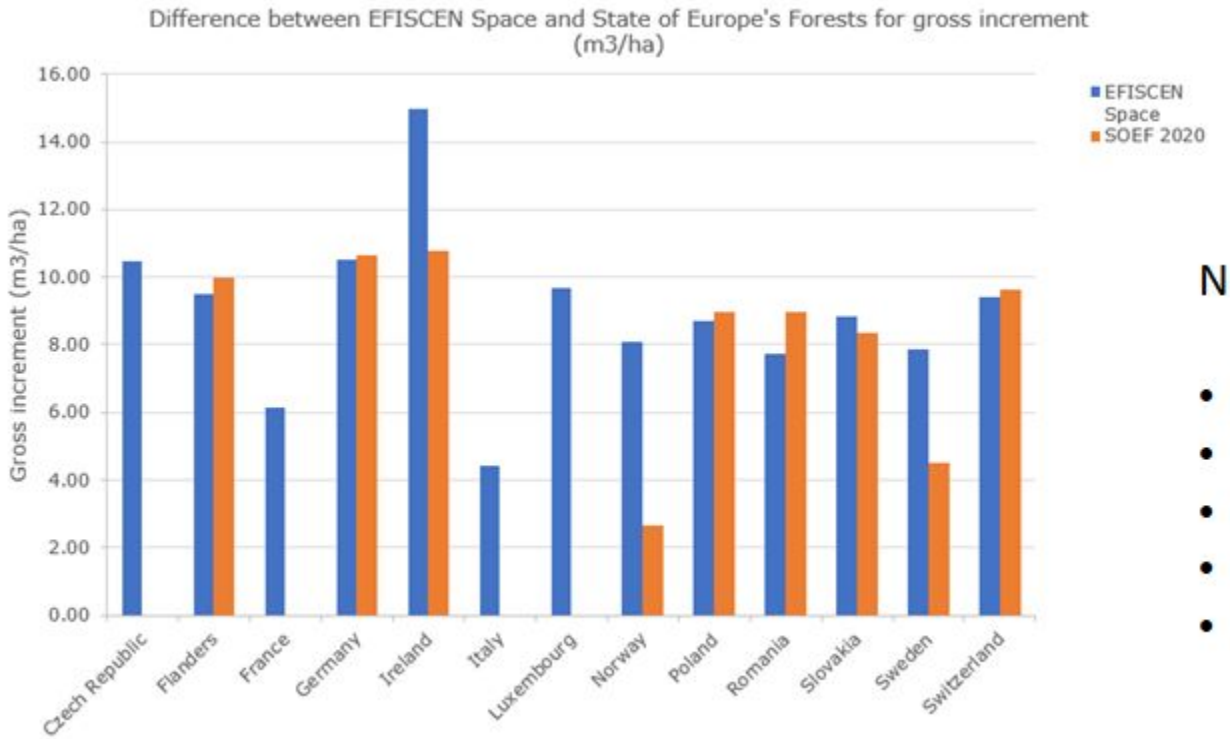




EFISCEN Space (WUR)

Growth functions in EFISCEN Space work well

... and result in increment rates close to what countries report



Next steps:

- Include more countries
- Check of results by countries
- Soil carbon module
- Cost module
- Dynamic mortality

T3.2 Forestry by IIASA's G4M/FLAM

VERIFY Input data:

Meteo data

HARMONIE daily dataset: cruhar_v3_1 and shortwave solar radiation (cruhar_v3_2) for 2002-2018;

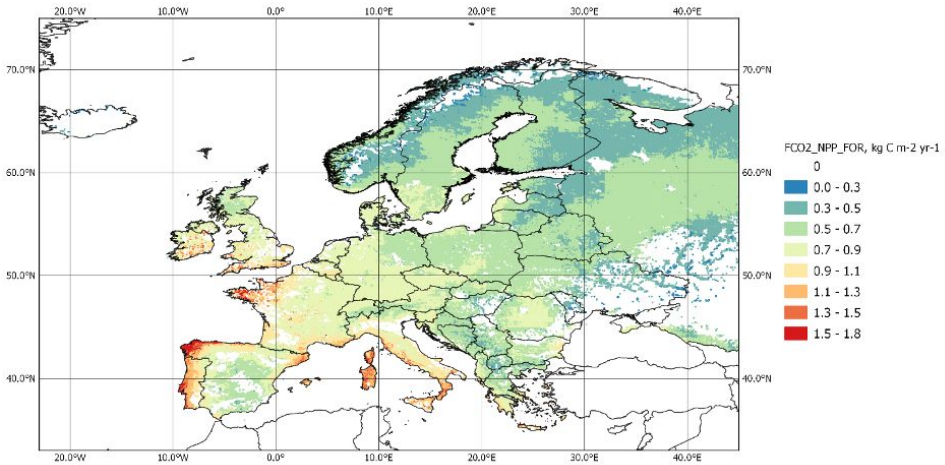
ERA dataset (cruera_v1.1) for 2019

Land cover

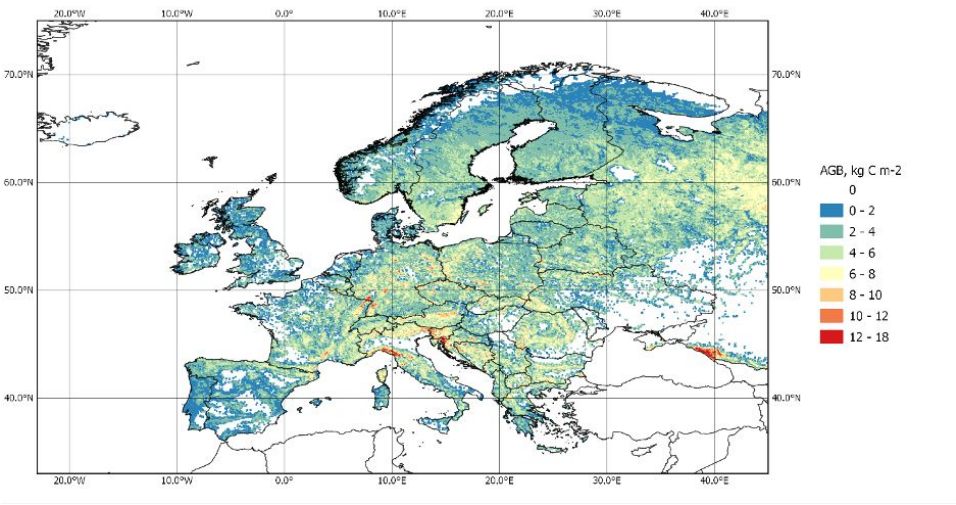
Annual maps from HILDA+ for 2001-2015

IIASA's G4M/FLAM output variables of carbon cycle

Variable	Unit	Description	Temporal aggregation
FCO2_NPP_FOR	kg C m^{-2} yr^{-1}	FCO2_NPP_FOR / Fluxes per square meter of forest	Annual
AGB	kg C m^{-2}	Above Ground Biomass	Annual



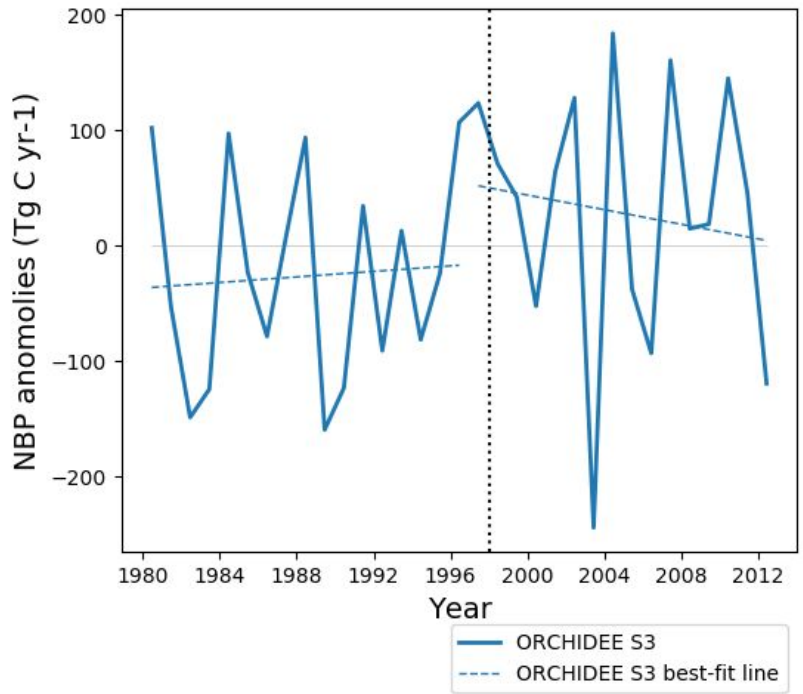
FCO2_NPP_FOR (kg C m^{-2} yr^{-1}) in 2019

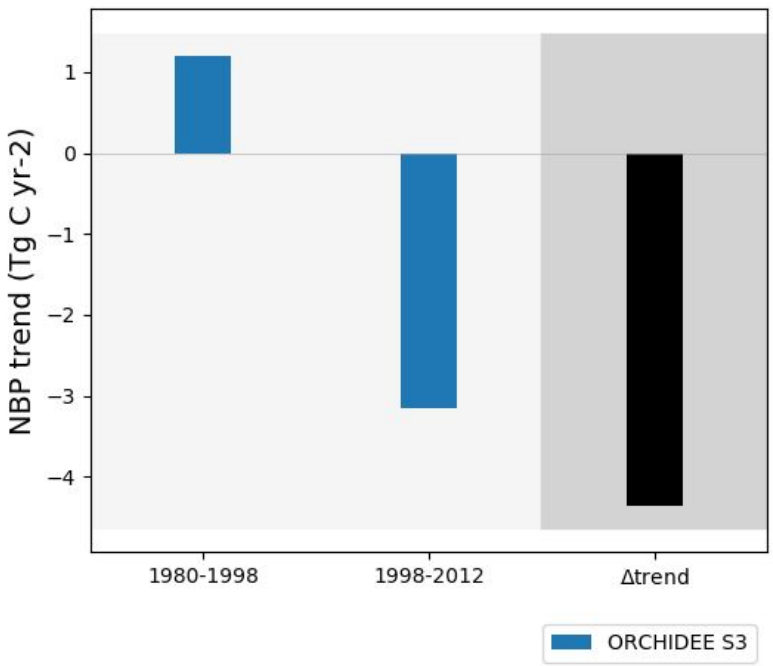


AGB (kg C m^{-2}) in 2019

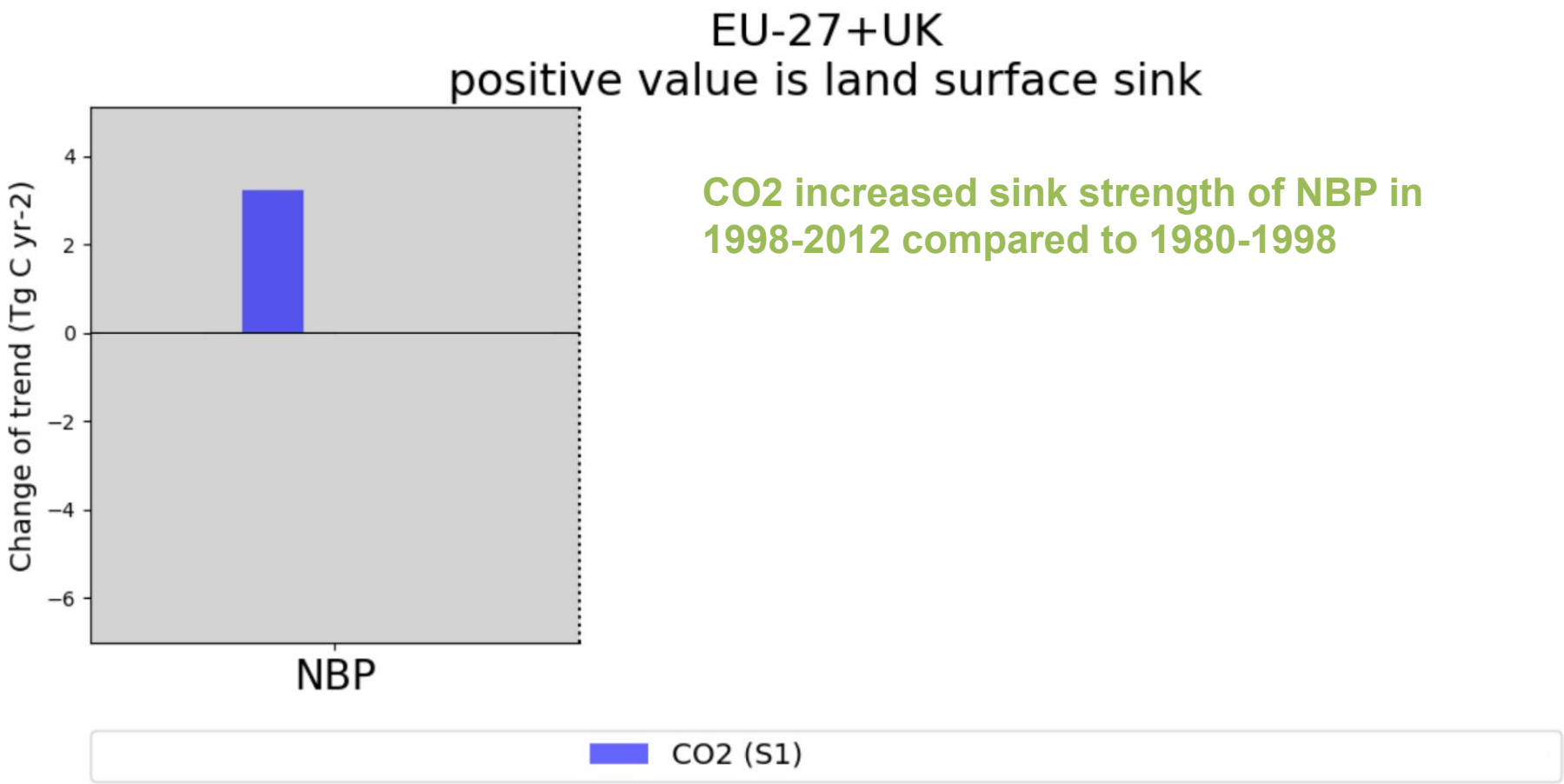
T3.2 Analysis of the drivers of CO2 fluxes

What drives the change in NBP trend between 1980-1998 and 1998-2012 in Europe?



