ITINERIS

Why do we measure fluxes?

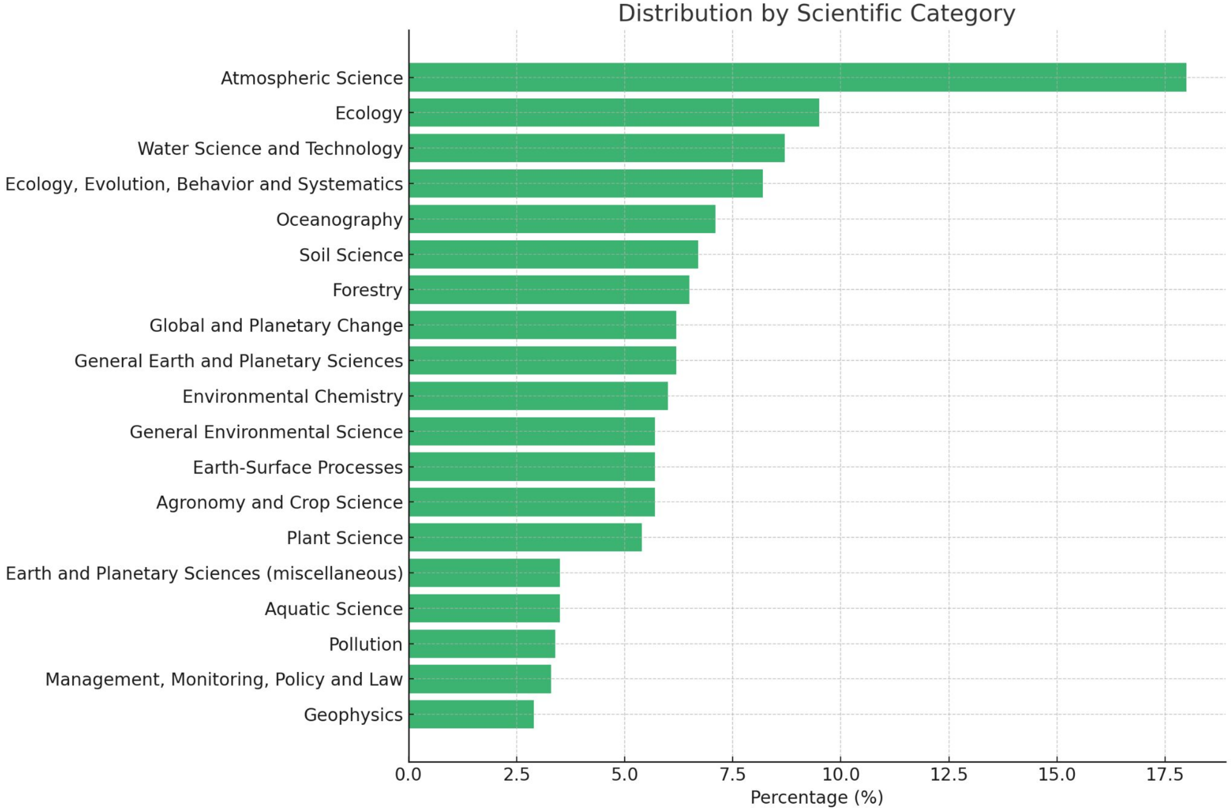
Module

- Marta Galvagno

IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-Mission 4 “Education and Research” - Component 2: “From research to business” - Investment 3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”

Finanziato dall'Unione europea NextGenerationEU
Ministero dell’Università e della Ricerca
Italiadomani

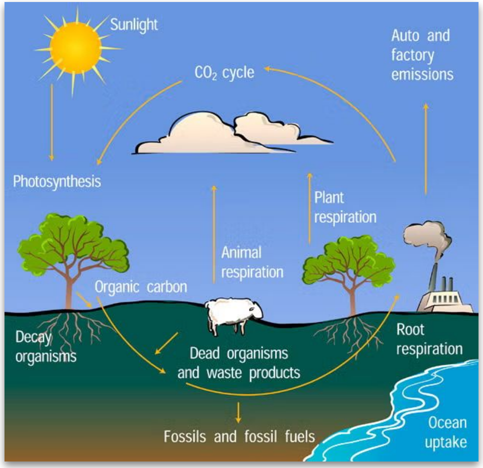
Eddy covariance fields



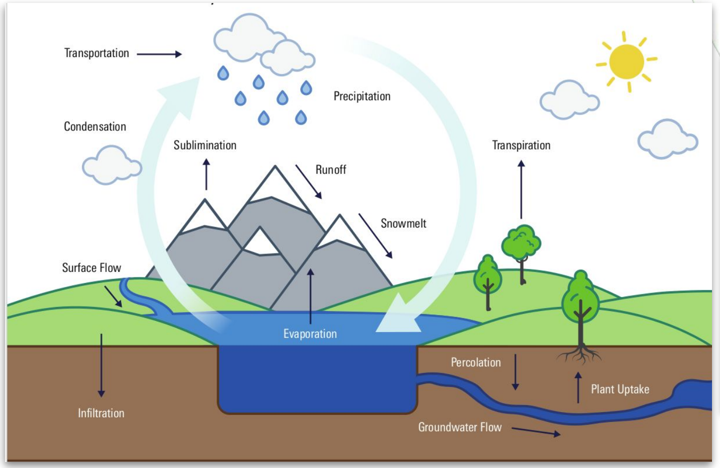
1. **Why do we measure fluxes?**
2. Key ecosystem processes (carbon cycle, NEE, Reco, GPP) and drivers
3. Time scales
4. Applications and Examples
5. Policy

Fluxes

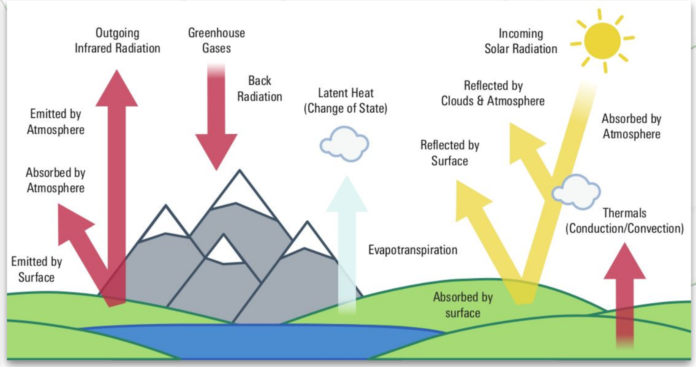
CARBON CYCLE



WATER CYCLE



ENERGY BUDGET



Burba, G., 2022. LI-COR Biosciences

Sources ⟷ Sinks

35.2 GtCO$_2$/yr

89%

4.5 GtCO2/yr

11%

19.1 GtCO2/yr

48%

11.4 GtCO2/yr

29%

10.5 GtCO2/yr

26%

Source: [Friedlingstein et al 2022](); [Global Carbon Project 2022]()

Sources ⟷ Sinks

35.2
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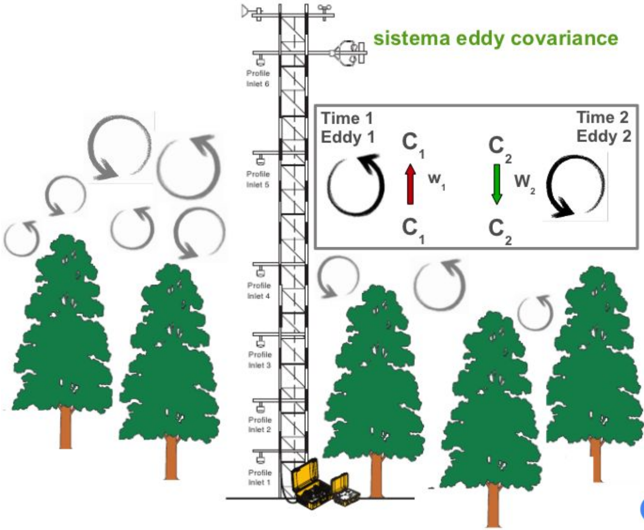
Source: Friedlingstein et al 2022; Global Carbon Project 2022

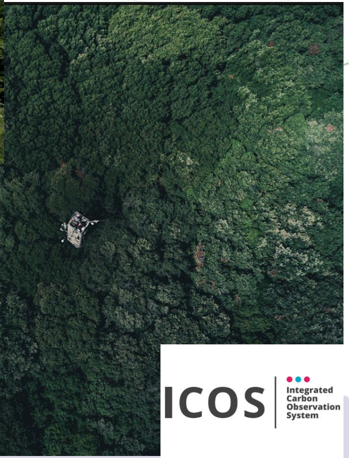
INVITED RESEARCH REVIEW

Global Change Biology WILEY

How eddy covariance flux measurements have contributed to our understanding of *Global Change Biology*

Dennis D. Baldocchi

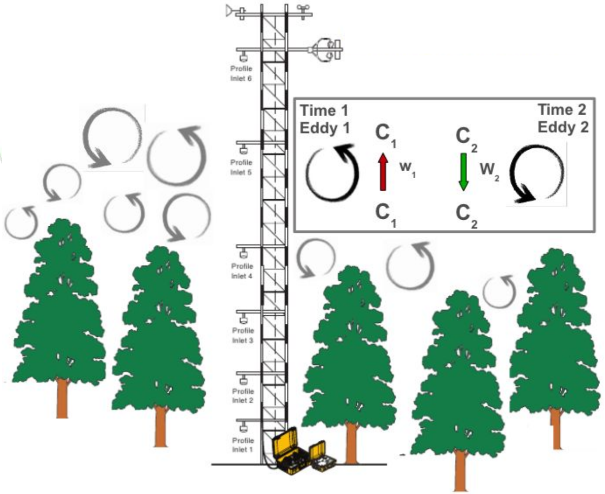




Google Scholar :about 211,000 results

Flux towers

- Flux towers measure the **gas exchange** between the **vegetation** and the atmosphere
- **Ecosystem scale**, no disturbance, continuous with 30 minutes time resolution



Eddy covariance fields

- Micrometeorology & Atmospheric Science
- Ecosystem Ecology & Biogeochemistry
- Hydrology and Water Resources
- Climate Science & Earth System Science
- Validation and Calibration of Remote Sensing & Models
- Agricultural Science
- Land Management, Forestry
- Urban and Applied Environmental Research
- Policy (eg. MRT)

1. Why do we measure fluxes?
2. **Key ecosystem processes and drivers**
3. Time scales
4. Applications and Examples
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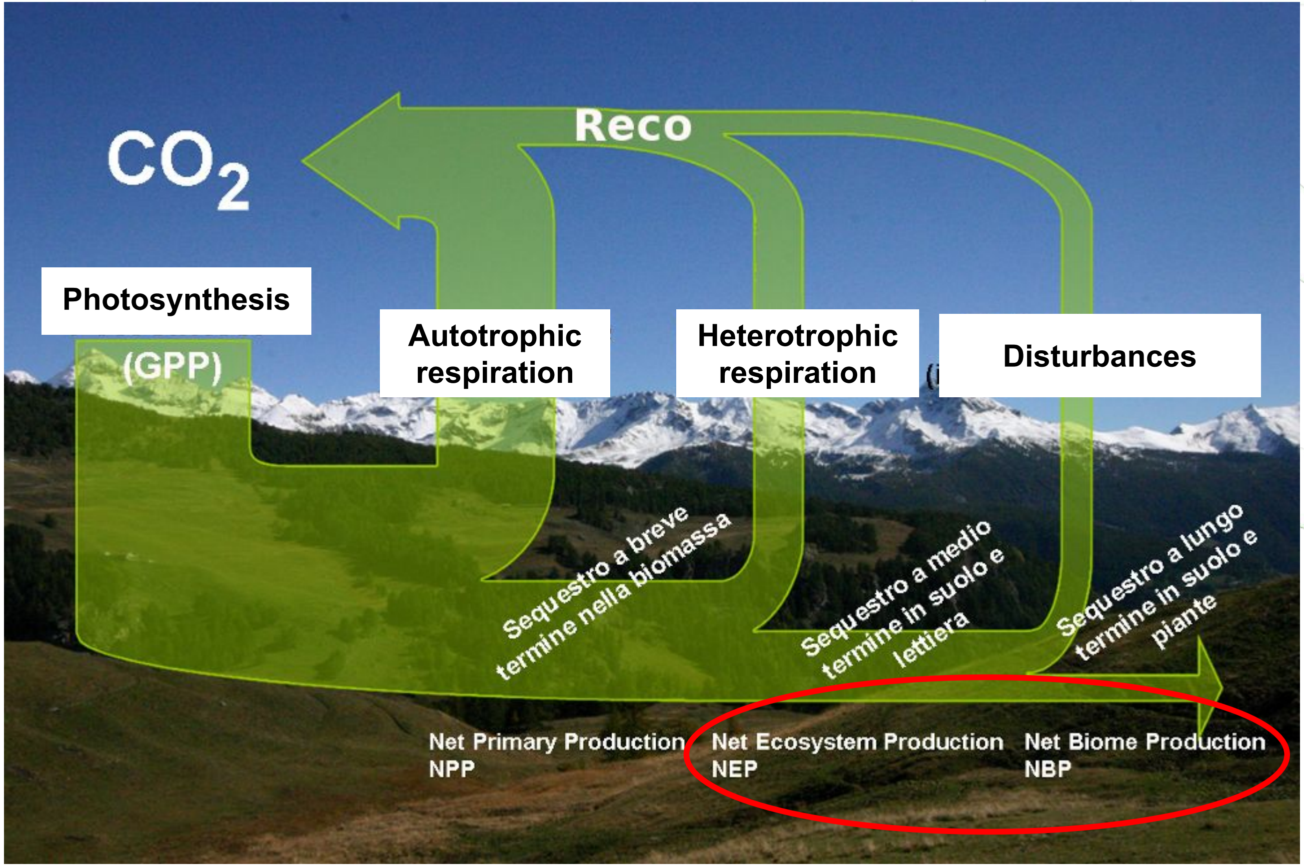
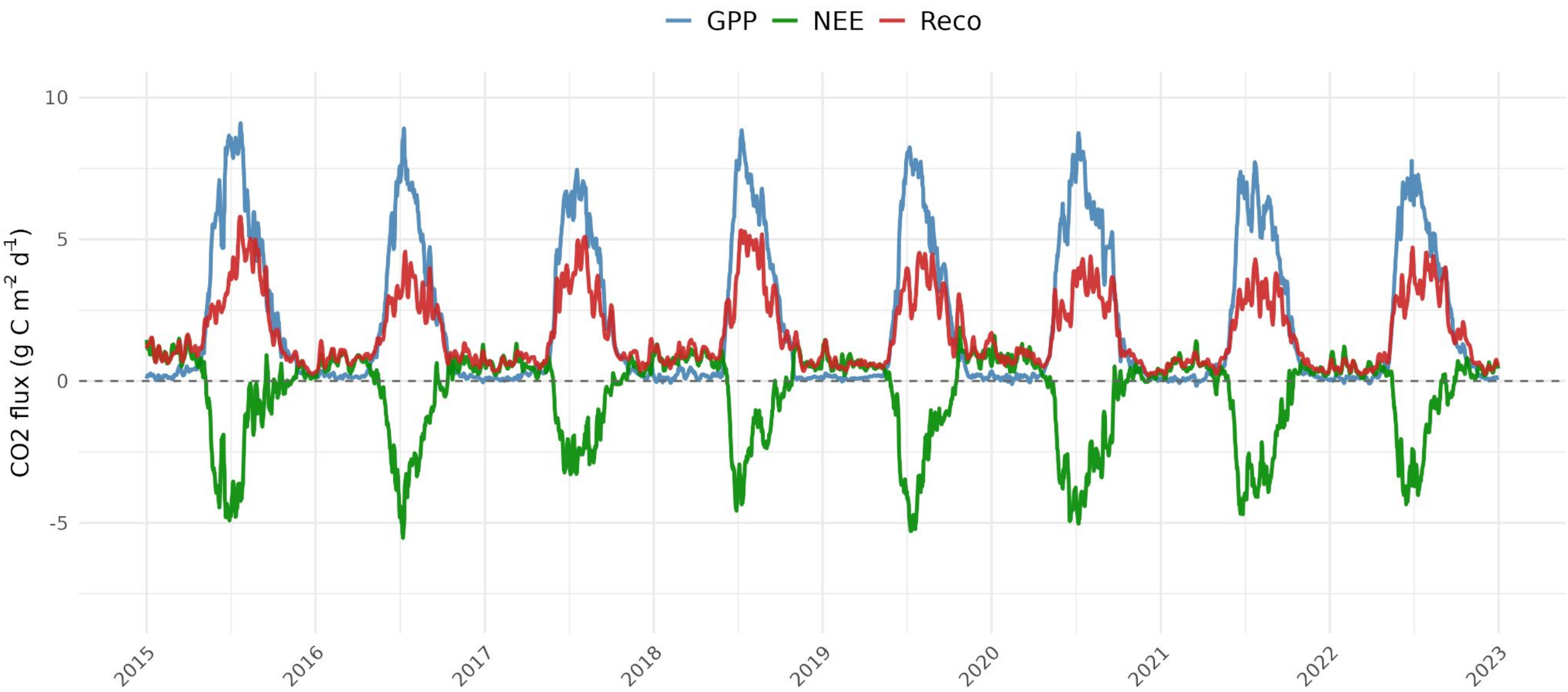
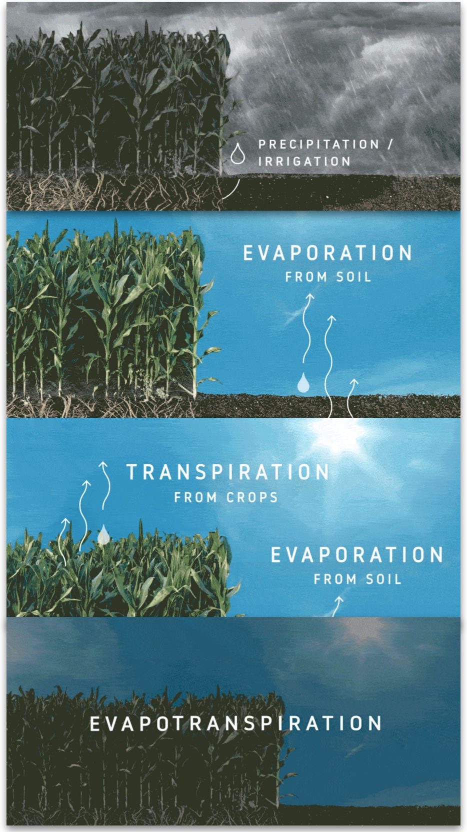
Key ecosystem processes

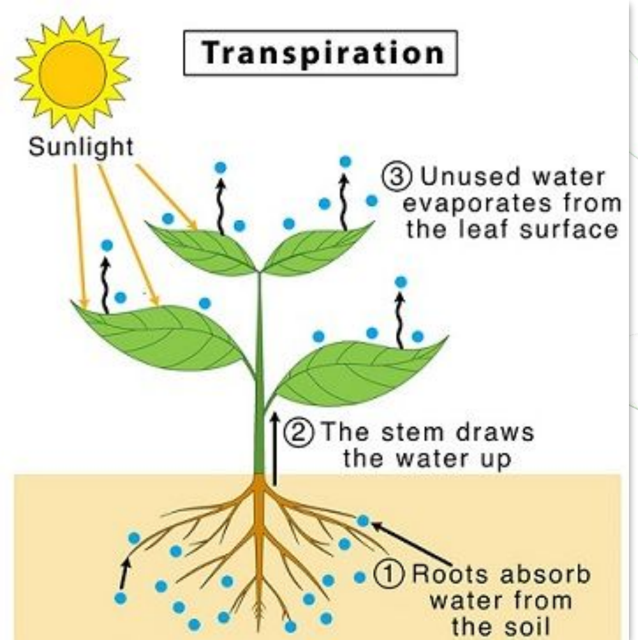


Key ecosystem processes



Key ecosystem processes





Drivers

1. Environmental Drivers

Light

Temperature

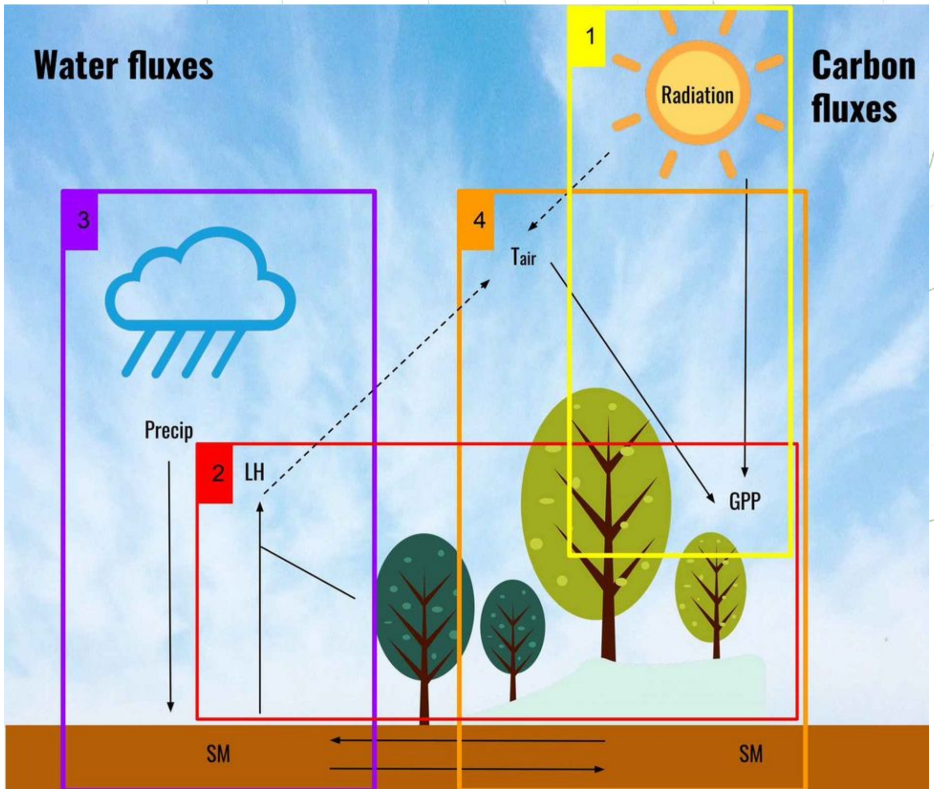
Rainfall and soil moisture

Climate Change and extremes

2. Biological and Structural Drivers

Phenology

Structural and functional traits

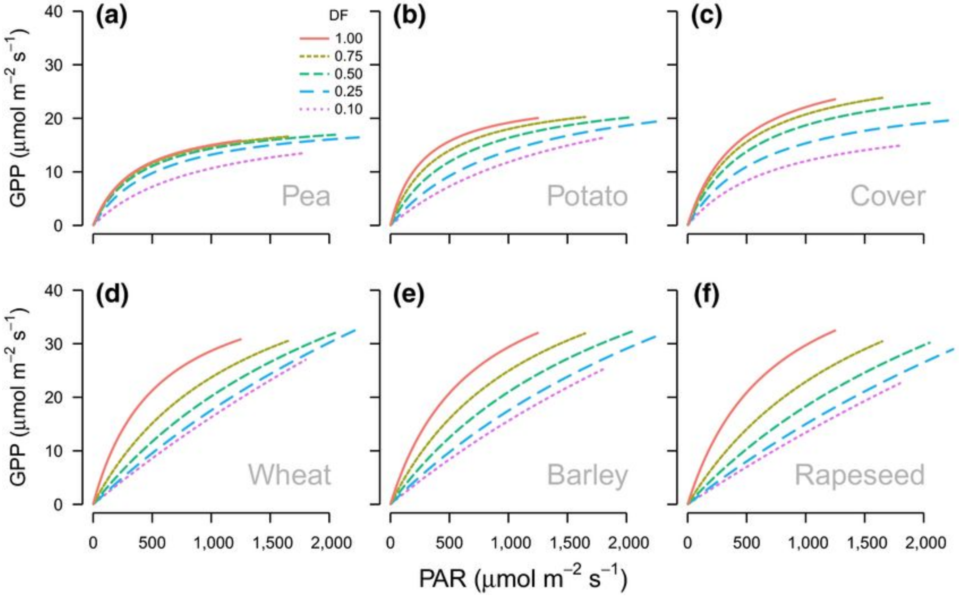


Díaz et al 2022 Scientific reports

Drivers

Light

- GPP does not increase linearly with light; it saturates at high irradiance levels -> not as simple as first thought
- Photosynthetic efficiency improves under diffuse light (e.g., clouds, aerosols).

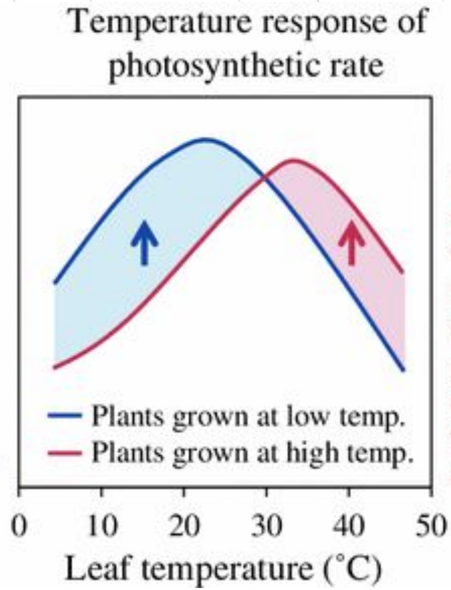


Emmel et al. 2020 - GCB

Drivers

Temperature

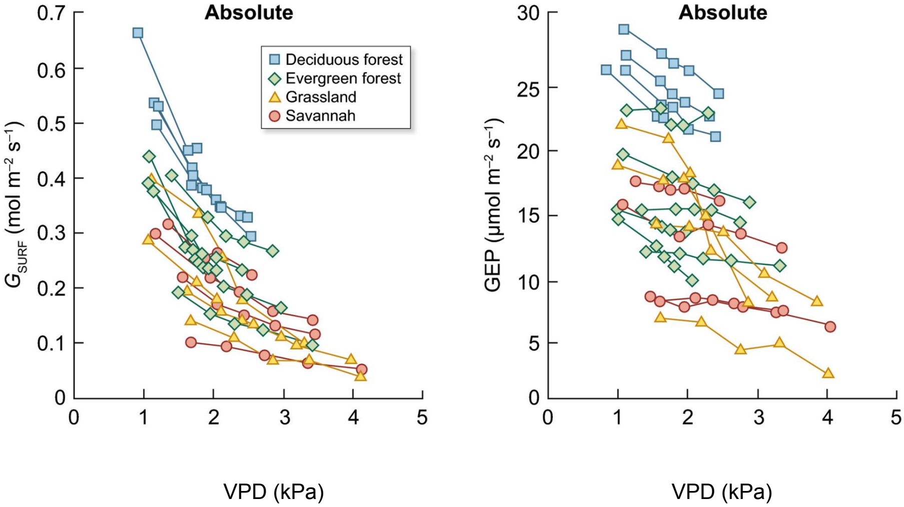
- Photosynthesis peaks at specific temperatures and acclimates to local conditions.
- Respiration increases with temperature (Q10 ~ 1.4) but is modulated by phenology, LAI, and water availability.



Drivers

Atmospheric and Soil Moisture

- Water scarcity limits GPP and Reco (via stomatal closure and microbial stress).

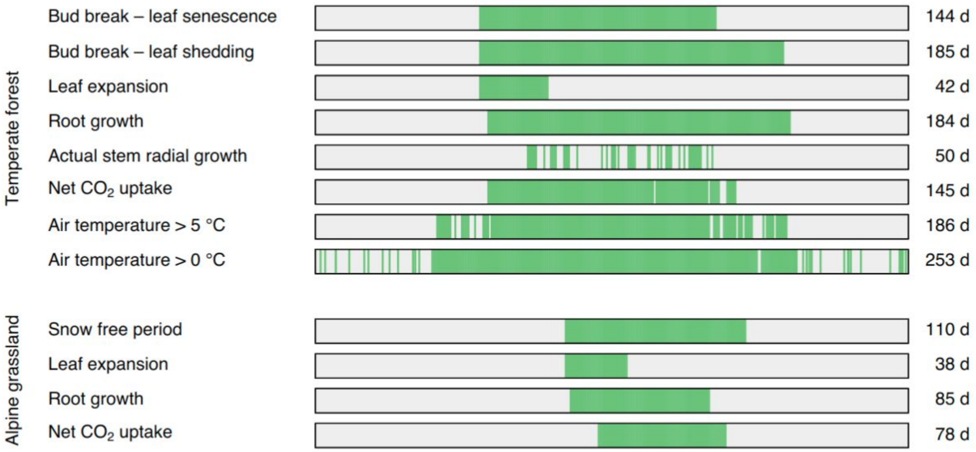


Grossiord et al 2019 New Phytologist

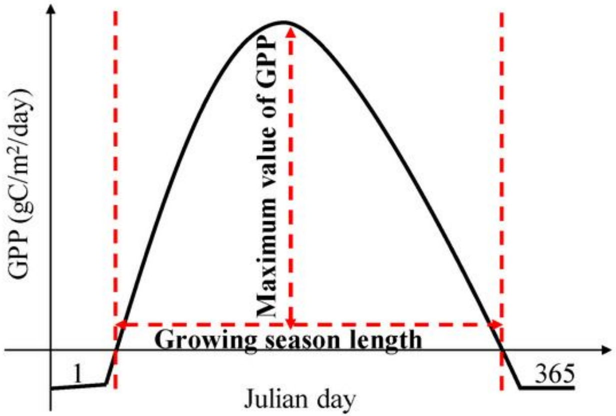
Drivers

Phenology

- The length of the growing season is a determinant of the total annual C sink



Korner et al 2023 Ecology letters



Lv et al 2023 Forests

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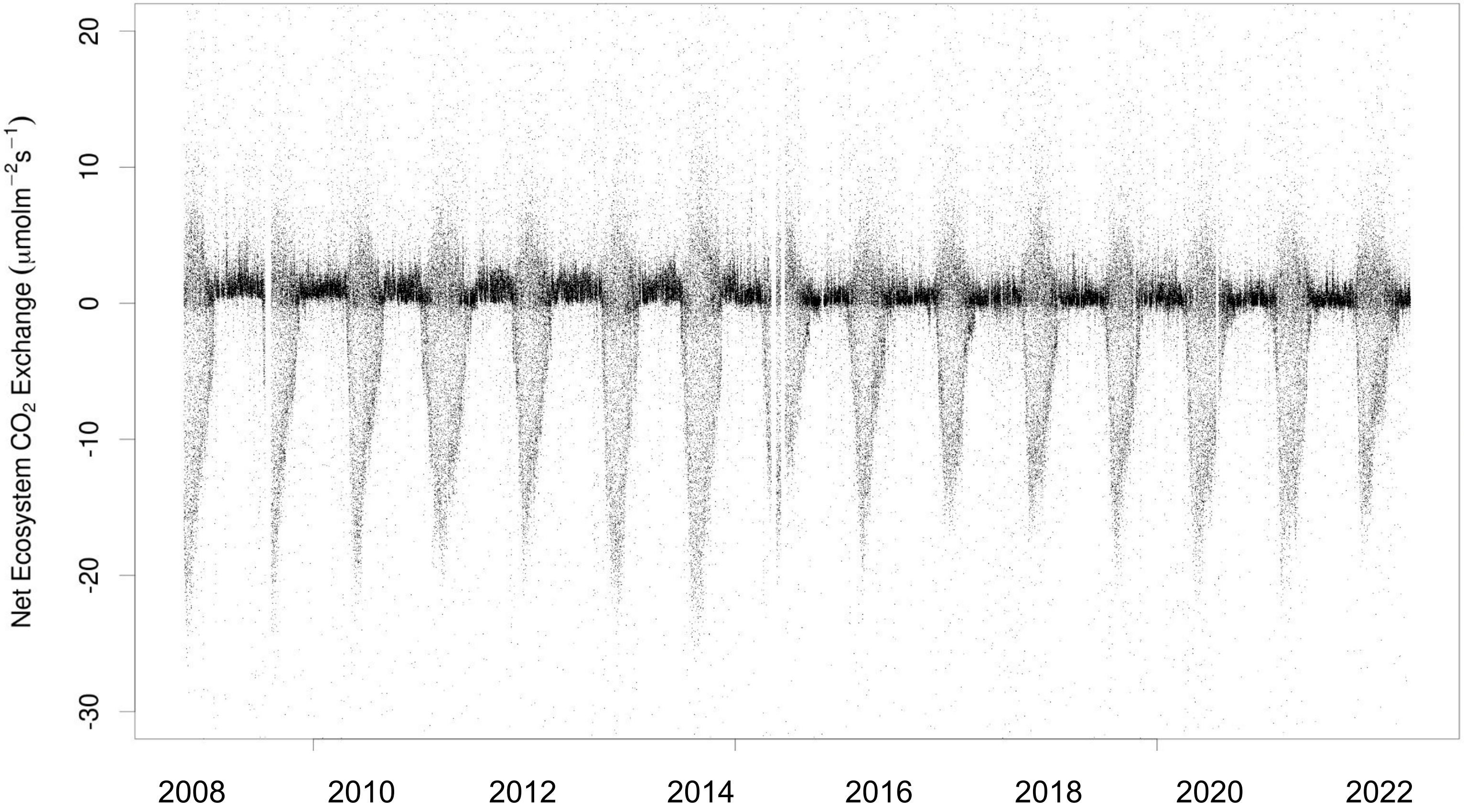
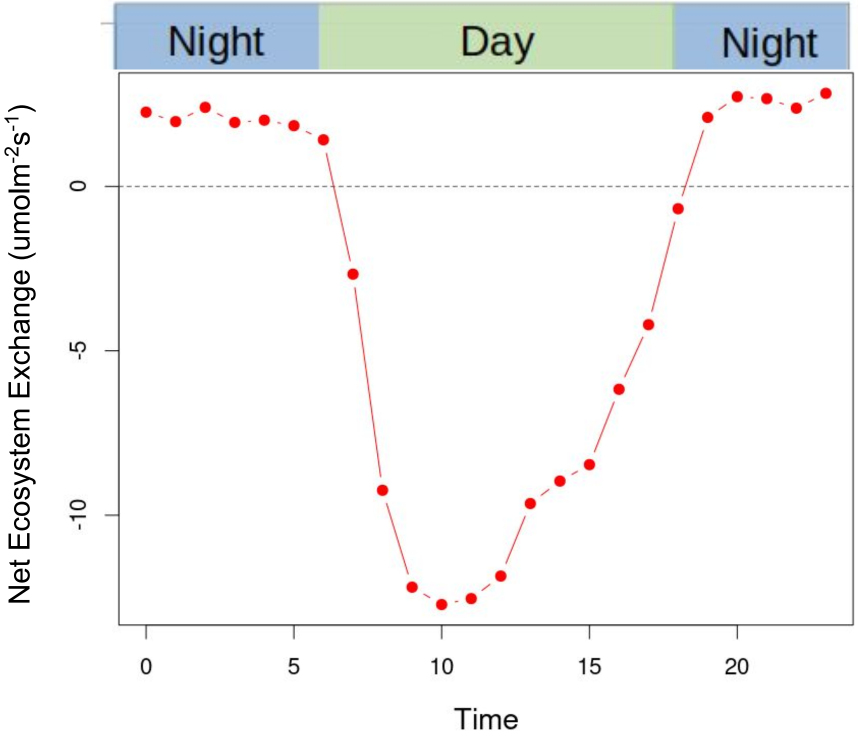
Half-hourly data