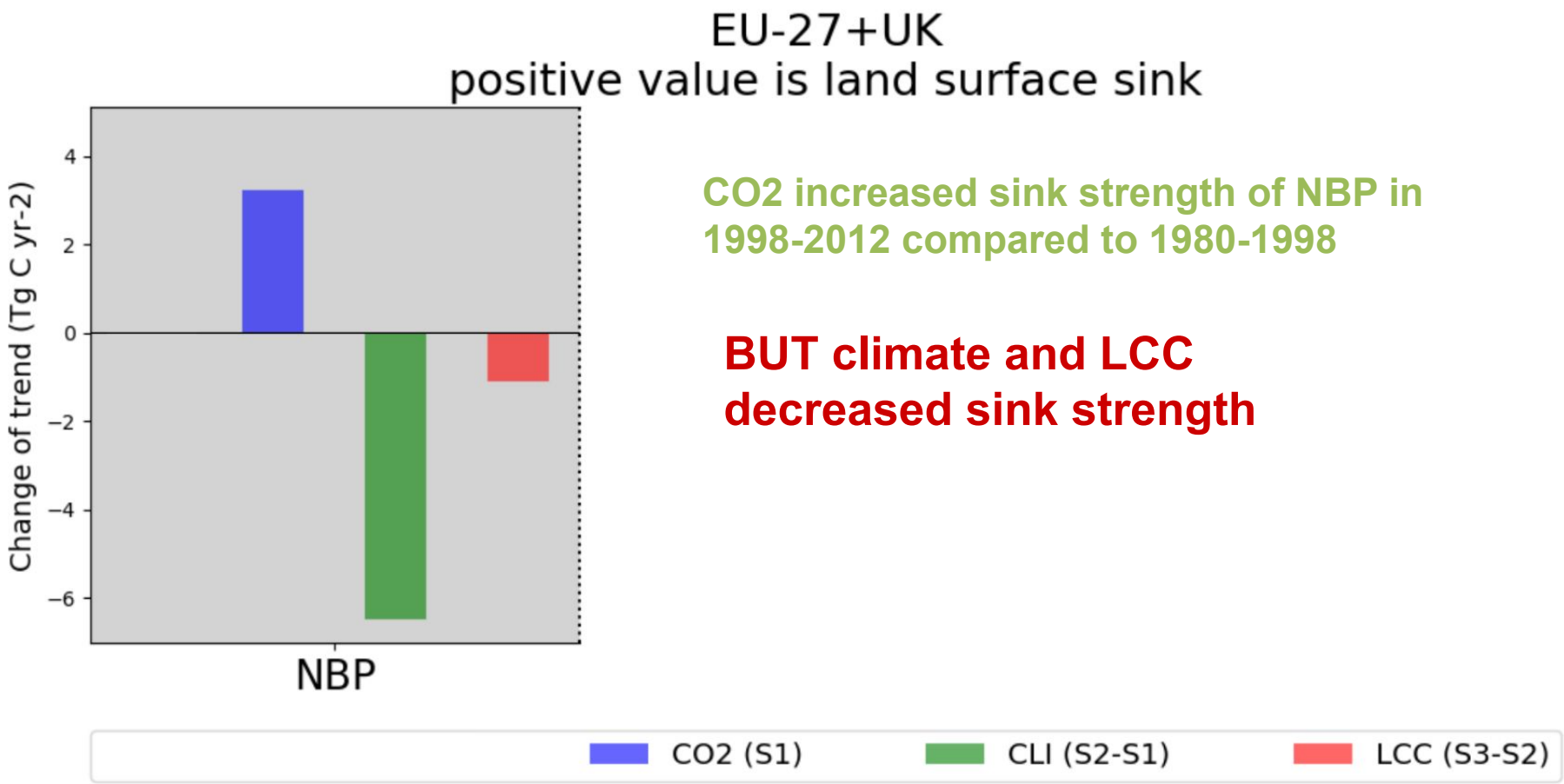


T3.2 Analysis of the drivers of CO2 fluxes



CO2 increased sink strength of NBP in 1998-2012 compared to 1980-1998

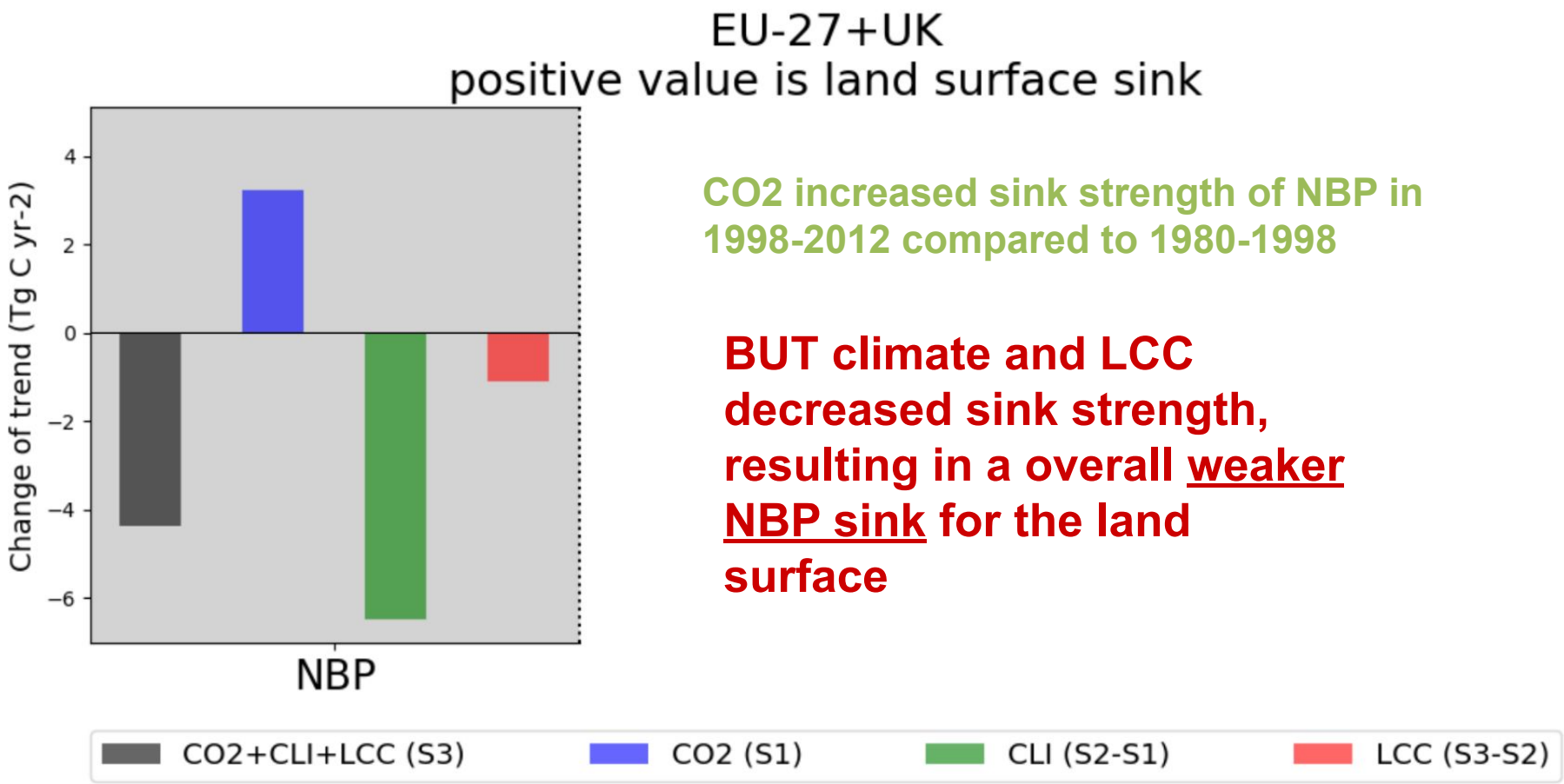
T3.2 Analysis of the drivers of CO2 fluxes



CO2 increased sink strength of NBP in 1998-2012 compared to 1980-1998

BUT climate and LCC decreased sink strength

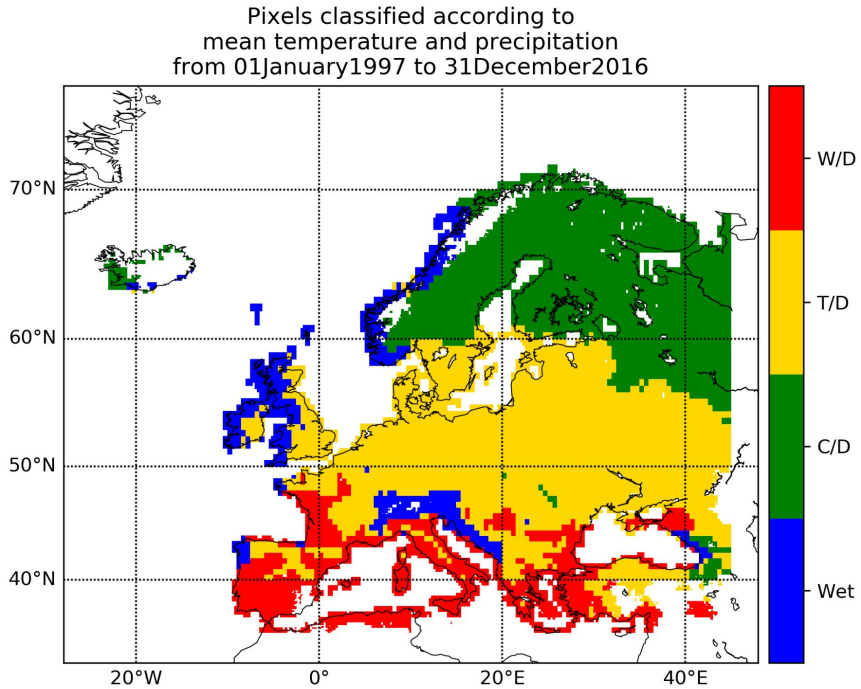
T3.2 Analysis of the drivers of CO2 fluxes