CO2 Emission

CO2 uptake

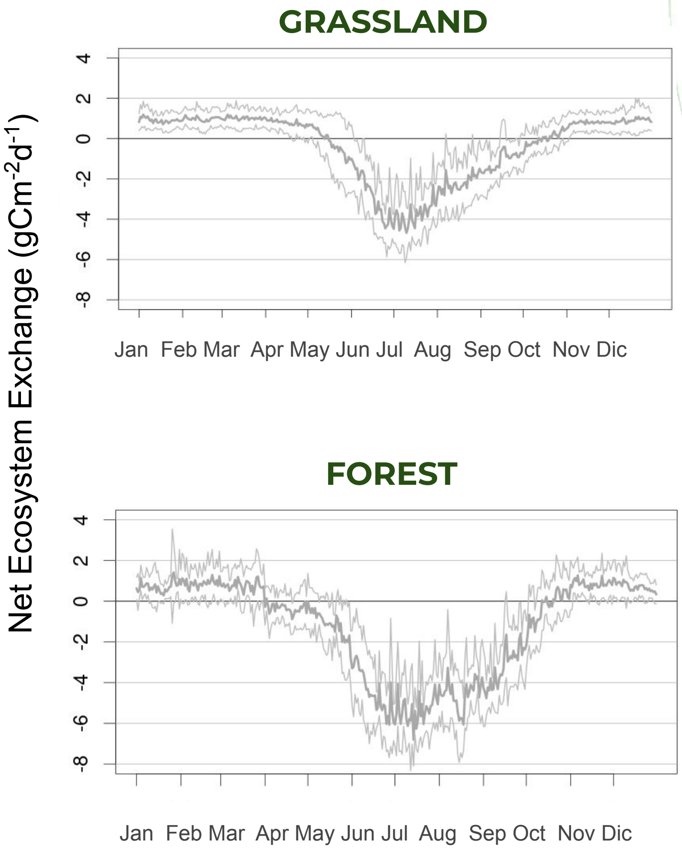
Diurnal cycle

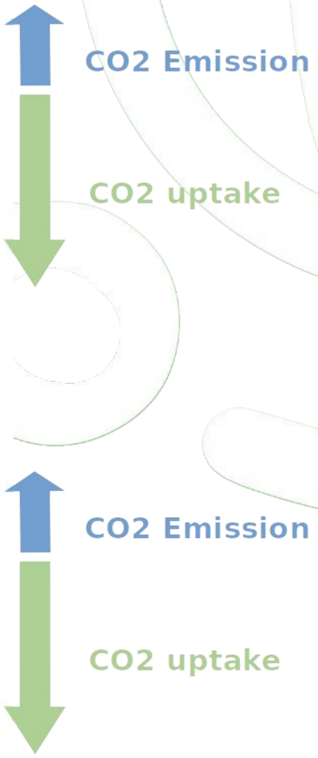


CO2 Emission

CO2 uptake

Seasonal cycle





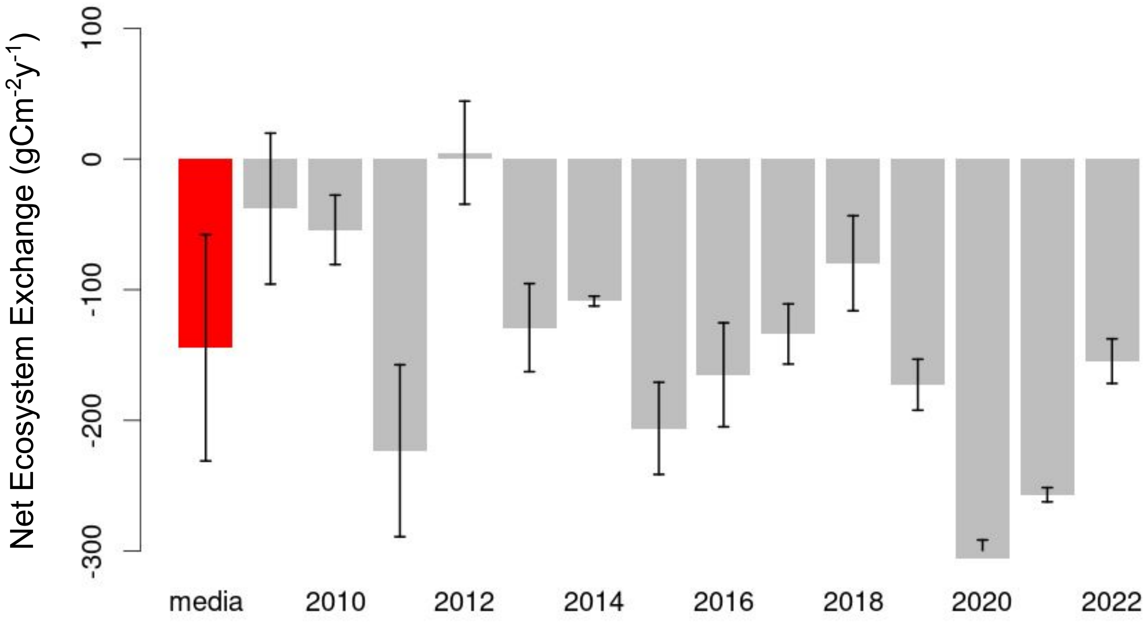
CO2 Emission

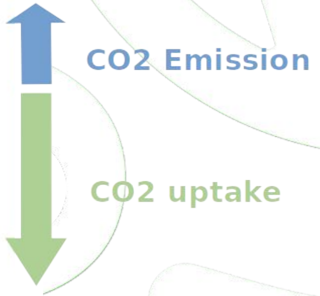
CO2 uptake

CO2 Emission

CO2 uptake

Interannual variations





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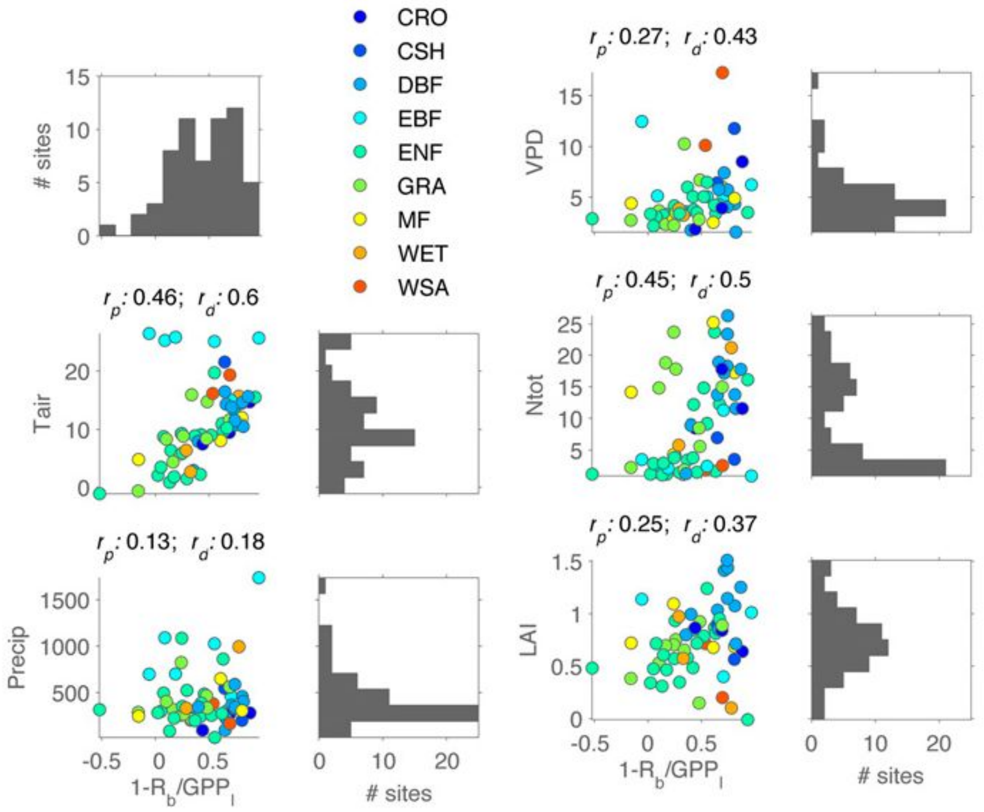
Understanding Ecosystem Metabolism

How ecosystem metabolism responds to a wide range of biophysical drivers, including:

- **Light, temperature, rainfall, soil moisture, atmospheric CO_2**
- **CUE, WUE**
- Phenology and seasonal dynamics



Migliavacca et al. 2021 - Nature

Reichstein et al. 2014 - Pnas

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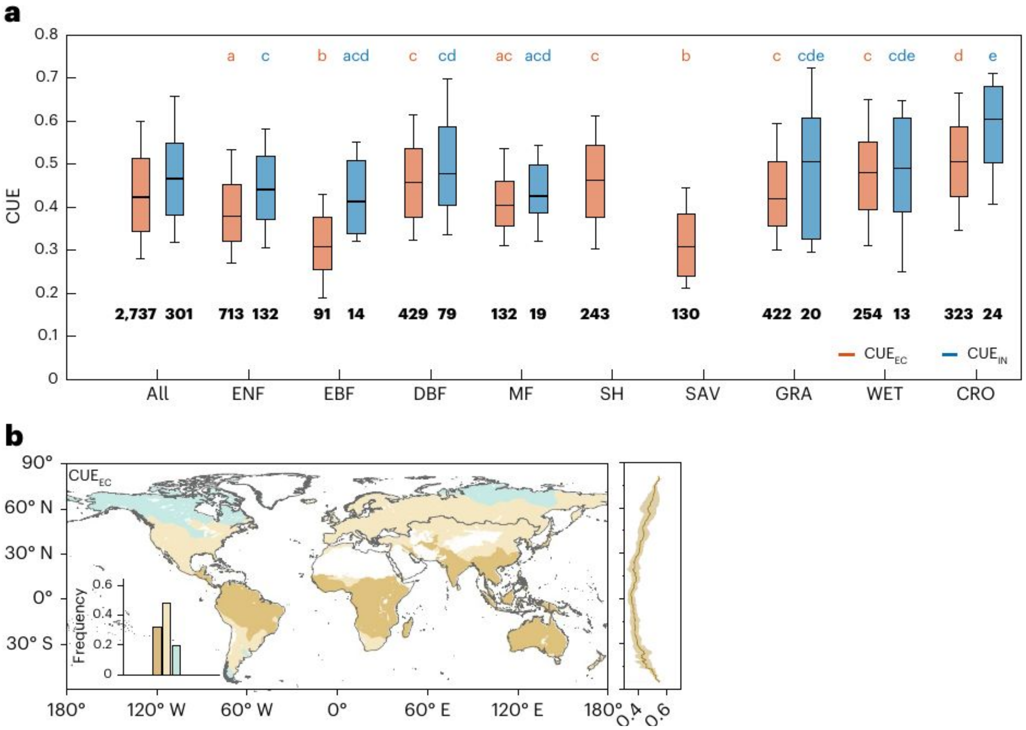

Luo et al. 2025 - Nature Ecology and Evolution

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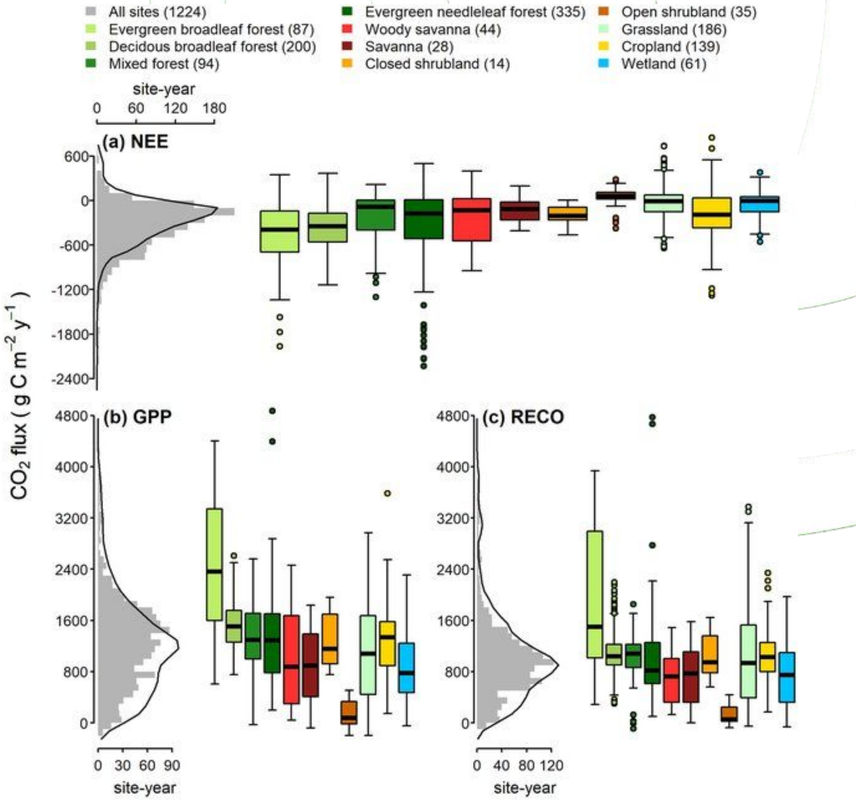
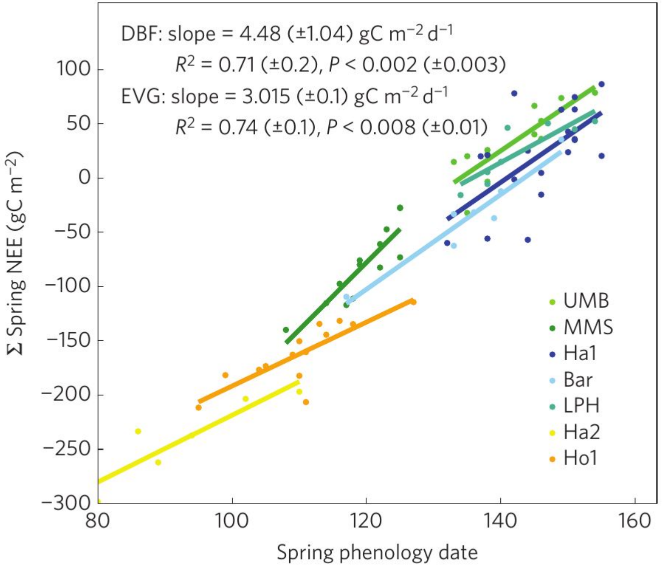


Pastorello et al 2020 - Scientific data

Tracking Long-Term Environmental Change

Long-term flux records (decadal scale) are key to understanding how ecosystems respond to trends in the environment:

- Rising CO_2 and global warming
- Changes in precipitation and soil water availability
- Nitrogen deposition
- **Shifts in phenology**
- Land-use change and management practices



Keenan et al. 2014 - Nature Climate Change

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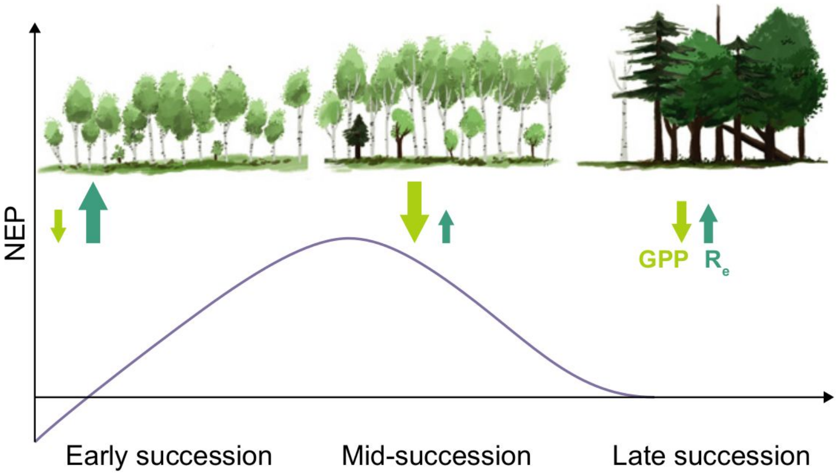
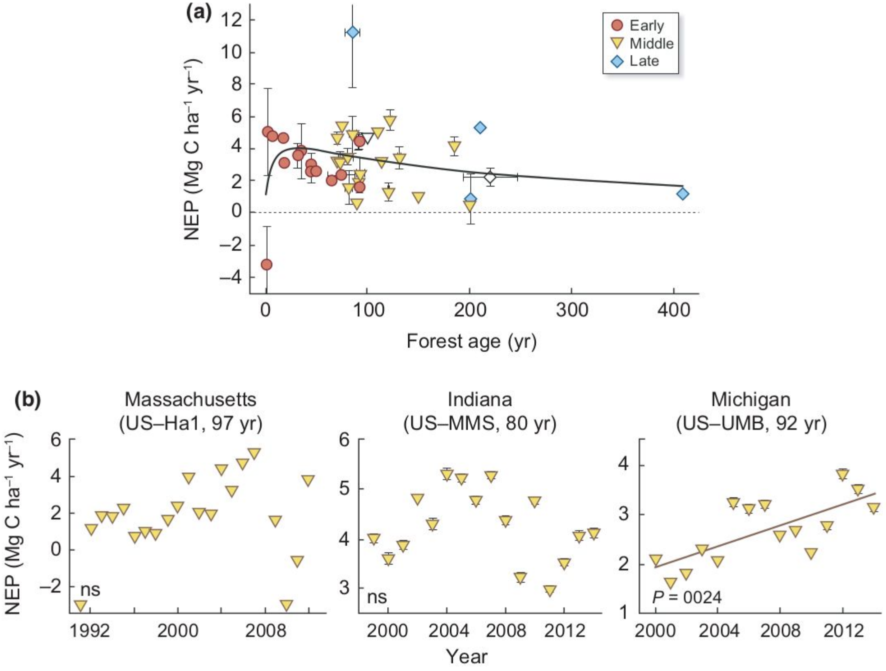
Tracking Long-Term Environmental Change

- **Land-use change**

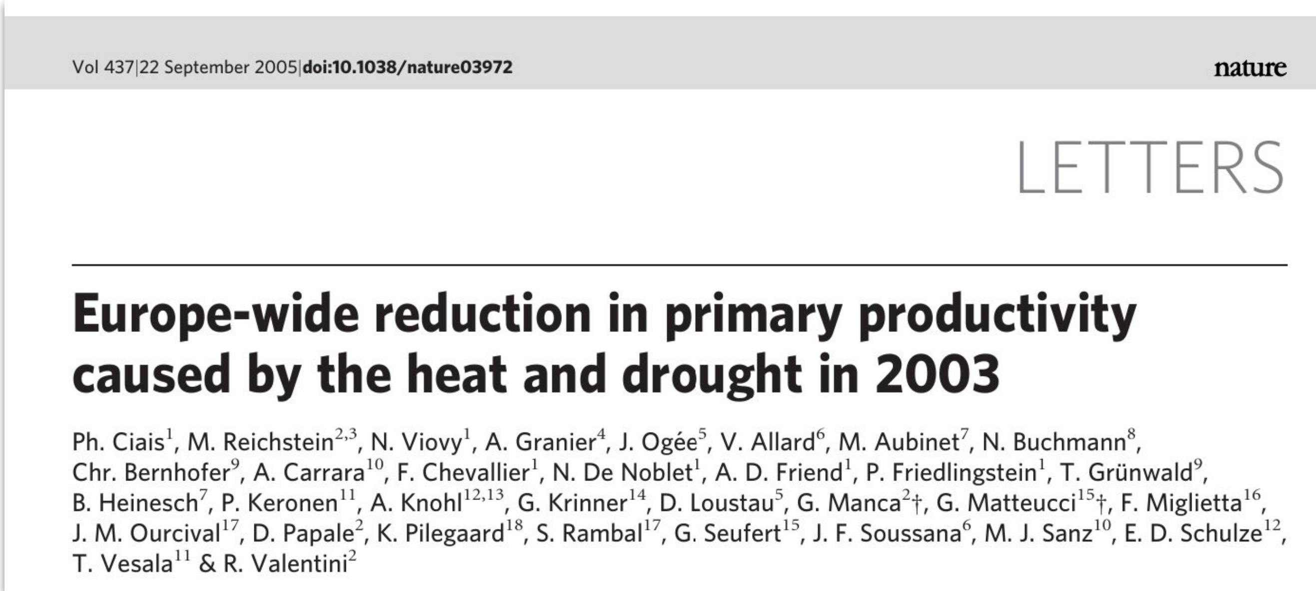




Curtis et al. 2018 - New Phytologist

Capturing Extreme Events

Continuous measurements allow detection of short-term disturbances like: heatwaves, droughts, storms, insect and parasite outbreaks offering insights into ecosystem resilience and recovery.



Vol 437|22 September 2005|**doi:10.1038/nature03972** **nature**

LETTERS

Europe-wide reduction in primary productivity caused by the heat and drought in 2003

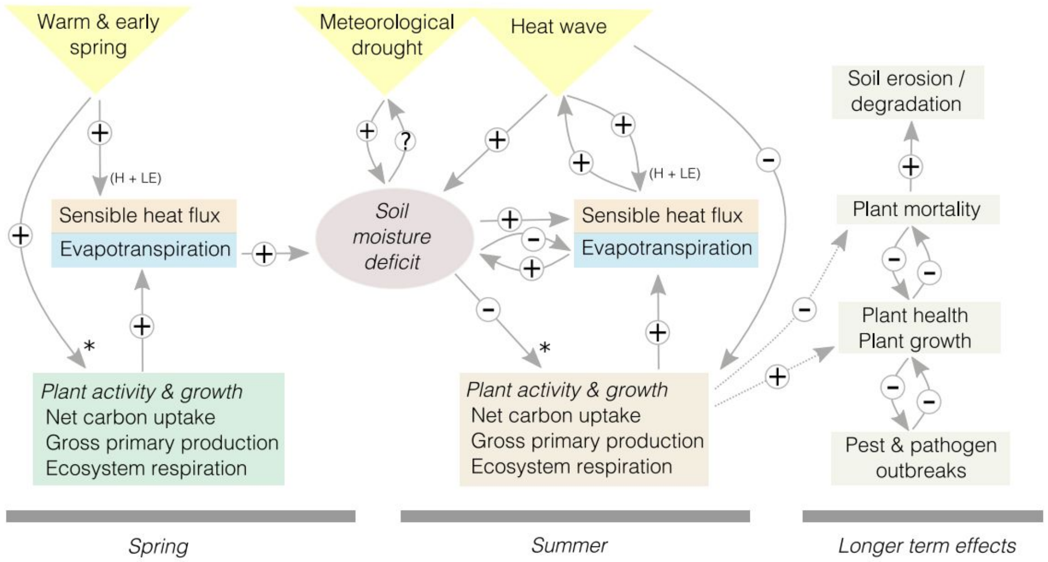
Ph. Ciais[1], M. Reichstein[2,3], N. Viovy[1], A. Granier[4], J. Ogée[5], V. Allard[6], M. Aubinet[7], N. Buchmann[8], Chr. Bernhofer[9], A. Carrara[10], F. Chevallier[1], N. De Noblet[1], A. D. Friend[1], P. Friedlingstein[1], T. Grünwald[9], B. Heinesch[7], P. Keronen[11], A. Knohl[12,13], G. Krinner[14], D. Loustau[5], G. Manca[2]†, G. Matteucci[15]†, F. Miglietta[16], J. M. Ourcival[17], D. Papale[2], K. Pilegaard[18], S. Rambal[17], G. Seufert[15], J. F. Soussana[6], M. J. Sanz[10], E. D. Schulze[12], T. Vesala[11] & R. Valentini[2]

Capturing Extreme Events

Extreme weather events will become more **frequent** and more **intense**

- Different ecosystem have different
- **resistance** and **resilience** potential

- **Timing** and **phenology** have a crucial role



Warm & early spring

Meteorological drought

Heat wave

Soil erosion / degradation

(H + LE)

Sensible heat flux

Evapotranspiration

Soil moisture deficit

(H + LE)

Sensible heat flux

Evapotranspiration

Plant mortality

Plant health

Plant growth

Plant activity & growth

Net carbon uptake

Gross primary production

Ecosystem respiration

Plant activity & growth

Net carbon uptake

Gross primary production

Ecosystem respiration

Pest & pathogen outbreaks

Spring

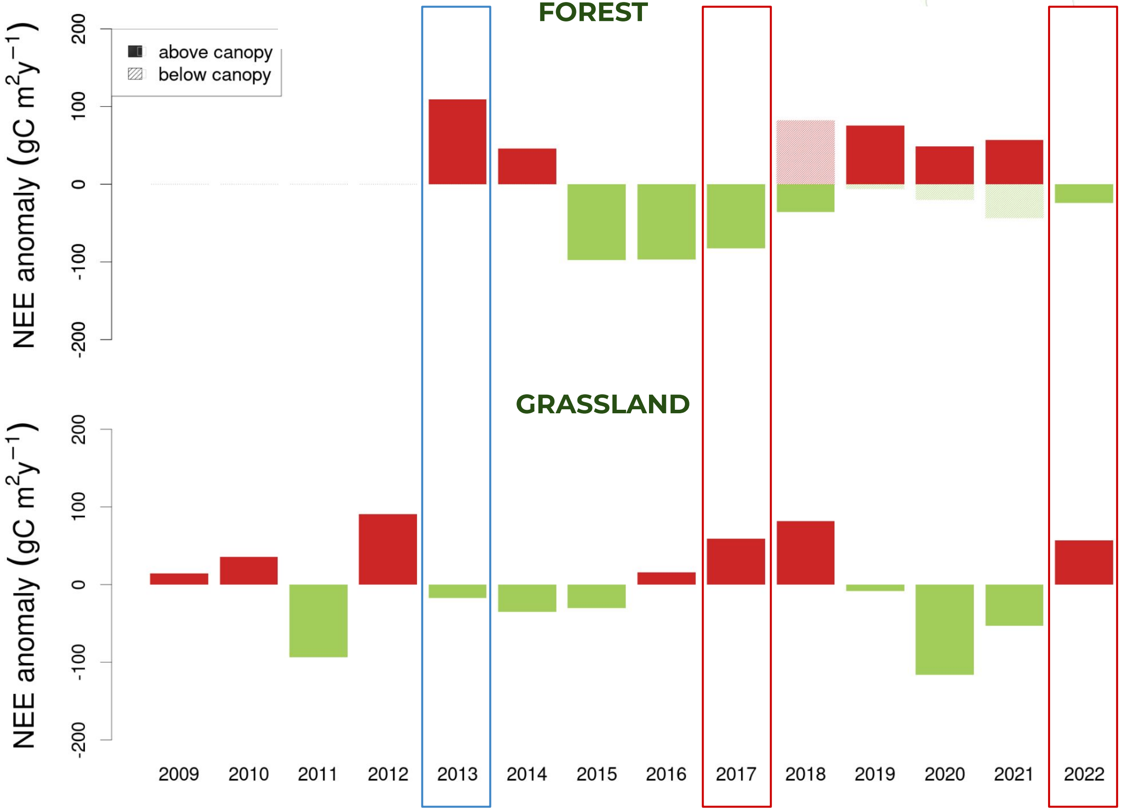
Summer

Longer term effects

* Climate effects on ecosystem carbon fluxes are shown only in qualitative terms. Individual fluxes might be affected differently by climate extremes (see text).

Sippel et al. (2016) Proceedings of the National Academy of Sciences

Capturing Extreme Events



2017-2022 warm and **dry** years

2013 cold and **wet** years.

During warm/drier years:

Forest:
higher CO2 uptake
Grassland:
Lower CO2 uptake

Capturing Extreme Events

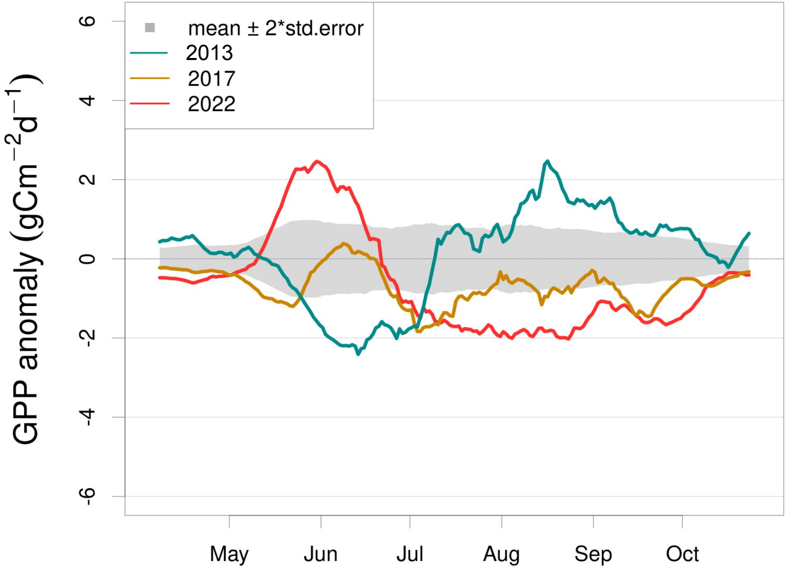
2017:
VPD + 25 %
TA + 0.6 °C

2022:
VPD + 11 %
TA + 1.5 °C

GRASSLAND

Growing phase

Decreasing phase

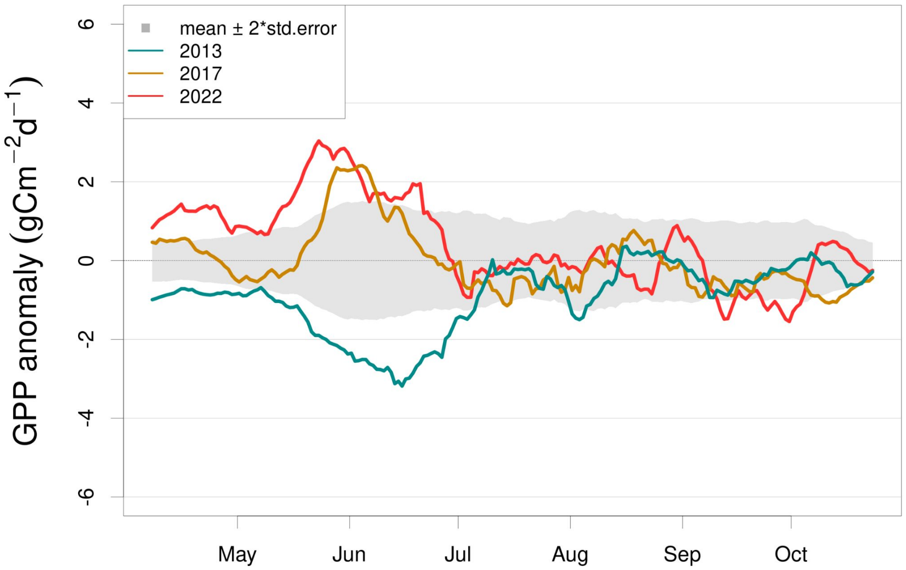


FOREST

Needle elongation

Full needle formation

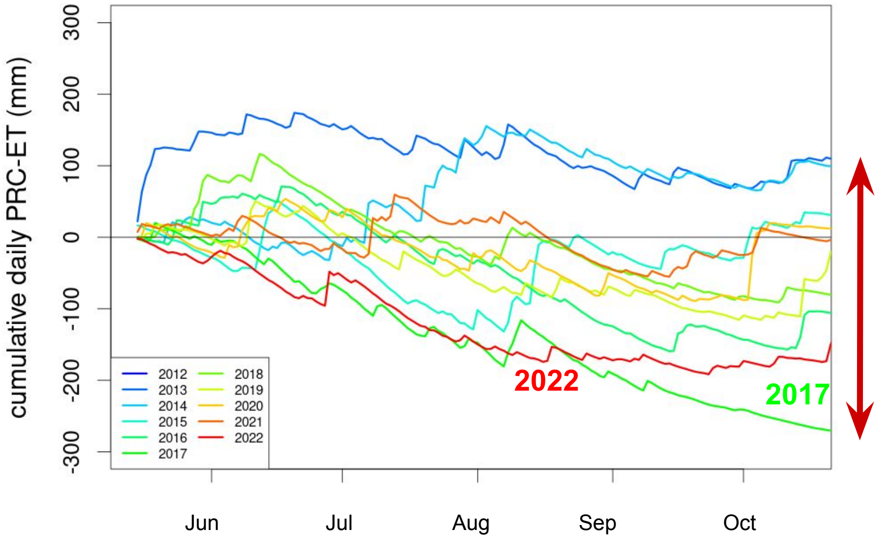
Senescence



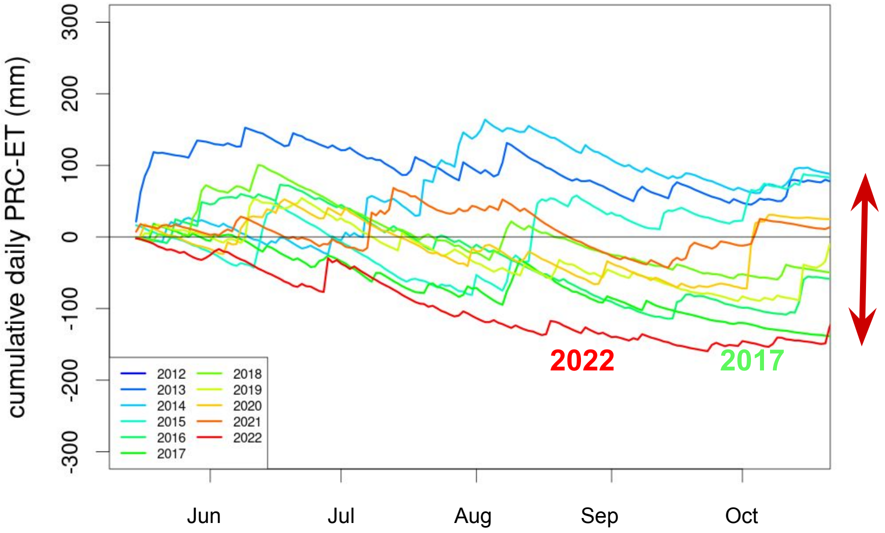
Capturing Extreme Events

2022 has lower **SWC** values compared to **2017**

GRASSLAND



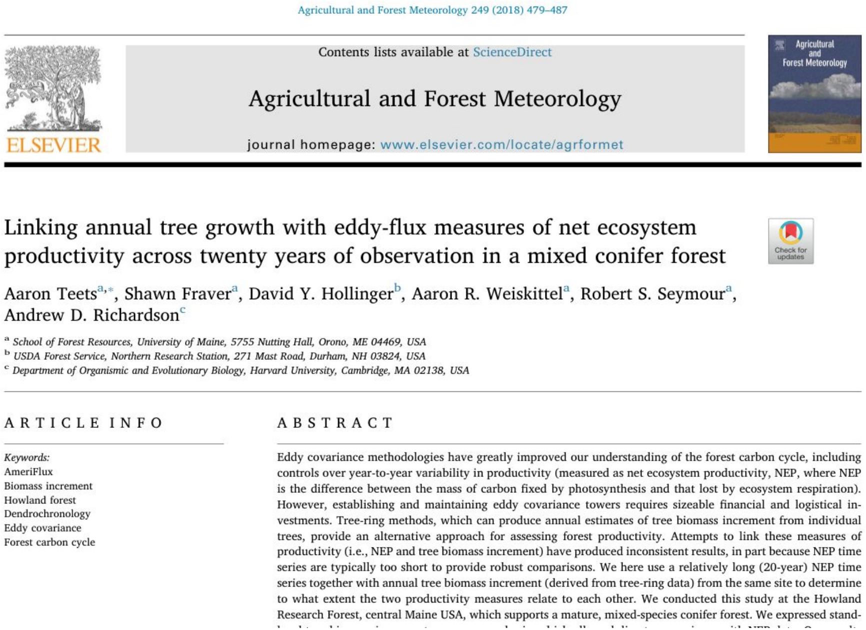
FOREST



Experimental Applications

When combined with other methods, control/treatment designs or along environmental gradients, flux measurements can be used to test specific hypotheses related to:

- Carbon pools
- Soil dynamics
- Nitrogen
- Biodiveristy
- .....



Agricultural and Forest Meteorology 249 (2018) 479–487

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Linking annual tree growth with eddy-flux measures of net ecosystem productivity across twenty years of observation in a mixed conifer forest

Aaron Teets[a,*], Shawn Fraver[a], David Y. Hollinger[b], Aaron R. Weiskittel[a], Robert S. Seymour[a], Andrew D. Richardson[c]

[a] *School of Forest Resources, University of Maine, 5755 Nutting Hall, Orono, ME 04469, USA*
[b] *USDA Forest Service, Northern Research Station, 271 Mast Road, Durham, NH 03824, USA*
[c] *Department of Organismic and Evolutionary Biology, Harvard University, Cambridge, MA 02138, USA*

ARTICLE INFO

Keywords:
AmeriFlux
Biomass increment
Howland forest
Dendrochronology
Eddy covariance
Forest carbon cycle

ABSTRACT

Eddy covariance methodologies have greatly improved our understanding of the forest carbon cycle, including controls over year-to-year variability in productivity (measured as net ecosystem productivity, NEP, where NEP is the difference between the mass of carbon fixed by photosynthesis and that lost by ecosystem respiration). However, establishing and maintaining eddy covariance towers requires sizeable financial and logistical investments. Tree-ring methods, which can produce annual estimates of tree biomass increment from individual trees, provide an alternative approach for assessing forest productivity. Attempts to link these measures of productivity (i.e., NEP and tree biomass increment) have produced inconsistent results, in part because NEP time series are typically too short to provide robust comparisons. We here use a relatively long (20-year) NEP time series together with annual tree biomass increment (derived from tree-ring data) from the same site to determine to what extent the two productivity measures relate to each other. We conducted this study at the Howland Research Forest, central Maine USA, which supports a mature, mixed-species conifer forest. We expressed stand-

Experimental Applications

Discrepancies between inventories and flux measurements

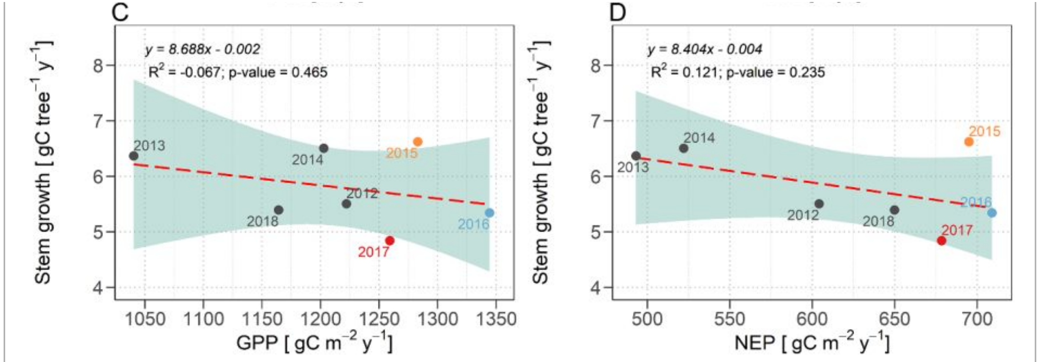
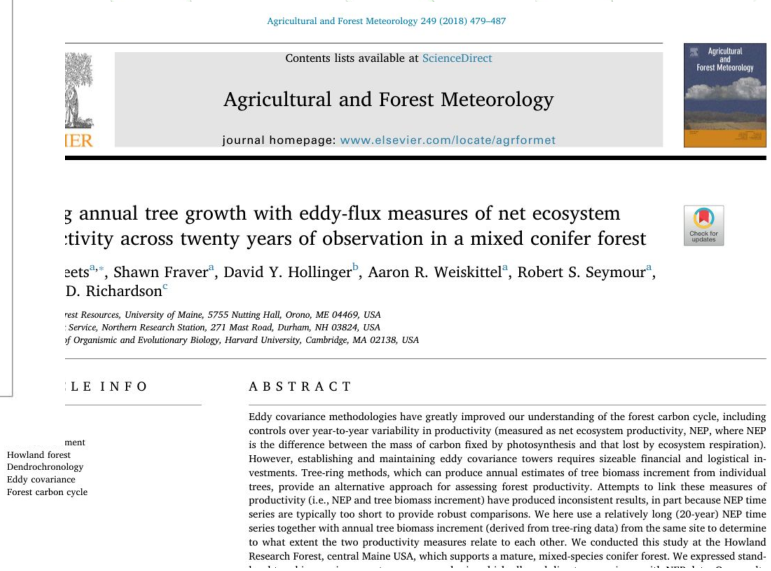


Figure 6. Cumulative (A) gross primary production (GPP) (B) and stem growth vs. growing season length (GSL) (i.e. days from budburst to needle fall); stem growth vs. GPP (C) and net ecosystem production (NEP) (D).



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LETTER • **OPEN ACCESS**

Contrasting responses of forest growth and carbon sequestration to heat and drought in the Alps

Ludovica Oddi[1], Mirco Migliavacca[2,3], Edoardo Cremonese[4], Gianluca Filippa[4], Giorgio Vacchiano[5], Consolata Siniscalco[1], Umberto Morra di Cella[4] and Marta Galvagno[6,4]

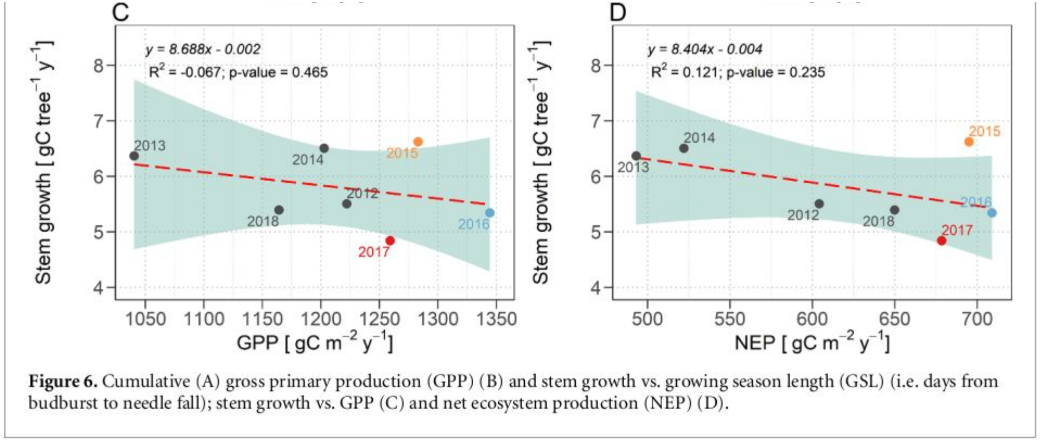
Published 24 March 2022 • © 2022 The Author(s). Published by IOP Publishing Ltd

Environmental Research Letters, Volume 17, Number 4

Focus on Earth System Resilience and Tipping Behavior

Experimental Applications

Discrepancies between inventories and flux measurements



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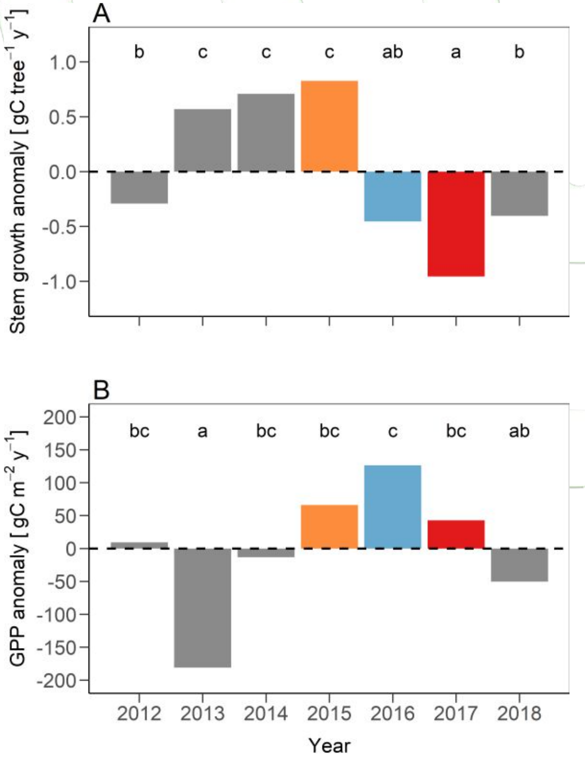
Environmental Research Letters, Volume 17, Number 4

Focus on Earth System Resilience and Tipping Behavior



2017
-17 %

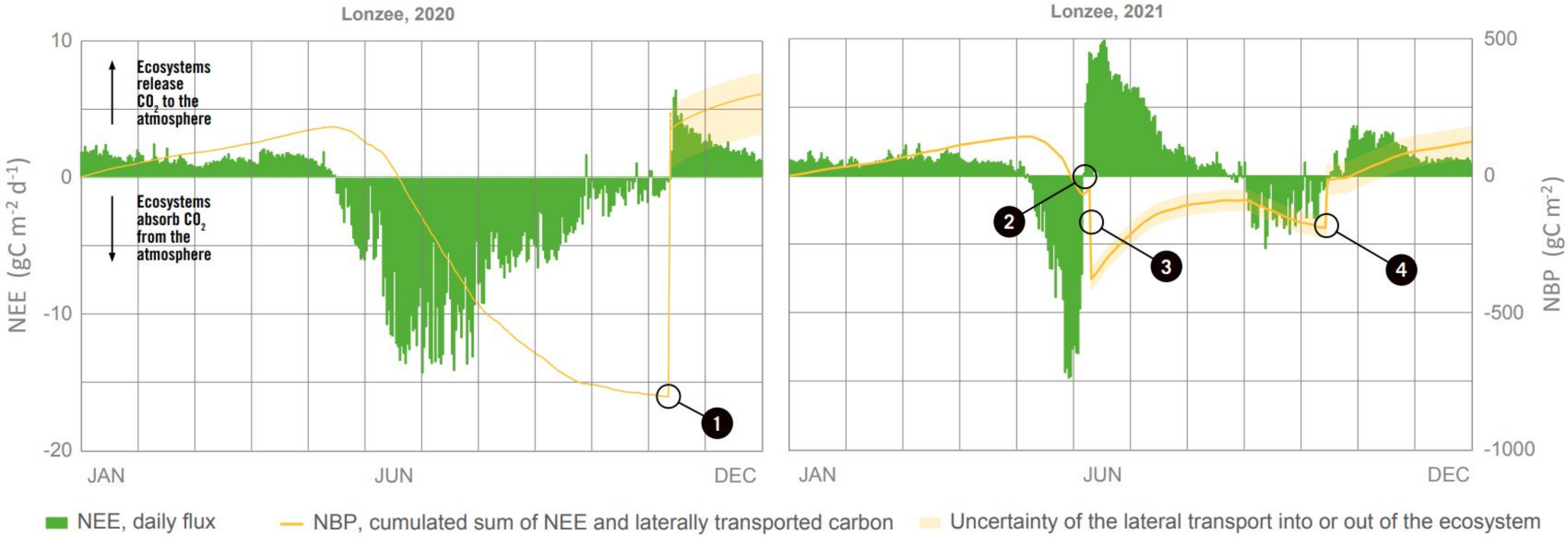
Smart Agriculture

Understanding and managing water use, carbon sequestration, and greenhouse gas emissions:

- Optimizing Irrigation
- Field productivity
- Greenhouse gas emissions


Photo: Pekka Pelkonen, ICOS RI

Smart Agriculture

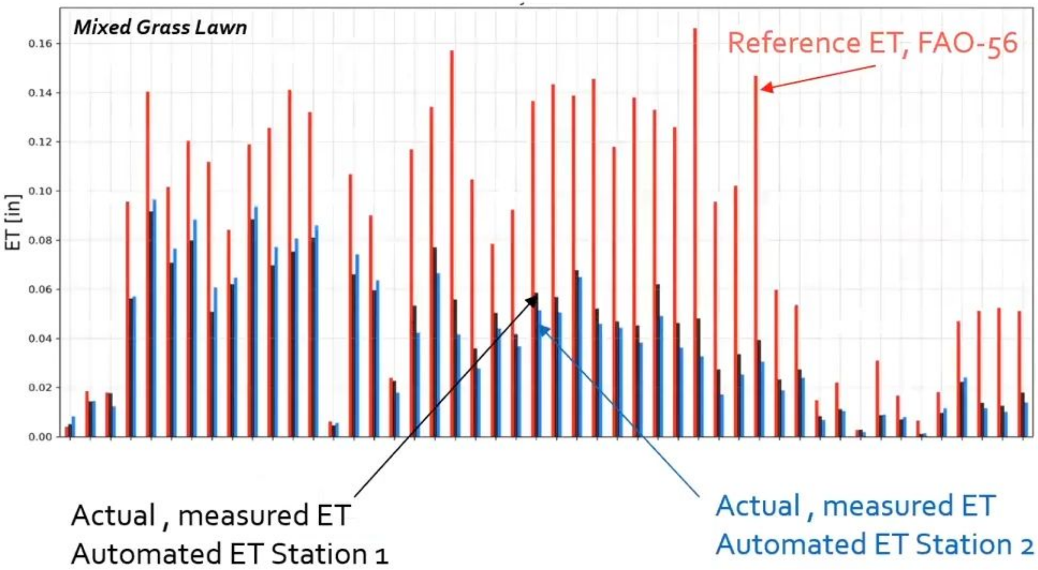


FLUXES 2022

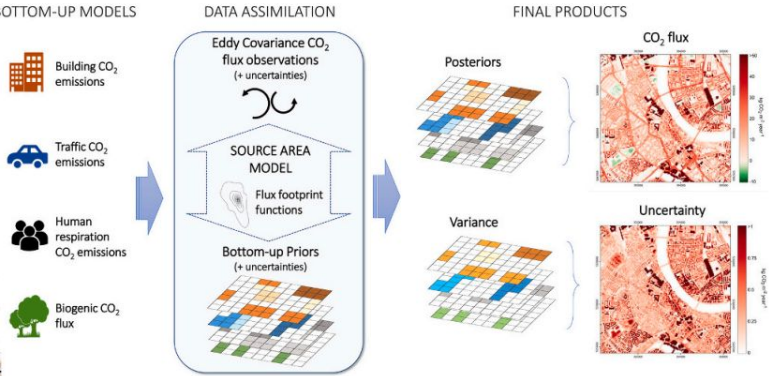
Smart Agriculture

Improve estimation of evapotranspiration (ET) by using direct measurements, enhancing the modeling of Irrigation Water Requirements (IWR) vs. FAO-56 .