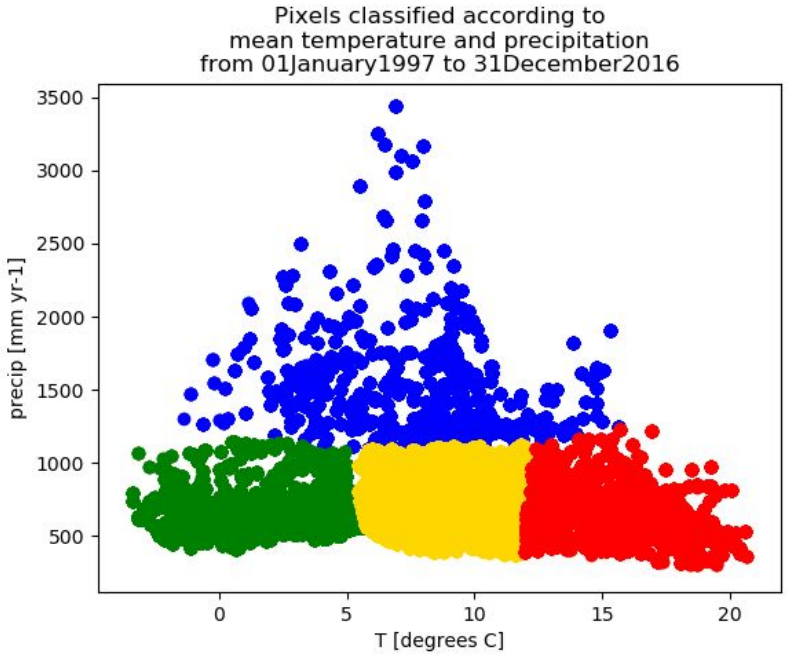


CO2 increased sink strength of NBP in 1998-2012 compared to 1980-1998

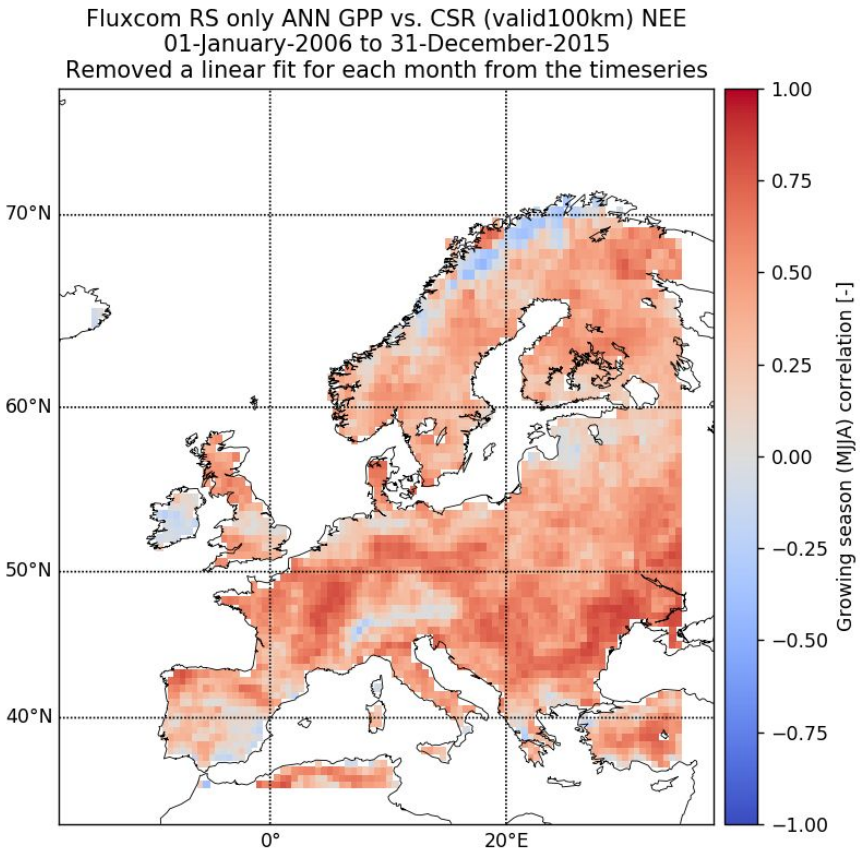
BUT climate and LCC decreased sink strength, resulting in a overall <u>weaker NBP sink</u> for the land surface

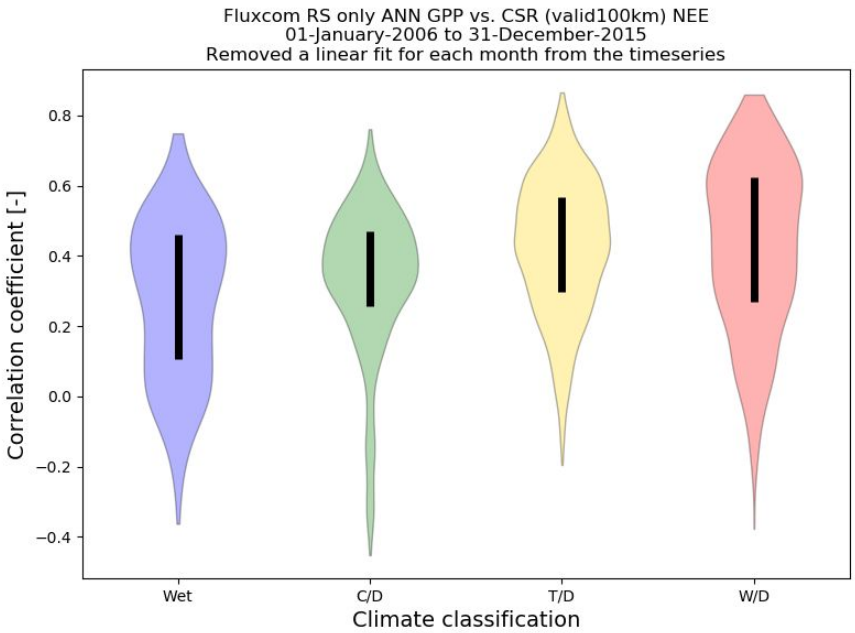
NEE driver: GPP or TER?





NEE driver: GPP or TER?





WP3 – Main achievement M19-M36

- T3.1: UPDATE state-of-the-art driving datasets
- T3.2: UPDATE the bottom-up budget of terrestrial CO2 fluxes using a few complementary models (statistical or process-based).
- **T3.3: UPDATE the Europe-wide <u>inversions</u> of NEE using in situ data of atmospheric CO2 and a high-resolution transport model.**
- T3.4: Develop new multi-data model fusion strategies to investigate CO2 budgets and trends; Specific focus on Eastern Europe.

T3.3 Inversion of NEE

- Based on one system: Jena CarboScope-Regional

- Two step scheme:
  Global inversion (TM3) to provide the lateral transport
  Regional EU inversion (STILT) at 0.25° resolution - 1h resolution

- Fossil fuel emissions and Ocean fluxes are prescribed

- Solve for terrestrial NEE fluxes for period 2006 - 2019 but using corrections at 0.5° - 3h resolutions

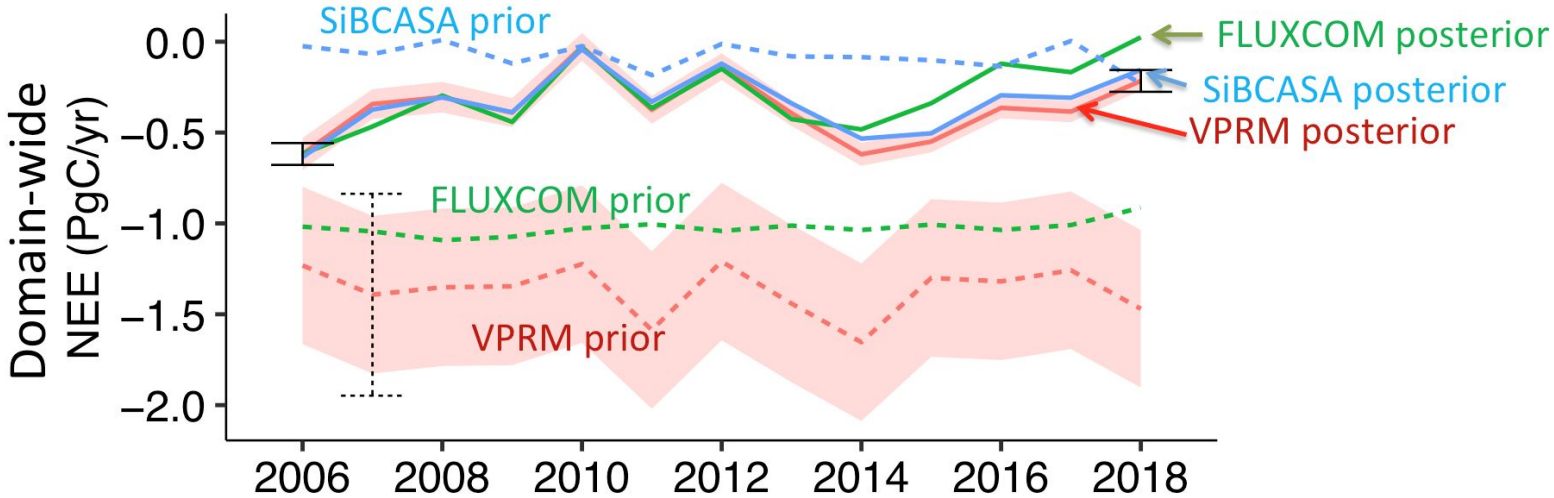
- Test different land NEE priors and ocean priors
  B0: VPRM : simple diagnostic model
  B1: Fluxcom : data-driven model
  B2: SIBCASA: process-based model

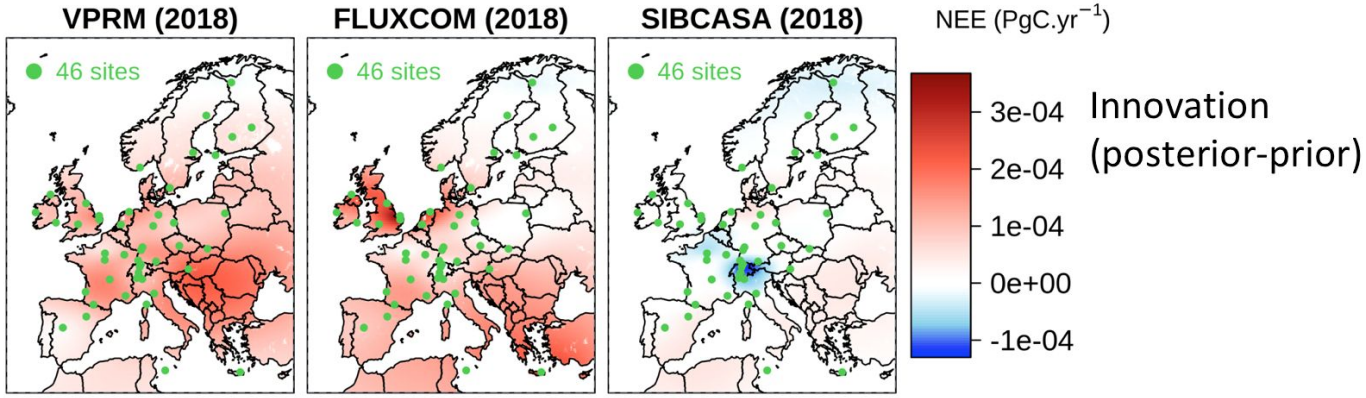
- Test also different [CO2] station networks

T3.3 Inversion of NEE

CarboScope-Regional inversions

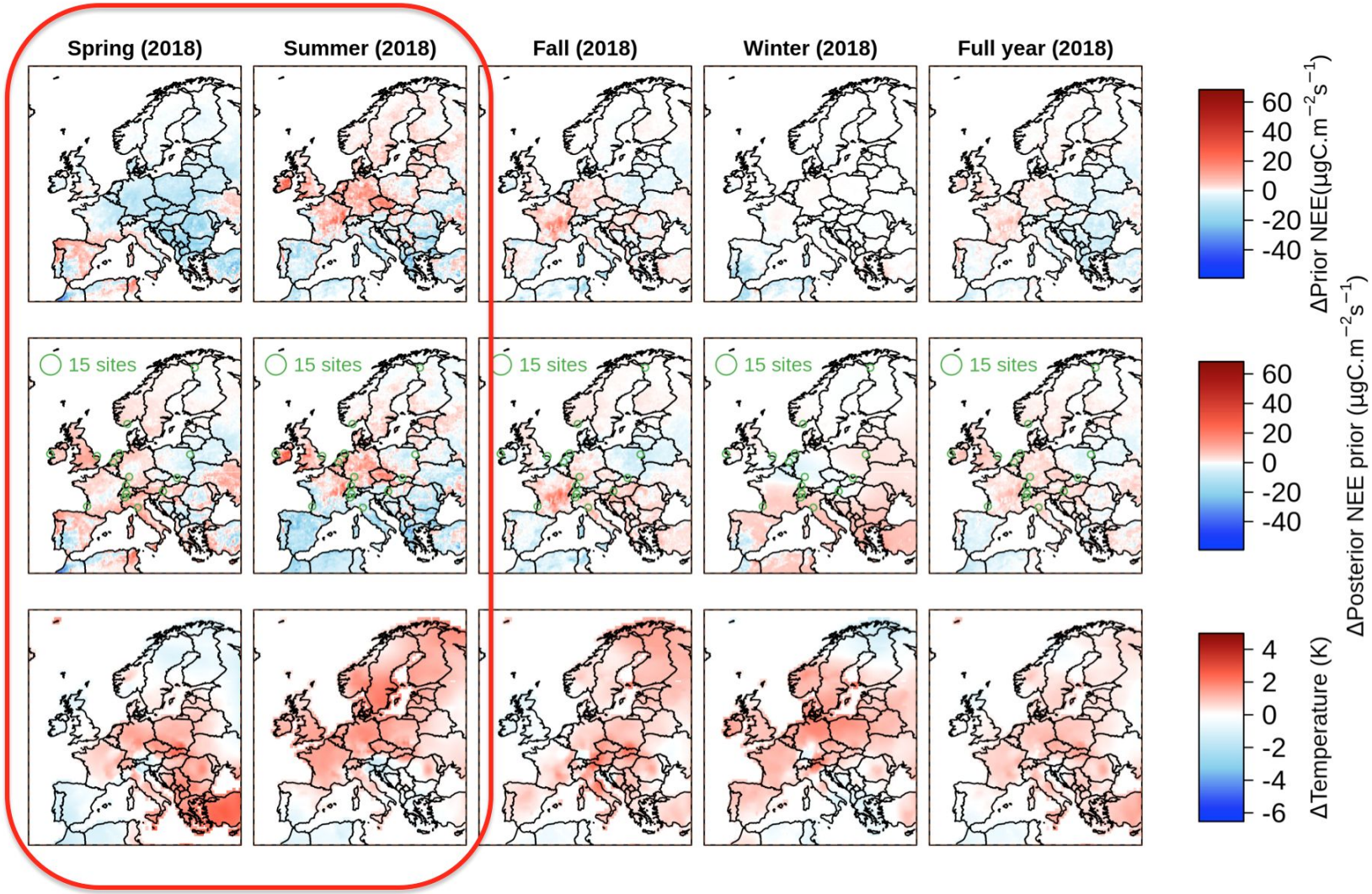
Different prior flux models, similar posterior fluxes





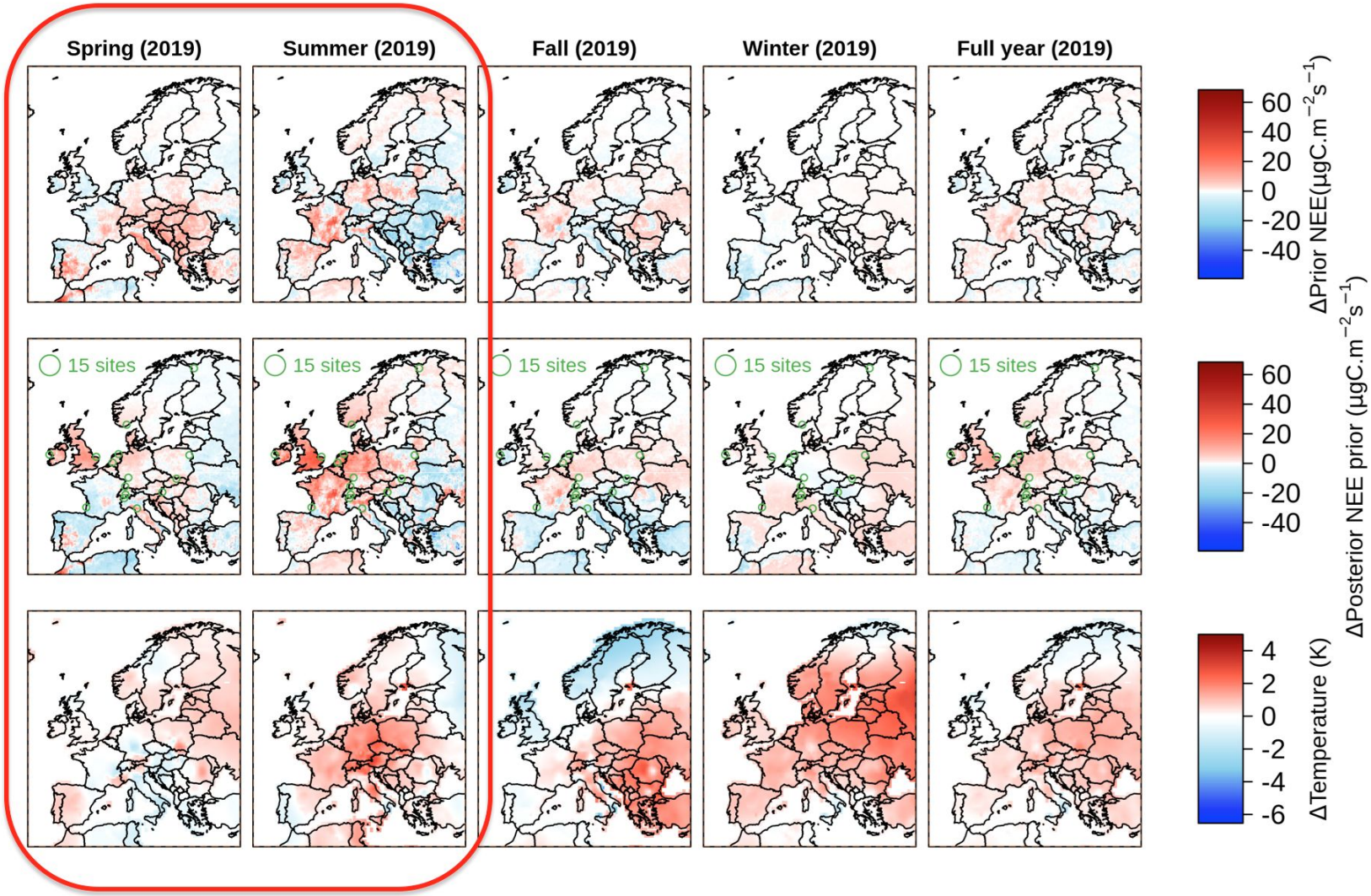
T3.3 Inversion of NEE

CarboScope-Regional NEE and Temp. anomalies



T3.3 Inversion of NEE

CarboScope-Regional NEE and Temp. anomalies



T3.3 Inversion of NEE

Key messages

- Posterior NEE strongly driven by atm. CO2 data (not prior, not ocean)
- But posterior fluxes depend critically on station network; much more than on the prior NEE fluxes
- Interannual variations of Posterior NEE resembles that of prior from VPRM
- CO2 sink for 2019 was stronger than in 2018 over all Europe, specifically for regions affected by the 2018 drought (north Europe)

Outlook

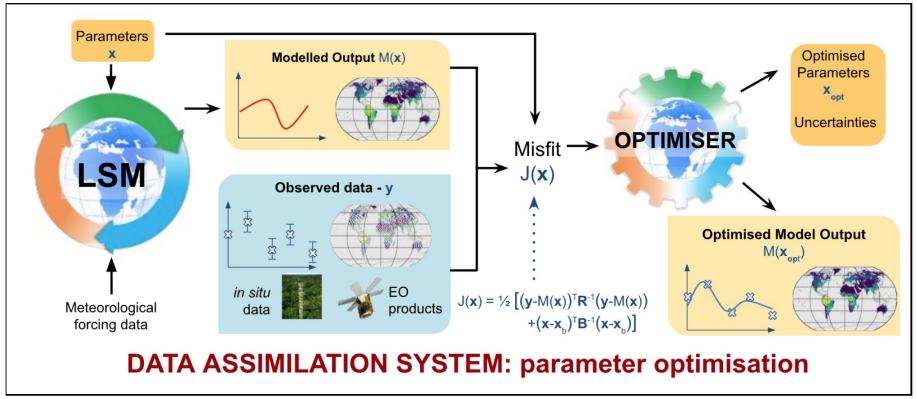
- Include prior fluxes also from Orchidee
- Include “coastal” ocean flux estimates and lake fluxes
- Additional transport model: footprints from Flexpart / LUMIA system (Guillaume Monteil, U. Lund)
- Use Community Inversion Framework (CIF) to assess transport model errors
- 2020 NEE estimates by Sep. 2021

WP3 – Main achievement M19-M36

- T3.1: UPDATE state-of-the-art driving datasets
- T3.2: UPDATE the bottom-up budget of terrestrial CO2 fluxes using a few complementary models (statistical or process-based).
- T3.3: UPDATE the Europe-wide inversions of NEE using in situ data of atmospheric CO2 and a high-resolution transport model.
- **T3.4: Develop new multi-data model fusion strategies to investigate <u>CO2 budgets and trends</u>; Specific focus on Eastern Europe.**

T3.4 Research need to reduce NEE uncertainties

- Carbon cycle data assimilation systems **(CCDAS)**



⇒ Simulations for late 2021

BETHY-CCDAS

Assimilation of
- Satellite soil moisture
- Satellite L-VOD
- In situ atm. CO2 data
- Nighlights (for FF model)

Two-step assimilation
- Fossil Fuel at 0.1 in FFDAS
- Biogenic fluxes at 0.25 in CCDAS

Optimisation of
around 70 parameters in CCDAS and 1.5M in FFDAS

ORCHIDEE-CCDAS

Assimilation of
- FluxNet in situ data
- Satellite Fluorescence
- In situ atm. CO2 data (using LMDZ model)

Optimisation of
- around 150 parameters
- stepwise assimilation of each datastream

CTDAS

Dynamic a-priori fluxes
Using near real-time statistical data (EU, Eurostat,...) and weather data to fill in short-term variations in fluxes at ~2km

Assimilation of
- ICOS CO2 mole fractions
- Δ14C, CO, NO2

Optimisation of
Around ~10 parameters per country, sectorial FF emissions, NEE per PFT

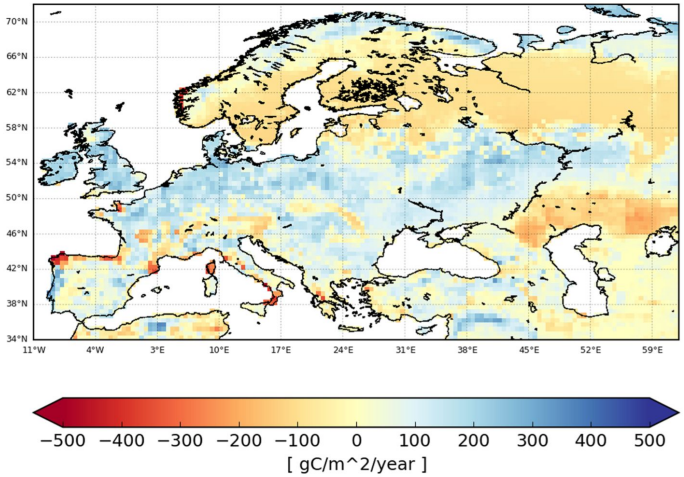
BETHY CCFFDAS:
Carbon Cycle Fossil Fuel Data Assimilation System

2-step optimization scheme:

1. FFDAS provides fossil fuel emission estimates consistent with observations of nightlights and emissions from point sources.
2. optimized fossil fuel emissions are used in CCDAS to provide terrestrial carbon fluxes consistent with observations from the SMOS satellite as well as atmospheric CO2 concentrations (currently running).

Results from step 2 based on CDIAC fossil fuel emissions (Boden et al, 2016) focussing on Europe (TRANSCOM region):

Mean annual NEP 2010-2015 (+ sink)

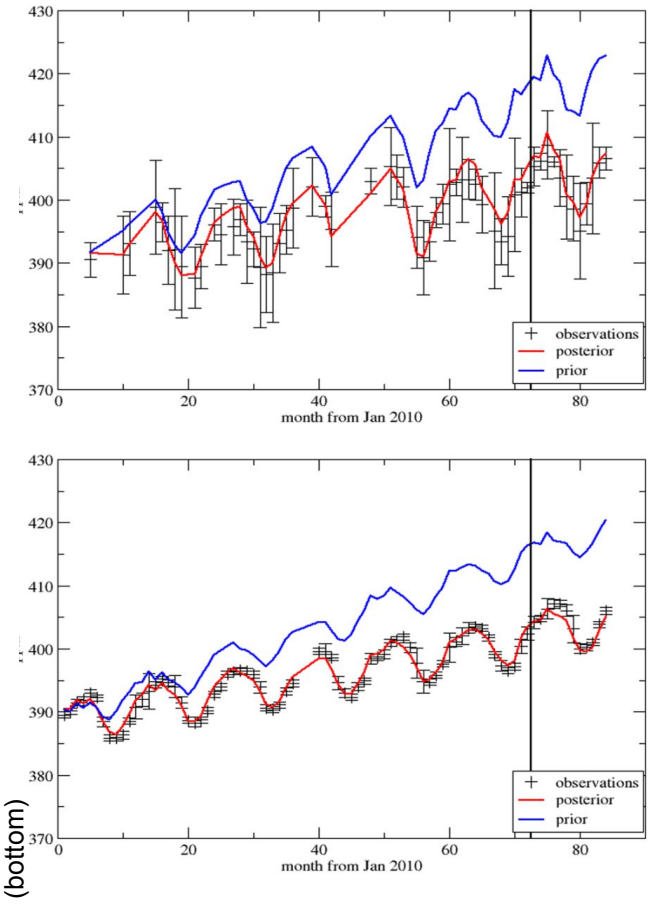


Scholze et al., GRL, 2019

Annual average 2010-15 in GtC/yr

	Europ. flux estimate	
Experiment	NEP	NPP
Prior	−0.024±1.19	4.60±0.81
CO2	0.18±0.12	4.82±0.16
CO2+SMOS	0.30±0.08	4.82±0.12