This supports efficient water use in agriculture, irrigation planning, drought monitoring, and satellite data validation



Urban fluxes



BOTTOM-UP MODELS

Building CO_2 emissions

Traffic CO_2 emissions

Human respiration CO_2 emissions

Biogenic CO_2 flux

DATA ASSIMILATION

Eddy Covariance CO_2 flux observations (+ uncertainties)

SOURCE AREA MODEL

Flux footprint functions

Bottom-up Priors (+ uncertainties)

FINAL PRODUCTS

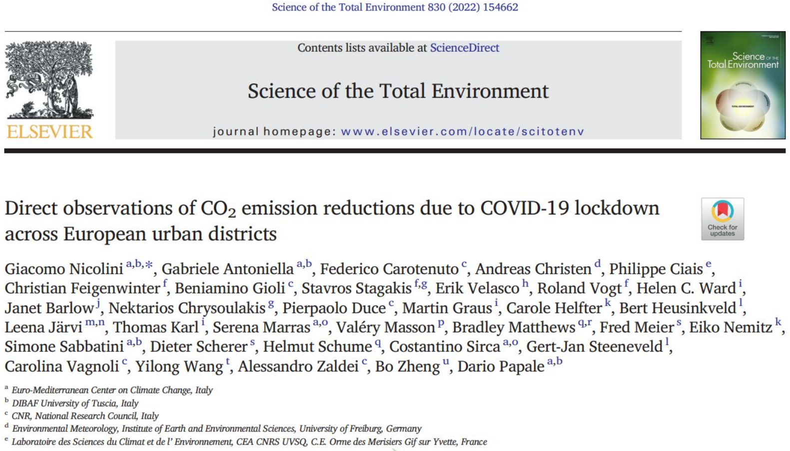
Posteriors

Variance

CO_2 flux

Uncertainty

Stagakis et al. 2023 - STOTEN



Science of the Total Environment 830 (2022) 154662

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Direct observations of CO_2 emission reductions due to COVID-19 lockdown across European urban districts

Giacomo Nicolini[a,b,*], Gabriele Antoniella[a,b], Federico Carotenuto[c], Andreas Christen[d], Philippe Ciais[e], Christian Feigenwinter[f], Beniamino Gioli[c], Stavros Stagakis[f,g], Erik Velasco[h], Roland Vogt[f], Helen C. Ward[i], Janet Barlow[j], Nektarios Chrysoulakis[g], Pierpaolo Duce[c], Martin Graus[i], Carole Helfter[k], Bert Heusinkveld[l], Leena Järvi[m,n], Thomas Karl[i], Serena Marras[a,o], Valéry Masson[p], Bradley Matthews[q,r], Fred Meier[s], Eiko Nemitz[k], Simone Sabbatini[a,b], Dieter Scherer[s], Helmut Schume[q], Costantino Sirca[a,o], Gert-Jan Steeneveld[l], Carolina Vagnoli[c], Yilong Wang[t], Alessandro Zaldei[c], Bo Zheng[u], Dario Papale[a,b]

[a] *Euro-Mediterranean Center on Climate Change, Italy*
[b] *DIBAF University of Tuscia, Italy*
[c] *CNR, National Research Council, Italy*
[d] *Environmental Meteorology, Institute of Earth and Environmental Sciences, University of Freiburg, Germany*
[e] *Laboratoire des Sciences du Climat et de l' Environnement, CEA CNRS UVSQ, C.E. Orme des Merisiers Gif sur Yvette, France*

ICOS Cities

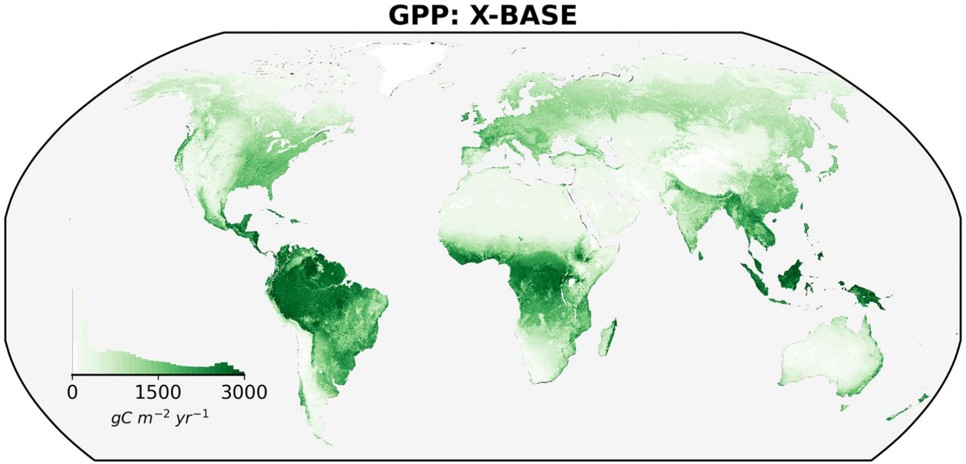
Validating and parameterizing models

- Multiple spatial scales
- Multiple temporal scales

Validating and parameterizing models

Large networks of flux towers, covering diverse biomes and climate zones, provide benchmark data to:

- Validate and calibrate global models
- Train machine learning models to generate spatially explicit maps of carbon and water fluxes



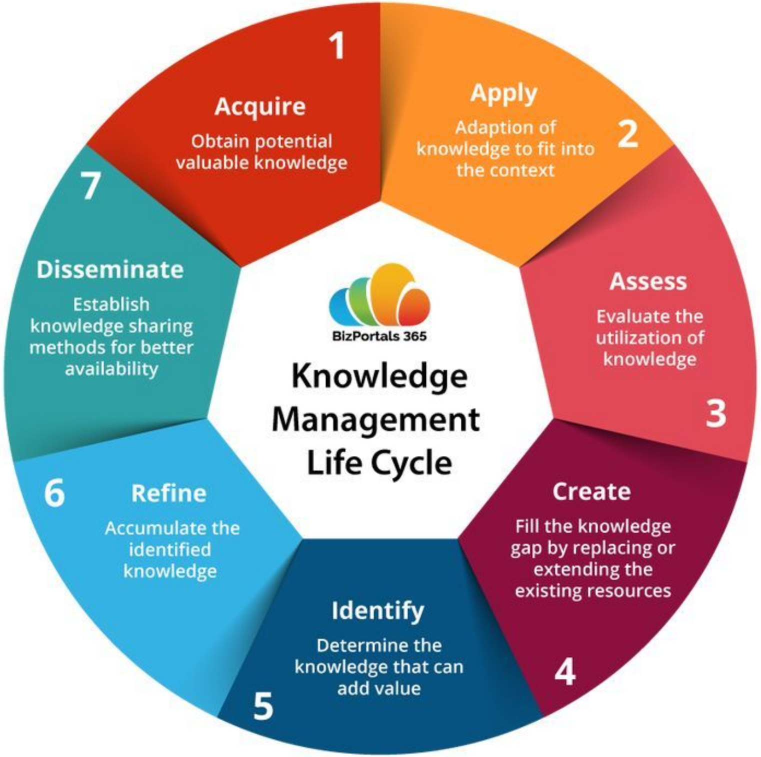
Nelson et al. 2024 - BG

1. Why do we measure fluxes?
2. Key ecosystem processes (carbon cycle, NEE, Reco, GPP) and drivers
3. Time scales
4. Applications and Examples
5. **Policy**

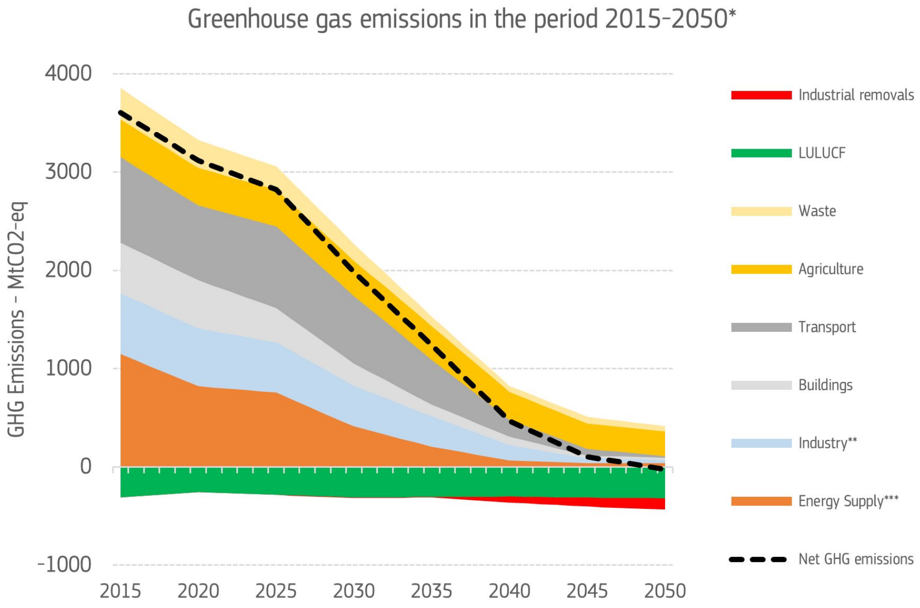
Why do we measure?

- To provide the best available knowledge to society

- To inform policy-making, individual decision-making, and public discourse about fundamental challenges to the environment and society



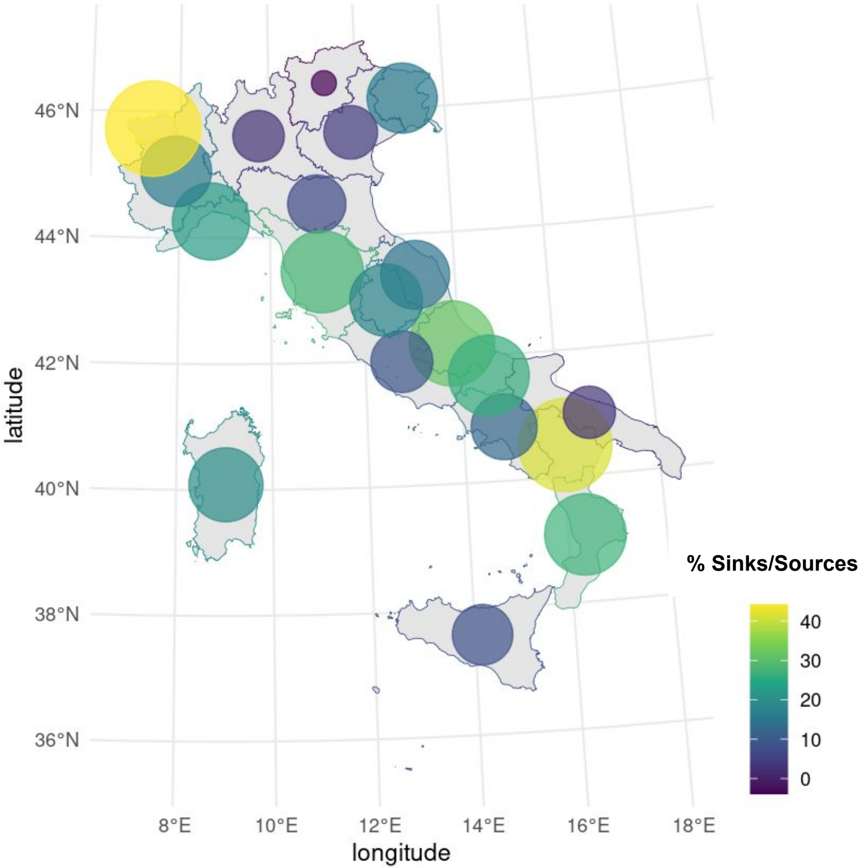
Climate Policy



*Source: PRIMES, GAINS, GLOBIOM
**Excluding non-BECCS industrial removals
***Including Bioenergy with carbon capture and storage (BECCS)

- Balance between anthropogenic emissions by sources and removals by sinks (net-zero) by 2050
- Prerequisite: accurate estimation of both large fluxes
- Regulation (EU) 2023/839: GHG inventories need to provide “near real time” estimate also for LULUCF

Inform Policy

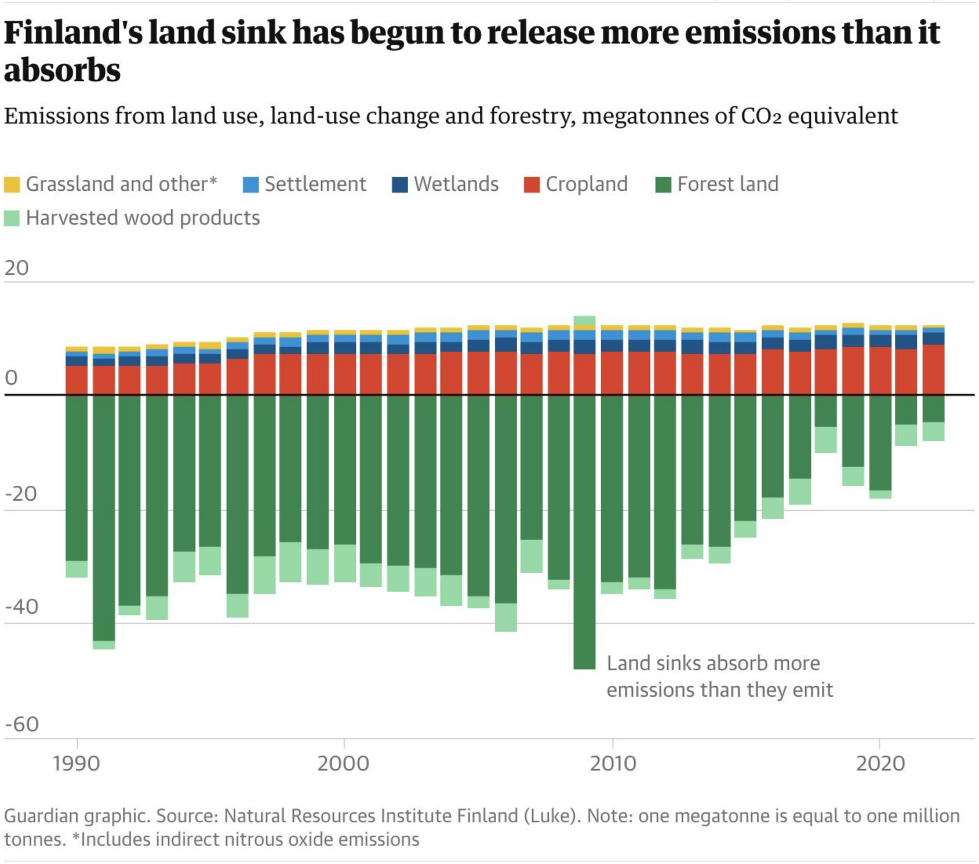


The role of LULUCF

Europe (2021):
Sources: **3471** MtCO2/anno
Sinks: **229** MtCO2/anno
LULUCF = ~**7%**