Evaluation against ind. CO2 data at Monte Cimone (top) and Assekrem (bottom)



CT Europe Lagrangian: joint FF-NEE optimization using radiocarbon and CO_2 mole fractions

PhD research Auke van der Woude

FF error

BIO error

Only CO_2 used

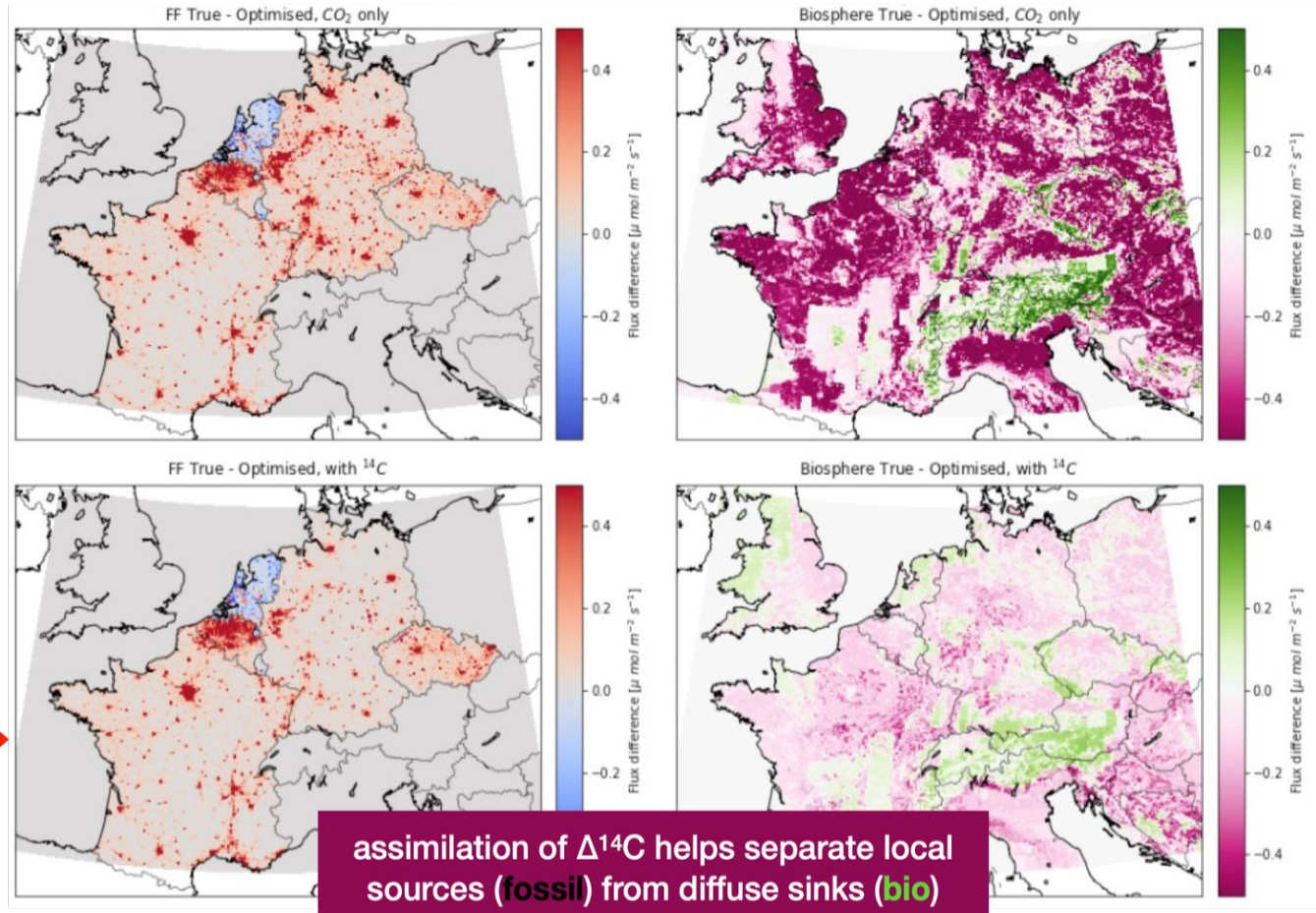
Data assimilation of CO_2 and radiocarbon (Δ14C) to constrain the sources and sinks of CO_2 in Western Europe.

-> Simulations of hourly varying FF emissions (households, traffic, industry, power production, renewables).

-> Simulations of hourly photosynthesis and respiration by biosphere (2x2km)

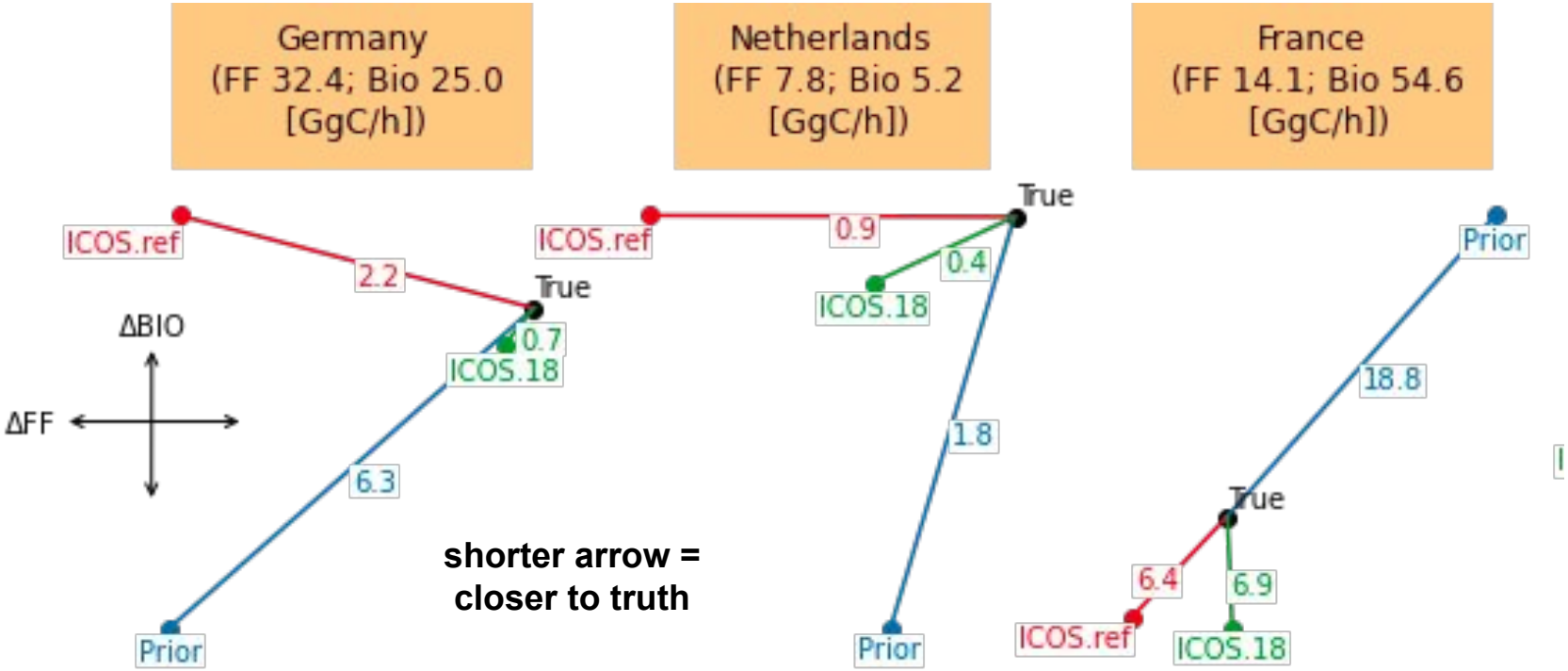
-> Simulations of atmospheric transport (CO_2, Δ14C, CO, NOx) and weather (renewables and biosphere)

Δ14C and CO_2 used



assimilation of $\Delta^{14}C$ helps separate local sources (fossil) from diffuse sinks (bio)

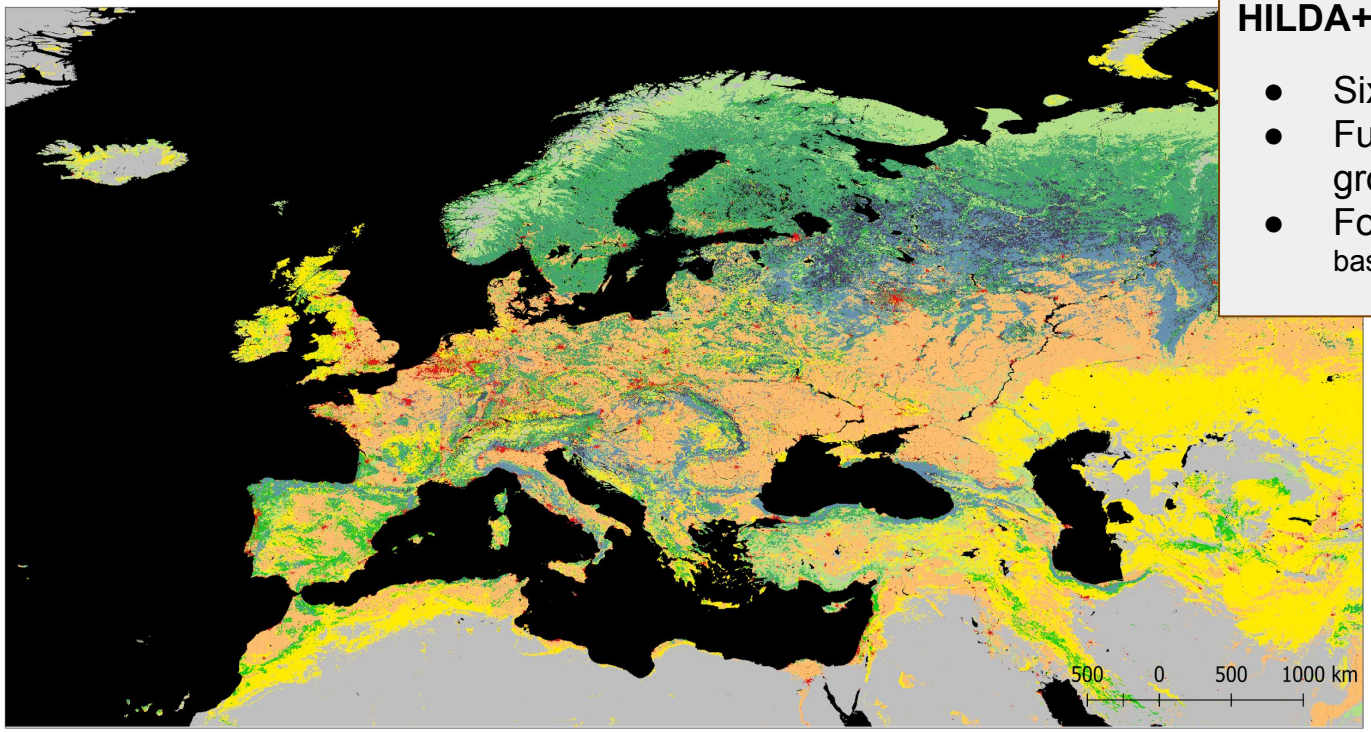
CT Europe Lagrangian: joint FF-NEE optimization using radiocarbon and CO_2 mole fractions



- Addition of Δ14C (18 samples/month/site) reduces uncertainty of FF *and* NEE
- Estimates come (much) closer to truth for ICOS well-covered countries
- RINGO (H2020 project) network also tested: going closer to FF sources and targeted sampling can help, but not as much as increasing # of sites for CO_2

T3.4 HILDA+ Land Use Change for Europe

HILDA+ land use/cover (LUC) change 1x1km/ global/ 1960-2019 (annual)



urban
cropland
pasture/rangeland
forest (deciduous, broad leaf)
forest (evergreen, broad leaf)
forest (evergreen, needle leaf)
forest (deciduous, needle leaf)
forest (mixed)
forest (unknown/other)
grass/shrubland
sparse/no vegetation
water

HILDA+ for Europe at a glance:

- Six main LUC classes
- Full land transitions = gross change
- Forest classes on top, based on ESA-CCI LC

⇨ **Synthesis LUC dataset with unprecedented spatial, temporal and thematic detail.**