Italy (2021):
Sources: **417** MtCO2/anno
Sinks: **27** MtCO2/anno
LULUCF = ~**7%**

Forest sink decline



Finland's land sink has begun to release more emissions than it absorbs

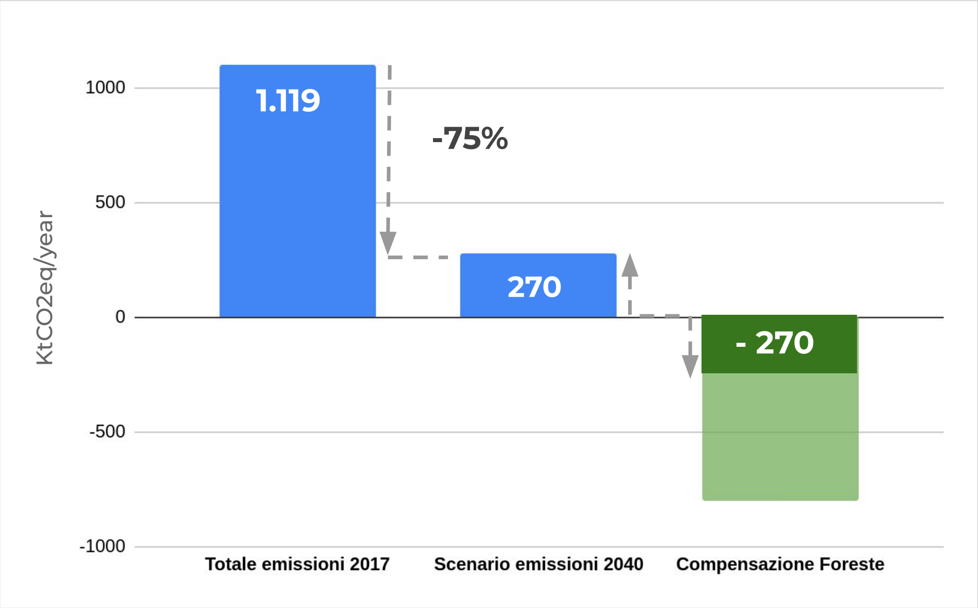
Emissions from land use, land-use change and forestry, megatonnes of CO_2 equivalent

Guardian graphic. Source: Natural Resources Institute Finland (Luke). Note: one megatonne is equal to one million tonnes. *Includes indirect nitrous oxide emissions

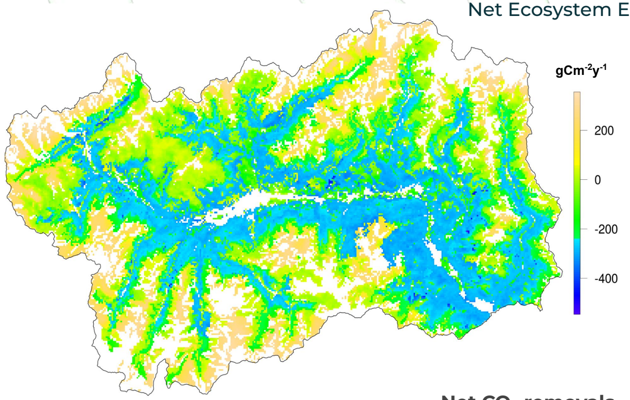
Opportunity in using eddy covariance to estimate IPCC emissions factors (ecosystem carbon uptake)

- 2000 site years of direct flux estimates suggest there is MORE carbon being taken up and stored in forests than default IPCC emission factors
- Eddy covariance can estimate sensitivity of ΔC to change more effectively than less frequently measured C stocks
- Eddy covariance can estimate ΔC in non-forest ecosystems effectively

Inform Policy



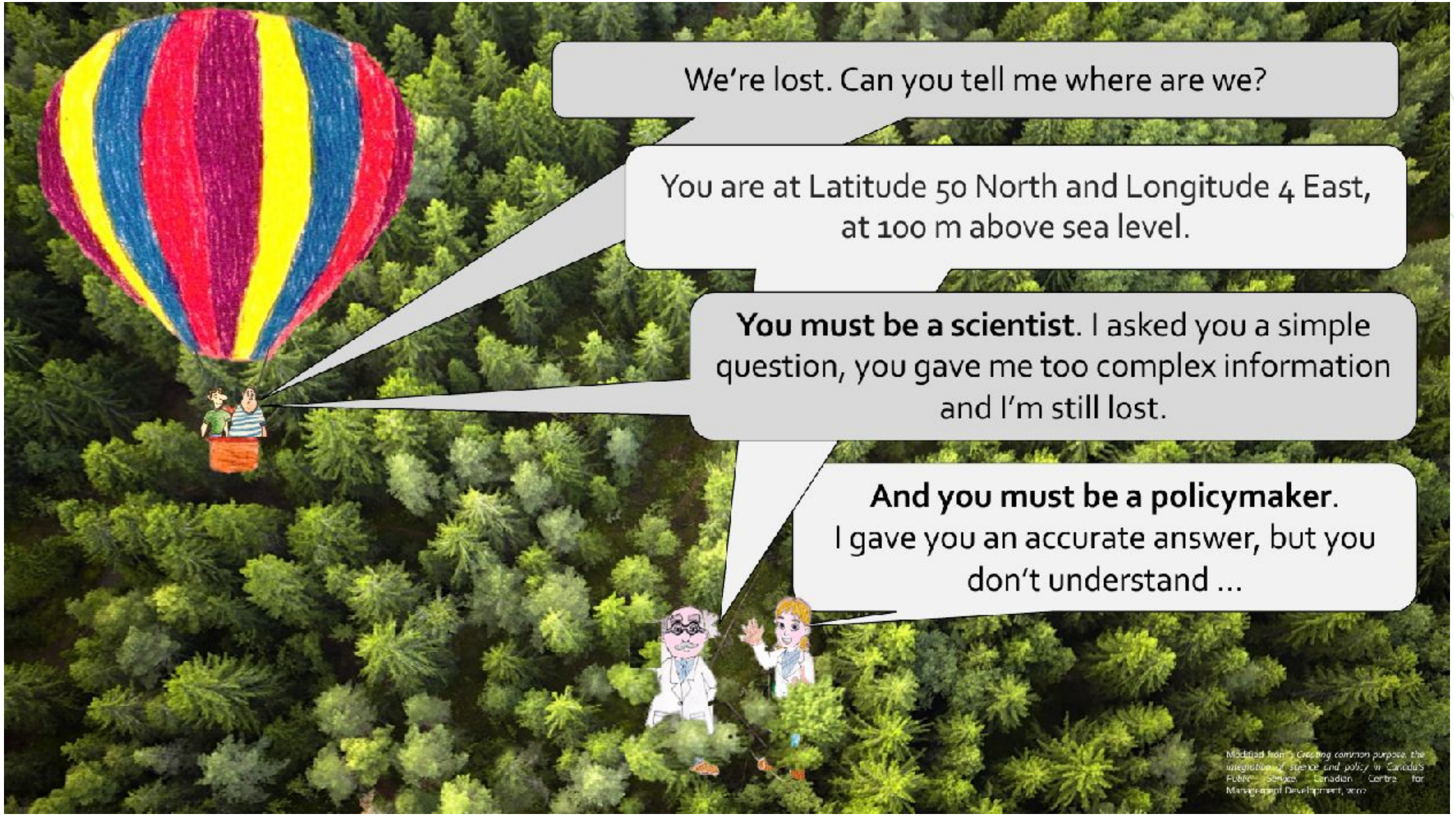
Net Ecosystem Exchange



Average altitude: 2100m asl
Max altitude: 4810m asl

Net CO_2 removals
by sinks: - 804 $KtCO_2y^{-1}$
(2010-2021 average)

Inform Policy

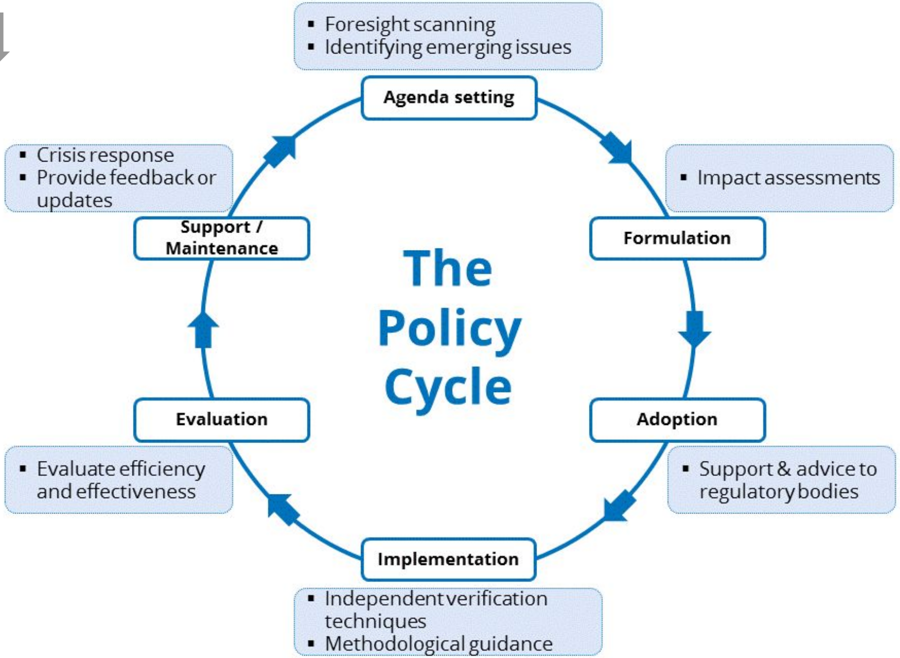


Modified from : *Creating common purpose: the integration of science and policy in Canada's* Public Service. Canadian Centre for Management Development, 2002

Giacomo Grassi (JRC) - ICOS Italy - September 2022

Inform Policy

Which could be the role of a flux scientist into the policy cycle?



The Policy Cycle

Agenda setting
- Foresight scanning
- Identifying emerging issues

Formulation
- Impact assessments

Adoption
- Support & advice to regulatory bodies

Implementation
- Independent verification techniques
- Methodological guidance

Evaluation
- Evaluate efficiency and effectiveness

Support / Maintenance
- Crisis response
- Provide feedback or updates

ITINERIS

Have Fun!

THANKS!

IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-Mission 4 “Education and Research” - Component 2: “From research to business” - Investment 3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”

Finanziato dall'Unione europea NextGenerationEU

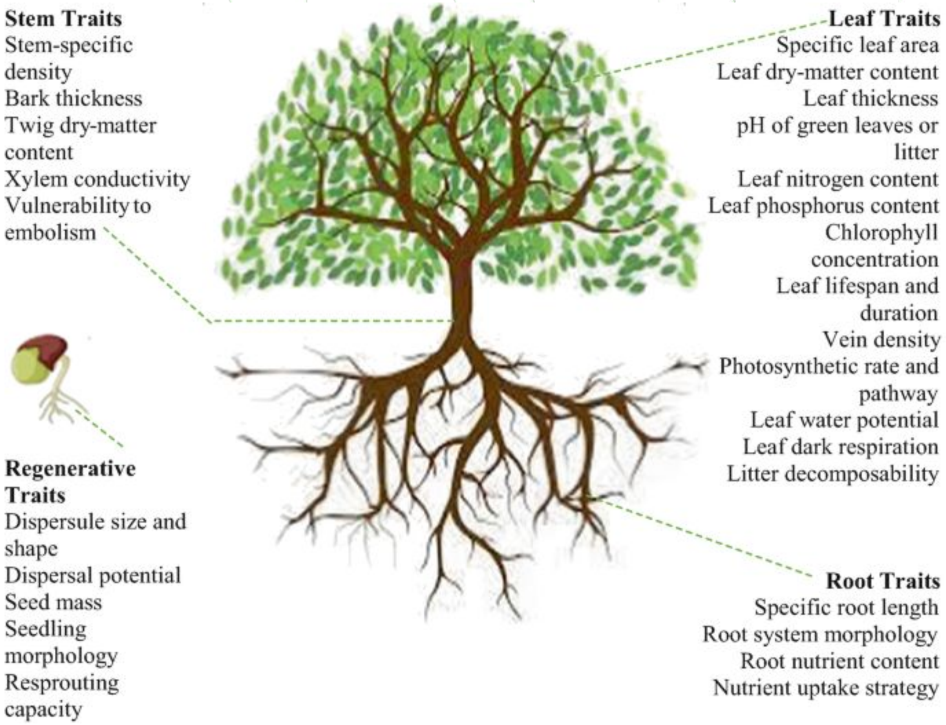
Ministero dell'Università e della Ricerca

Italiadomani

Drivers

Structural and Functional Traits

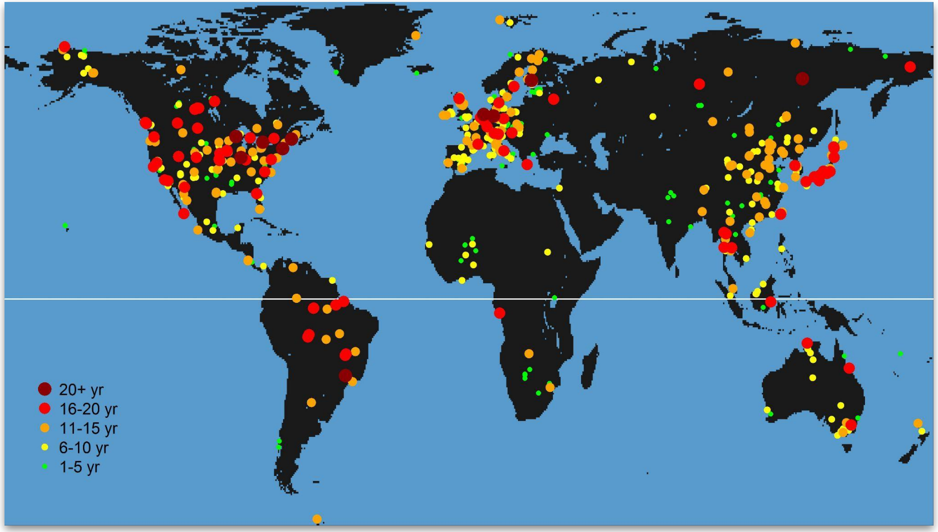
- LAI, leaf lifespan, nitrogen content, and photosynthetic traits influence GPP and Reco.
- WUE (Water Use Efficiency) and CUE (Carbon Use Efficiency) vary across ecosystems

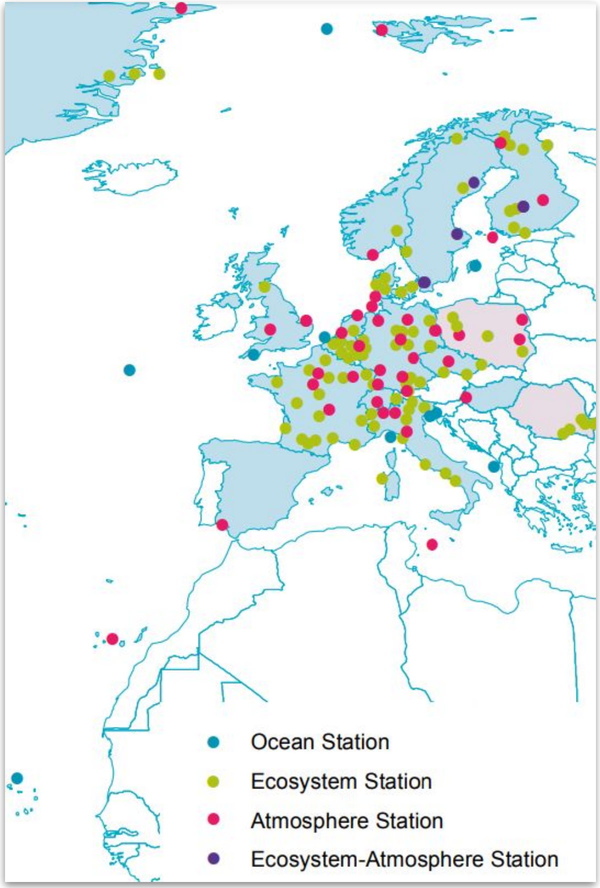


Tyagi 2024. Plant Functional Trait: Concept and Significance

1. Why measure ecosystem fluxes?
2. Key ecosystem processes (carbon cycle, NEE, Reco, GPP) and drivers
3. Time scales
4. Applications and Examples
5. **Networks**
6. Policy

NETWORKS


20+ yr
16-20 yr
11-15 yr
6-10 yr
1-5 yr


Ocean Station
Ecosystem Station
Atmosphere Station
Ecosystem-Atmosphere Station

Open data policy e Trasparenza

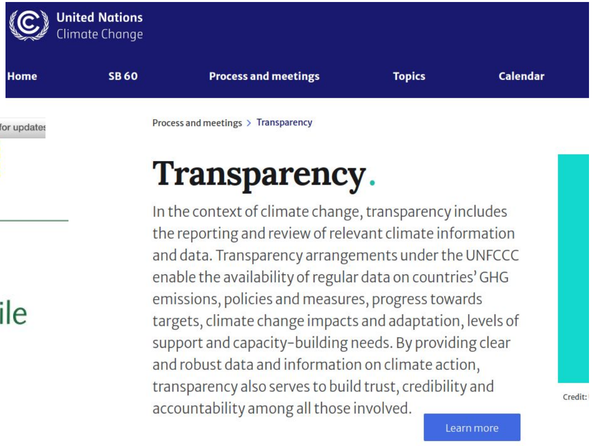
UNESCO
https://doi.org/10.54677/UTCD9302

Correspondence

New Phytologist

Check for updates

Finding the balance between open access to forest data while safeguarding the integrity of National Forest Inventory-derived information



United Nations
Climate Change

Home SB 60 Process and meetings Topics Calendar

Process and meetings > Transparency

Transparency.