Publication: Winkler et al. (2021): *Land use changes are four times greater than previously estimated*. Nat Comms (in press).
Dataset available at: https://doi.org/10.1594/PANGAEA.921846

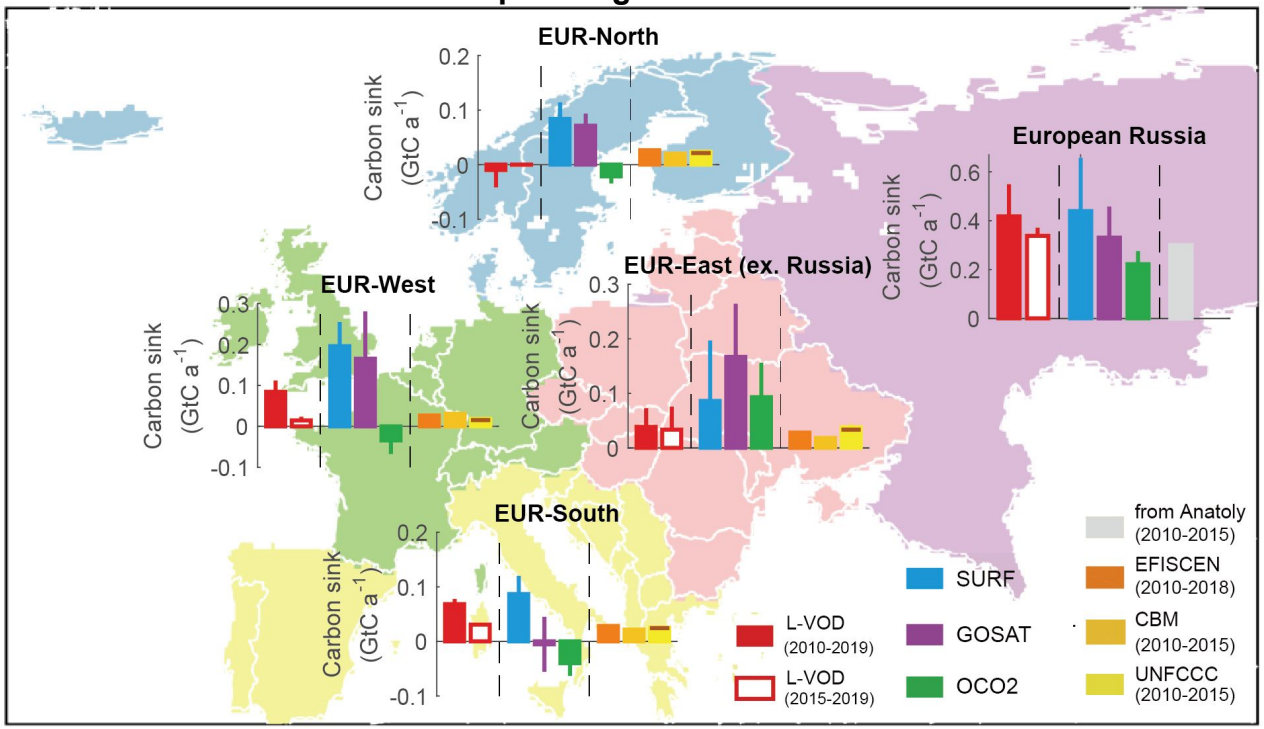
T3.4 The Eastern European carbon sink

K. Winkler, H. Yang, R. Ganzenmüller, R. Fuchs, F. Chevallier, J. Pongratz and P. Ciais

research ongoing

Carbon sink potential of Eastern Europe

Carbon sink estimates for European regions



Most of carbon sink occurs in Eastern European (EUR-East + European Russia):

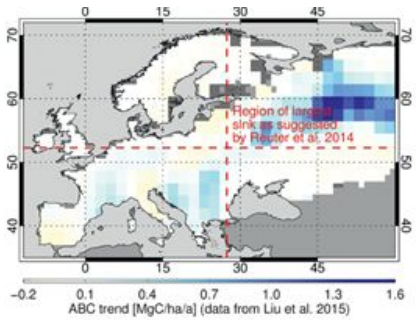
L-VOD AGB (2010-2019)	~**0.46** GtC a^{-1}
SURF, GOSAT, OCO2 Inversions	~**0.45** GtC a^{-1}
EFISCEN, CBM and UNFCCC	~**0.32** GtC a^{-1}

T3.4 The Eastern European carbon sink

K. Winkler, H. Yang, R. Ganzenmüller, R. Fuchs, F. Chevallier, J. Pongratz and P. Ciais

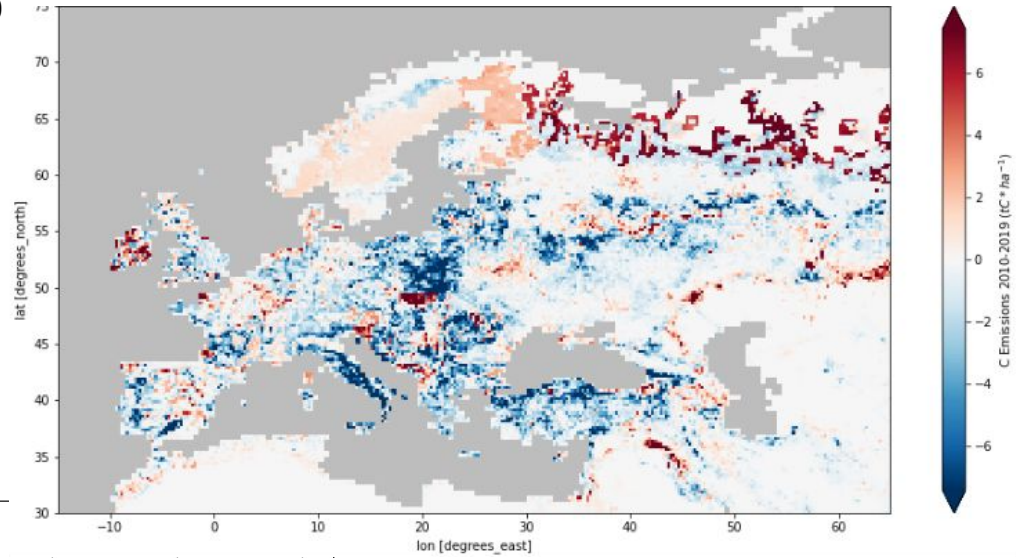
research ongoing

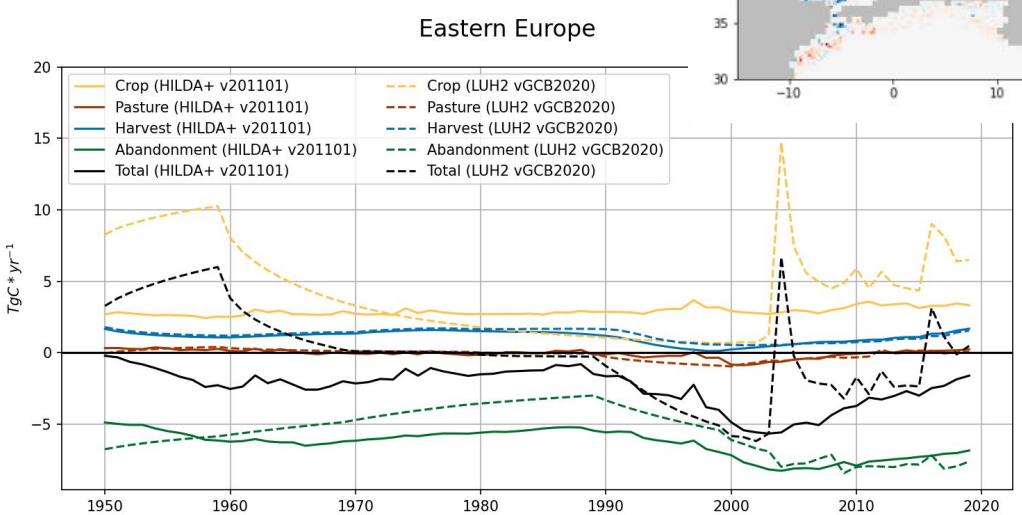
Carbon emissions from land use change



ABC trend 2003-10 (Reuter et al., 2017)

Aggregated carbon emissions from BLUE (based on HILDA+) 2010-2019





BLUE (HILDA+) **~0.03** GtC a^{-1} (net emissions)
→ **Forestry and agriculture decrease carbon sink effect from land abandonment.**

Thank you for your attention.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 776810

WP3 PARTNERS

Two co – leaders:

University of Aberdeen (**UNIABDN)**,
Commissariat à l'énergie atomique (**CEA**),

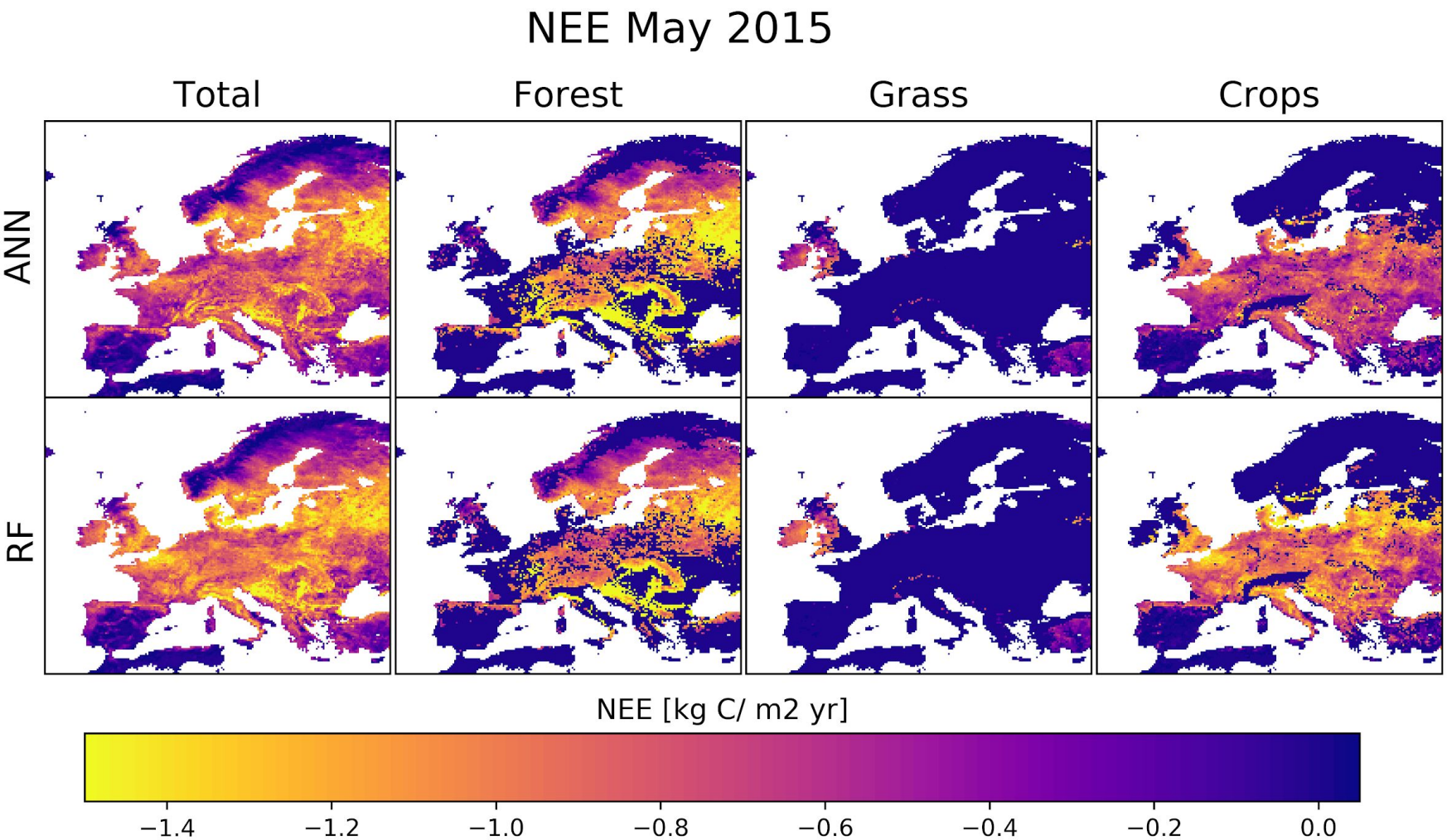
18 partners:

Joint Research Centre (**JRC**), Karlsruhe Institute of Technology (**KIT**),
Max Planck Society for the Advancement of Science (**MPG**),
Norwegian Institute for Air Research (**NILU**),
International Institute for Applied Systems Analysis (**IIASA**),
Integrated Carbon Observation System (**ICOS**) ERIC,
European Centre for Medium-Range Weather Forecasts (**ECMWF**),
Wageningen Environmental Research (**WEnR**),
University of Bremen (**UBremen**), University of East Anglia (**UEA**),
Vrije Universiteit Amsterdam (**VU**), Lund University (**ULUND**),
University of Bergen (**UiB**), Wageningen University & Research (**WUR**),
Université libre de Bruxelles (**ULB**), Saint Petersburg State University (**SPbU**),
Ural Federal University (**UrFU**), Ludwig-Maximilian Munich University (**LMU**)

Additional slides

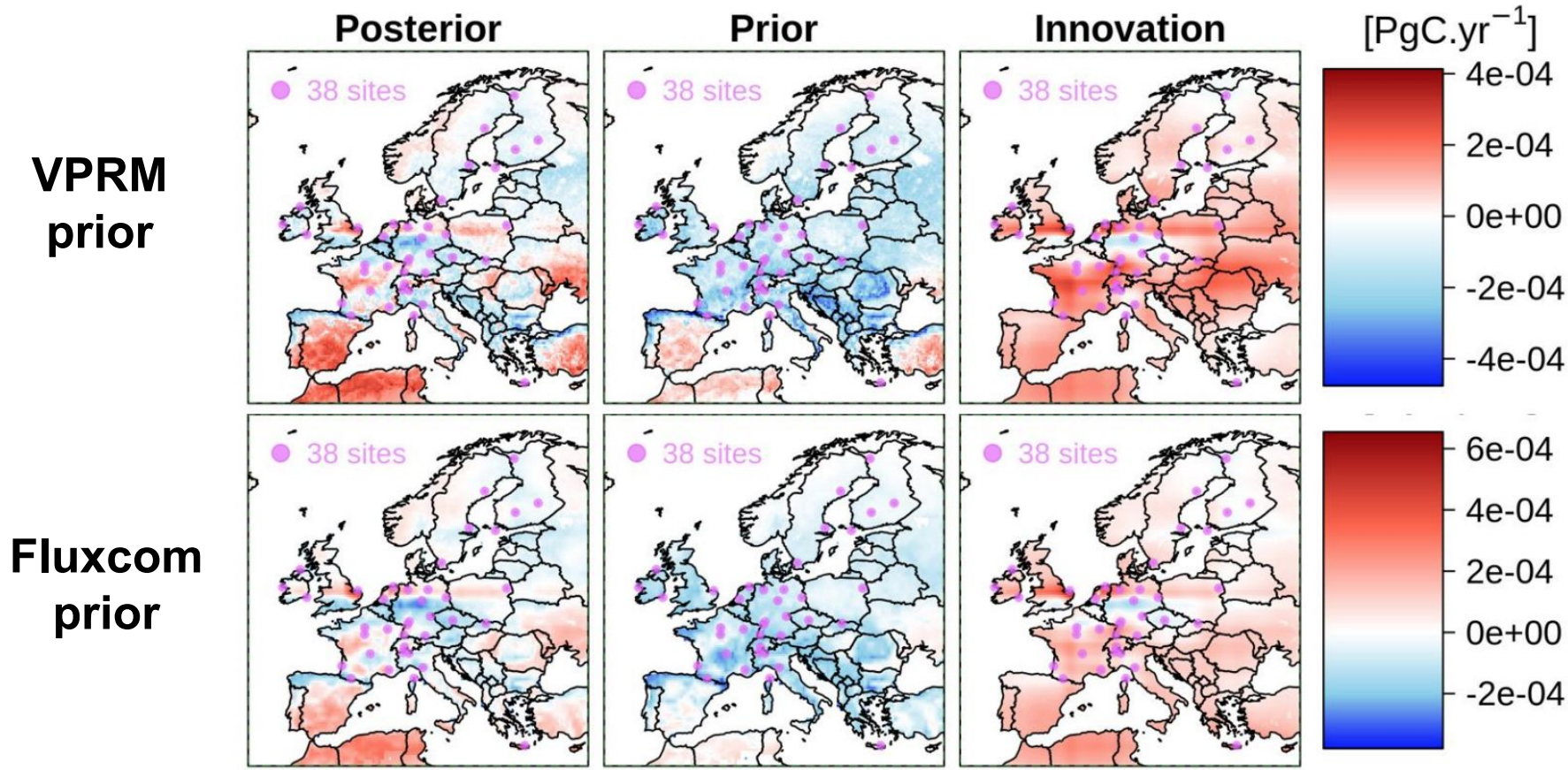
T3.2 Bottom up terrestrial CO2 fluxes

FLUXCOM data – driven model (MPI)



T3.3 Inversion of NEE

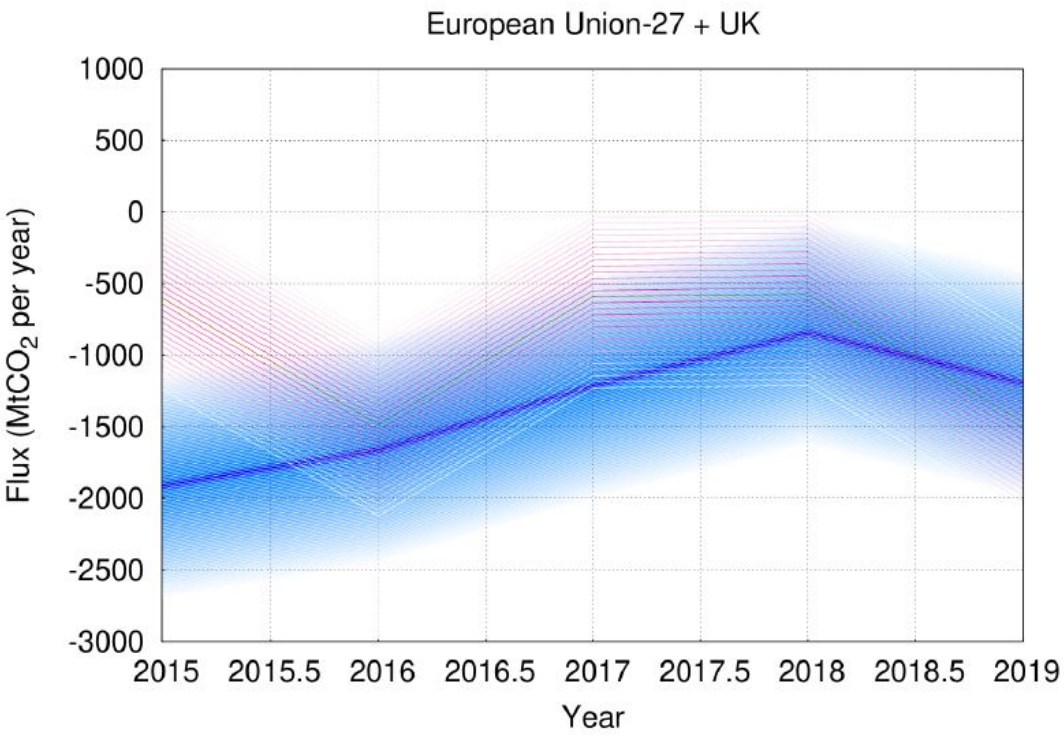
NEE estimates for 2019



T3.3 Inversion of NEE

Inversion using satellite OCO-2 data (LMDZ model)

Annual CO2 vegetation flux estimated by the 68% uncertainty envelope of the latest two CAMS inversions (blue for the surface-driven one and pink for the satellite-driven one) for the 27-member European Union and United Kingdom together. Positive values indicate a source of CO2 to the atmosphere.



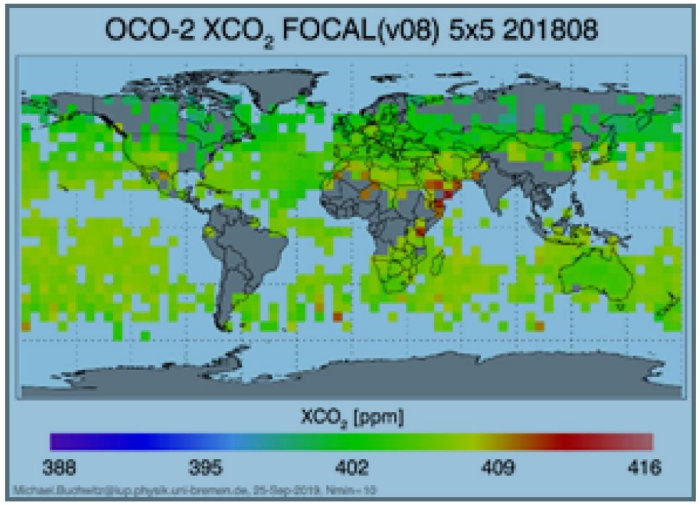
WP3 – Status of deliverables M19 - M36

D3.5	Second Bottom-up model simulations	CEA	31/12/2020	Submitted
D3.10	Community Inversion Framework (CIF)	CEA	31/1/2021	Submitted
D3.15	Ground based measurements of column CO2 in Russia and improved estimates of XCO2 from satellite data	KIT	31/7/2020	Submitted

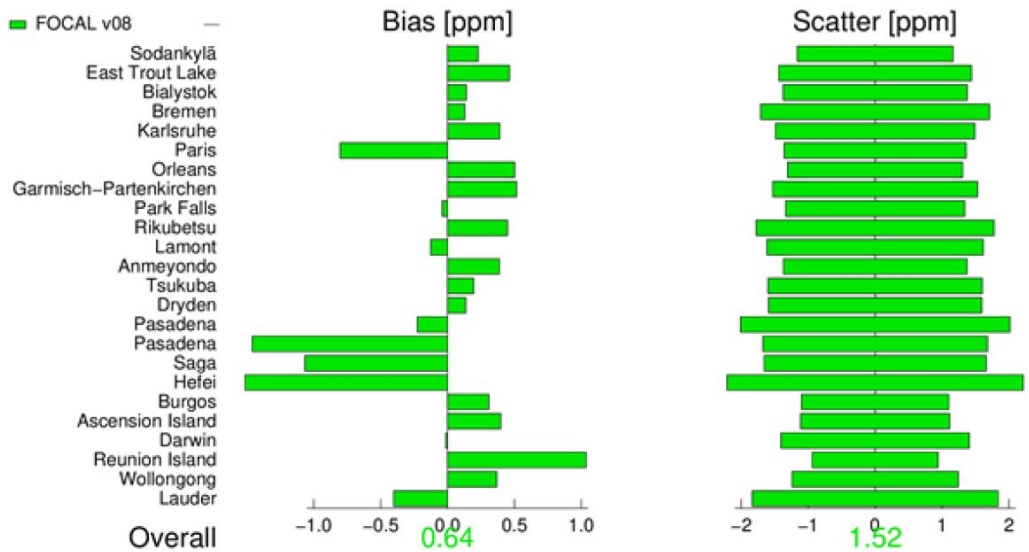
T3.4 Research need to reduce NEE uncertainties

OCO-2 satellite derived Column integrated CO2 conc.