In the context of climate change, transparency includes the reporting and review of relevant climate information and data. Transparency arrangements under the UNFCCC enable the availability of regular data on countries' GHG emissions, policies and measures, progress towards targets, climate change impacts and adaptation, levels of support and capacity-building needs. By providing clear and robust data and information on climate action, transparency also serves to build trust, credibility and accountability among all those involved.

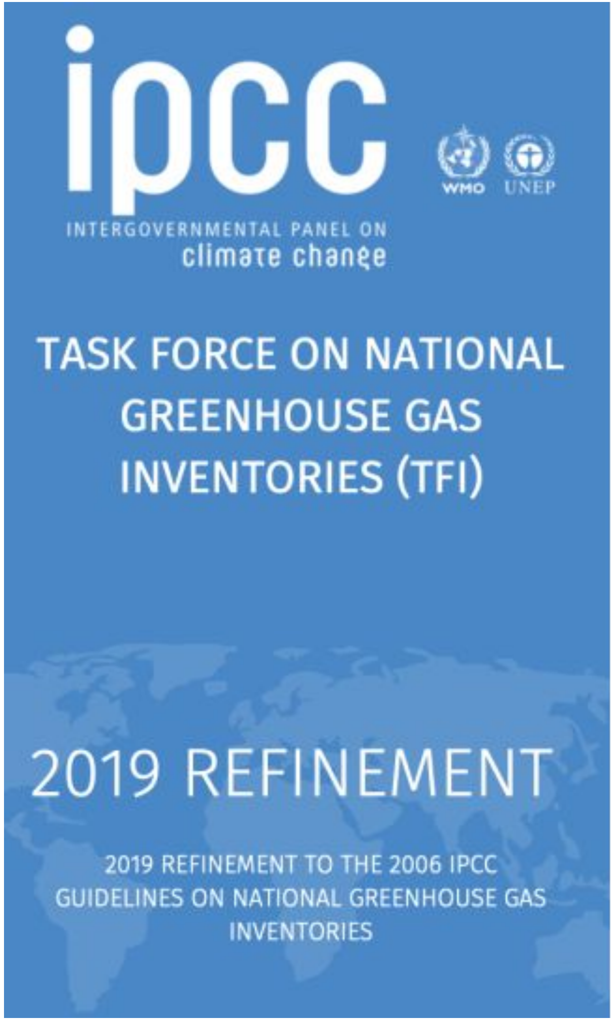
Learn more

Credit:

PNAS OPINION

We need a solid scientific basis for nature-based climate solutions in the United States

Kimberly A. Novick[a,1], Trevor F. Keenan[b,c], William R. L. Anderegg[d,e], Caroline P. Normile[f], Benjamin R. K. Runkle[g], Emily E. Oldfield[h], Gyami Shrestha[i], Dennis D. Baldocchi[b], Margaret E. K. Evans[j], James T. Randerson[k], Jonathan Sanderman[l], Margaret S. Torn[c,m], Anna T. Trugman[n], and Christopher A. Williams[o]



ipcc

INTERGOVERNMENTAL PANEL ON
climate change

TASK FORCE ON NATIONAL
GREENHOUSE GAS
INVENTORIES (TFI)

2019 REFINEMENT

2019 REFINEMENT TO THE 2006 IPCC
GUIDELINES ON NATIONAL GREENHOUSE GAS
INVENTORIES

Equation 2.2
Change in carbon stock
Above & Below ground
Gain – Loss method

$$\Delta C = \Delta C_G - \Delta C_L$$

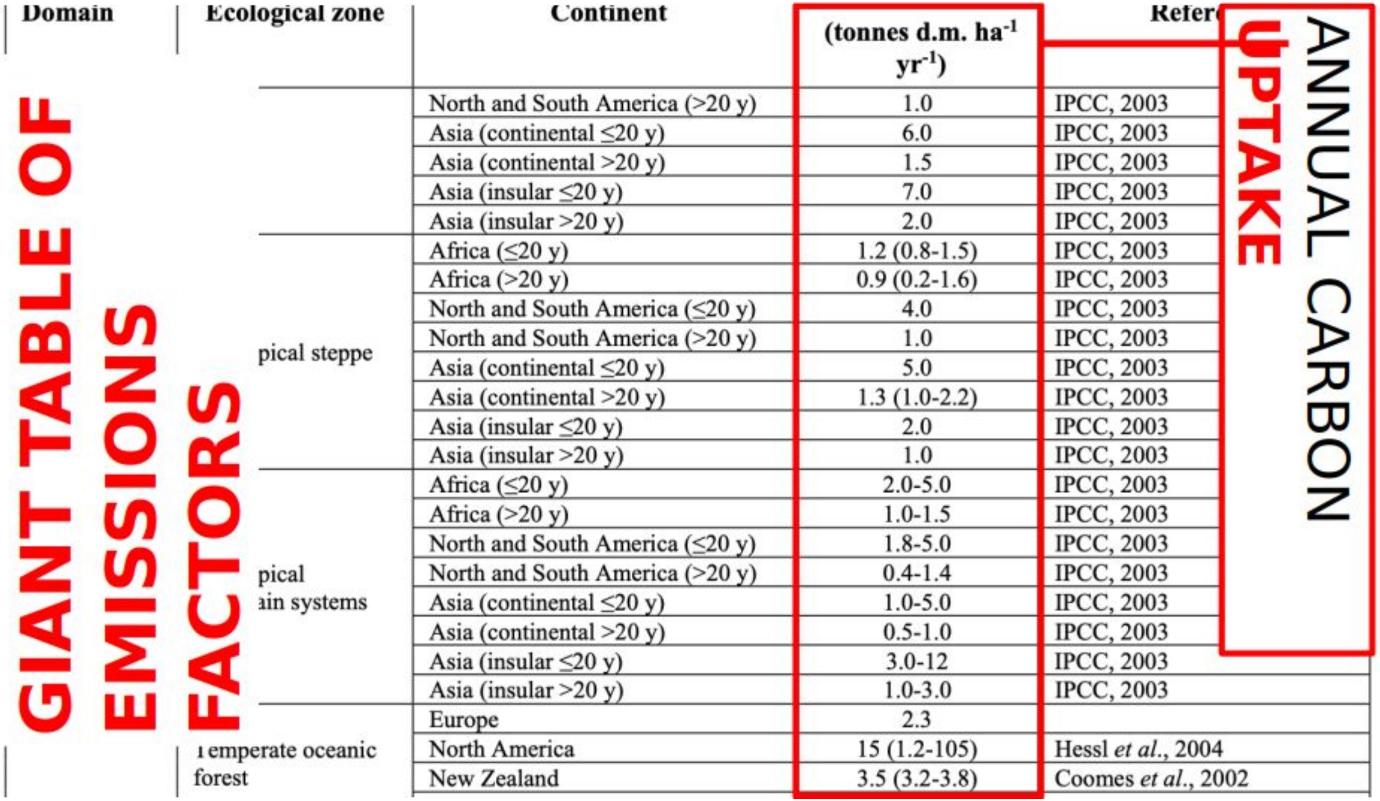
ΔC = annual carbon stock change in the pool, tonnes C yr^{-1}

ΔC_G = annual gain of carbon, tonnes C yr^{-1}

ΔC_L = annual loss of carbon, tonnes C yr^{-1}

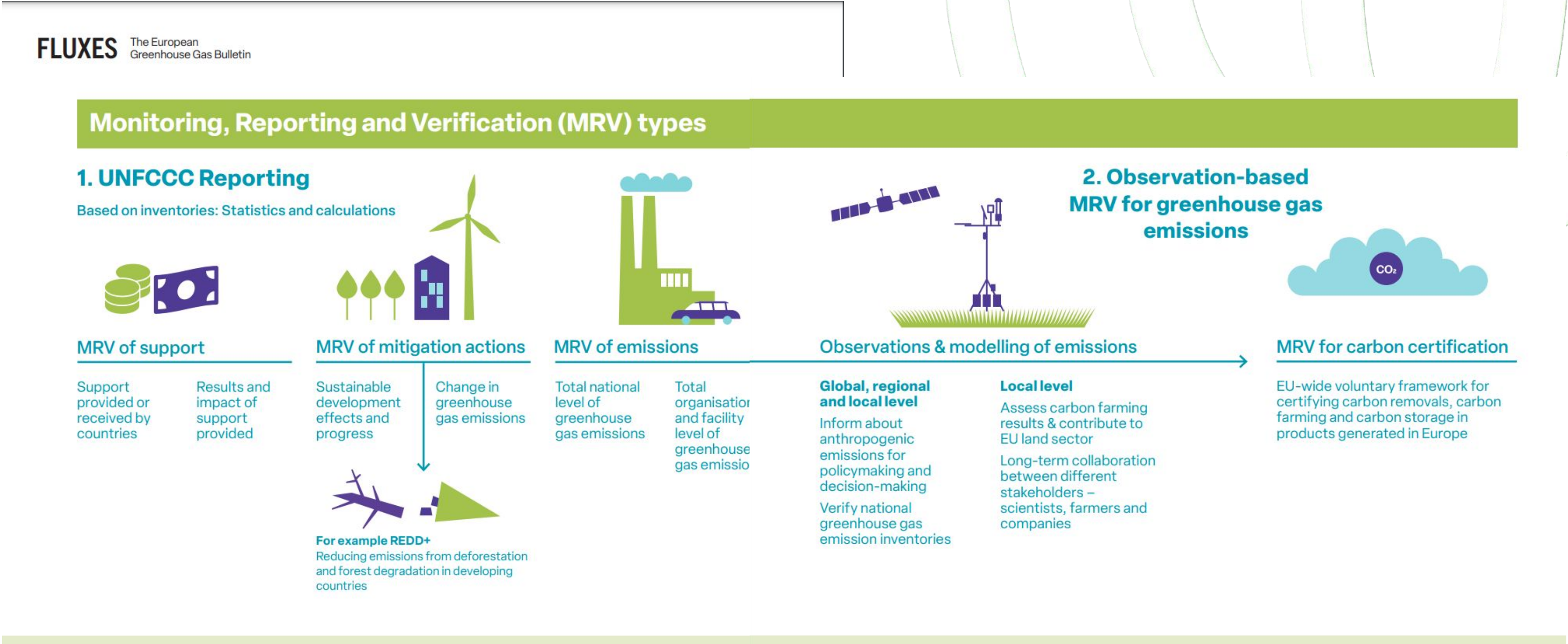
GIANT TABLE OF EMISSIONS FACTORS

ANNUAL CARBON UPTAKE



Domain	Ecological zone	Continent	(tonnes d.m. ha^{-1} yr^{-1})	Refer
		North and South America (>20 y)	1.0	IPCC, 2003
		Asia (continental ≤20 y)	6.0	IPCC, 2003
		Asia (continental >20 y)	1.5	IPCC, 2003
		Asia (insular ≤20 y)	7.0	IPCC, 2003
		Asia (insular >20 y)	2.0	IPCC, 2003
	pical steppe	Africa (≤20 y)	1.2 (0.8-1.5)	IPCC, 2003
		Africa (>20 y)	0.9 (0.2-1.6)	IPCC, 2003
		North and South America (≤20 y)	4.0	IPCC, 2003
		North and South America (>20 y)	1.0	IPCC, 2003
		Asia (continental ≤20 y)	5.0	IPCC, 2003
		Asia (continental >20 y)	1.3 (1.0-2.2)	IPCC, 2003
		Asia (insular ≤20 y)	2.0	IPCC, 2003
		Asia (insular >20 y)	1.0	IPCC, 2003
	pical ain systems	Africa (≤20 y)	2.0-5.0	IPCC, 2003
		Africa (>20 y)	1.0-1.5	IPCC, 2003
		North and South America (≤20 y)	1.8-5.0	IPCC, 2003
		North and South America (>20 y)	0.4-1.4	IPCC, 2003
		Asia (continental ≤20 y)	1.0-5.0	IPCC, 2003
		Asia (continental >20 y)	0.5-1.0	IPCC, 2003
		Asia (insular ≤20 y)	3.0-12	IPCC, 2003
		Asia (insular >20 y)	1.0-3.0	IPCC, 2003
	Temperate oceanic forest	Europe	2.3	
		North America	15 (1.2-105)	Hessl *et al.*, 2004
		New Zealand	3.5 (3.2-3.8)	Coomes *et al.*, 2002

Inform Policy



FLUXES The European Greenhouse Gas Bulletin

Monitoring, Reporting and Verification (MRV) types

1. UNFCCC Reporting

Based on inventories: Statistics and calculations

MRV of support

Support provided or received by countries

Results and impact of support provided

MRV of mitigation actions

Sustainable development effects and progress

Change in greenhouse gas emissions

For example REDD+
Reducing emissions from deforestation and forest degradation in developing countries

MRV of emissions

Total national level of greenhouse gas emissions

Total organisatio and facility level of greenhouse gas emissio

2. Observation-based MRV for greenhouse gas emissions

Observations & modelling of emissions

Global, regional and local level

Inform about anthropogenic emissions for policymaking and decision-making

Verify national greenhouse gas emission inventories

Local level

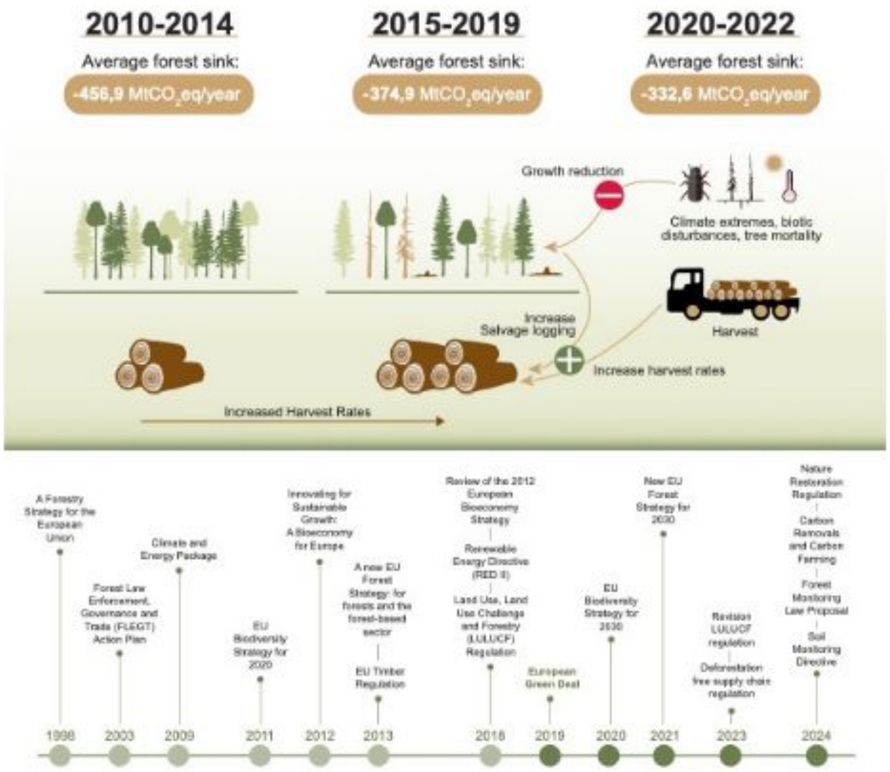
Assess carbon farming results & contribute to EU land sector

Long-term collaboration between different stakeholders – scientists, farmers and companies

MRV for carbon certification

EU-wide voluntary framework for certifying carbon removals, carbon farming and carbon storage in products generated in Europe

Forest sink decline, what are the causes?



-295 $\text{MtCO}_{2,eq}$/year
(2020-2023)
April 15 2025
(EEA Website)

Migliavacca et al., (in press)

How EC can support EU policies?

Monitoring, reporting, and verification:

- Timely information for country inventories and reporting of net CO_2 fluxes
    - Timeliness
    - Country level to regional (Tier 3 approach)
- Carbon removal and carbon farming: tools for quantification of “carbon removals” from land and carbon projects (parcel scale);
    - Forests, Croplands, Peatlands
    - Management/site history

Understanding and quantifying climate-driven vs anthropogenic (management) driven CO_2 sink reduction.