Ex.: August 2018



Evaluation against TCCON data



⇒ Next step: Evaluation against campaign data in St Petersburgh

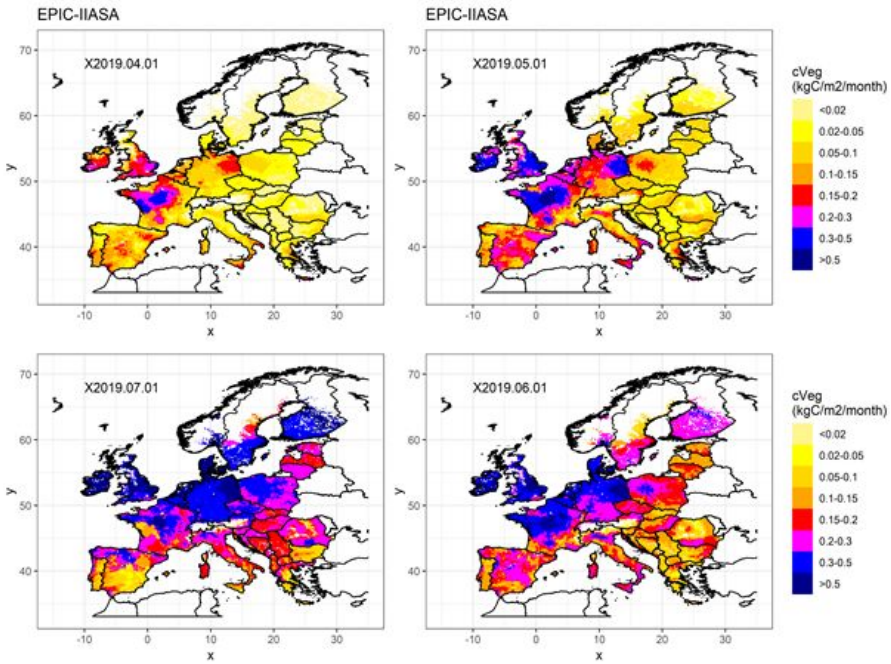
T3.2 EPIC crop model

VERIFY meteo data (CRUHAR v.3.1, 1981-2019)
VERIFY soil data
VERIFY land cover

Pan-European gridded model EPIC-IIASA

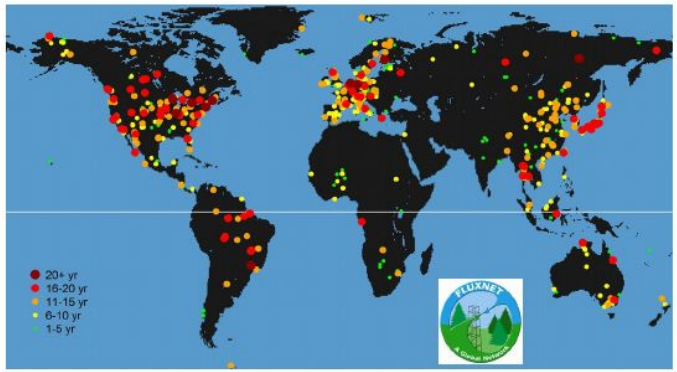
Variable	Unit	Description	Temporal aggregation
mrso	kg m^{-2} $month^{-1}$	Total Soil Moisture Content	1st day of month
mrro	kg m^{-2} $month^{-1}$	Total Runoff, Drainage, and Subsurface Runoff	Monthly sum of daily fluxes
evapotrans	kg m^{-2} $month^{-1}$	Total Evapo-Transpiration	Monthly sum
cVeg	kg C m^{-2} $month^{-1}$	Carbon in Vegetation	1st day of month
cLitter	kg C m^{-2} $month^{-1}$	Carbon in Litter	Monthly sum
cSoil	kg C m^{-2} $month^{-1}$	Carbon in Soil	1st day of month
npp	kg C m^{-2} $month^{-1}$	Net Primary Production - total	Monthly sum
npp(a)	kg C m^{-2} $month^{-1}$	Net Primary Production – aboveground	Monthly sum
npp(b)	kg C m^{-2} $month^{-1}$	Net Primary Production – belowground	Monthly sum
rh	kg C m^{-2} $month^{-1}$	Heterotrophic Respiration	Monthly sum
fHarvest	kg C m^{-2} $year^{-1}$	C Flux to Atmosphere from harvested crop biomass consumption	Last day of year
yoc	kg C m^{-2} $month^{-1}$	soil carbon loss with sediments (water erosion)	Monthly sum
clch	kg C m^{-2} $month^{-1}$	leached soluble carbon	Monthly sum

Monthly C stock and fluxes:

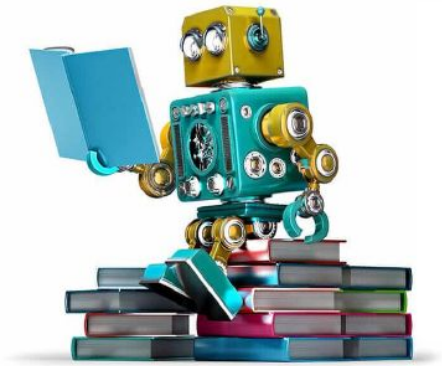


Regridded to VERIFY

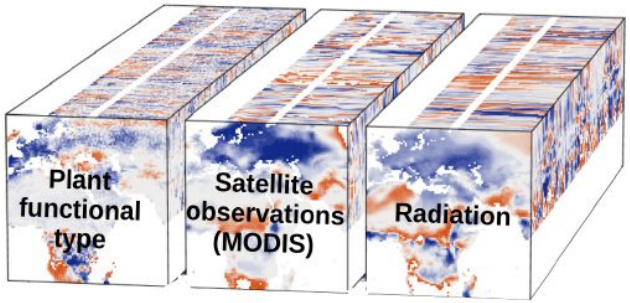
T3.2 FLUXCOM data – driven model (MPI)



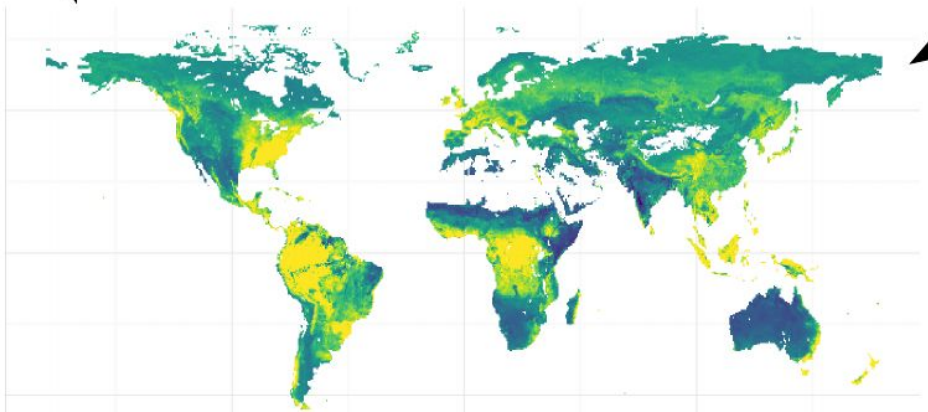
In-situ eddy-covariance carbon fluxes



machine learning



global gridded data sets of predictors



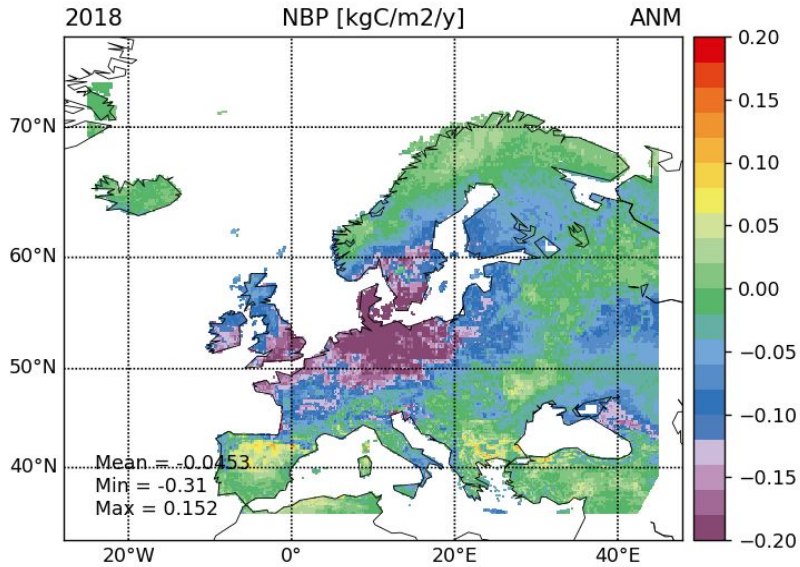
Global gridded estimates of carbon fluxes

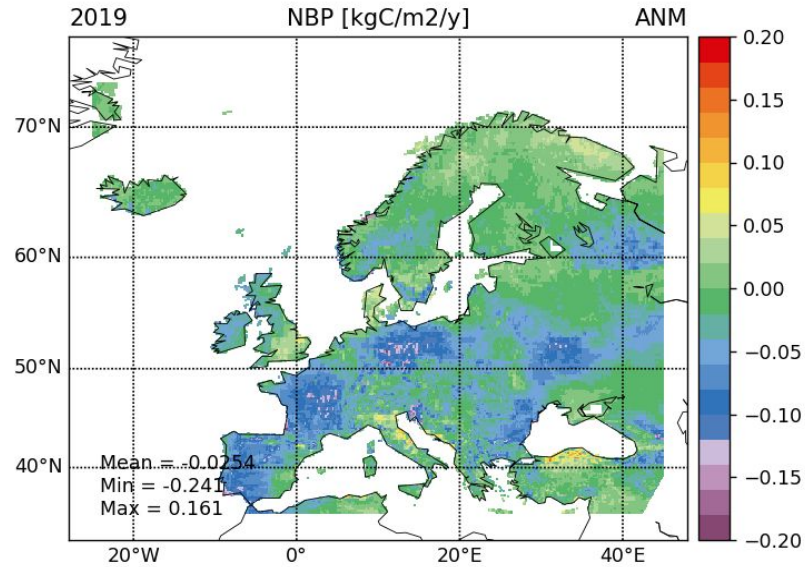
NEW and work in progress

- higher spatial resolution & subdaily
- extended and improved training and feature data sets
- new machine-learning methods

T3.2 Process-based : ORCHIDEE ecosystem model

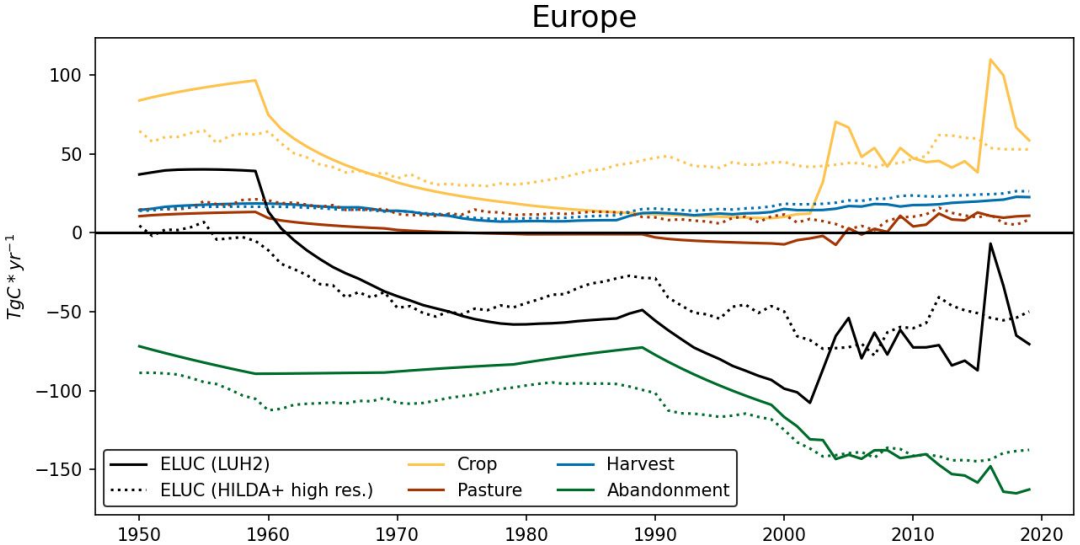
Drought effects (2018, 2019)

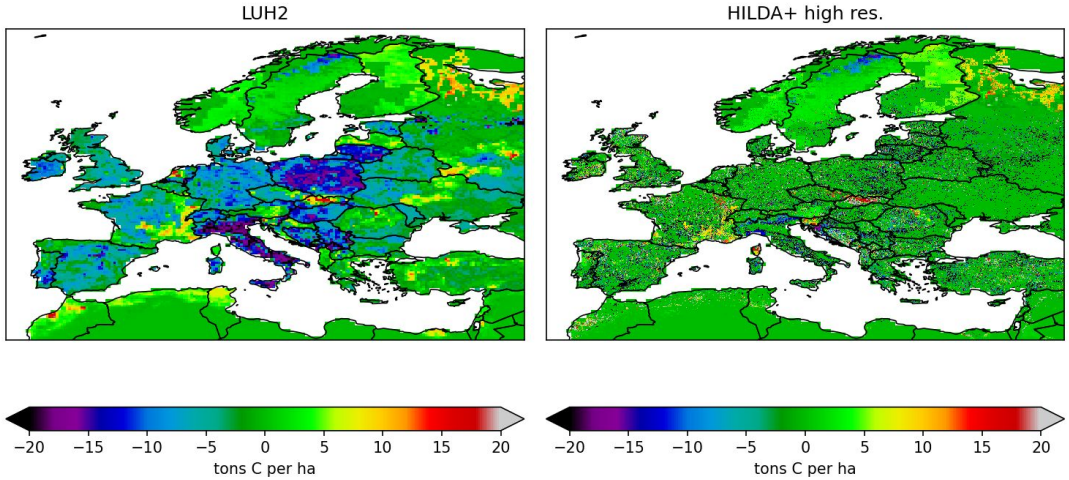




T3.2 Bookkeeping : land use flux model (BLUE)

- Implemented HILDA+ in BLUE
- Revised model setup for runs at 0.01° degrees (previously 0.25°)
- Total LULC emission estimates are comparable to runs based on LUH2 in size and trends for overall Europe but national differences exist
- Elimination of extreme values (i.e. 1960, 2015) in the BLUE runs based on HILDA+ suggests a higher reliability
- High resolution runs based on HILDA+ capture heterogeneity better and provide a more detailed picture of local sources and sinks





T3.2 Analysis of the drivers of CO2 fluxes

CROPLAND - SPAIN