CARBON Farming HUB

Estimating CO_2 fluxes in Forest Ecosystems

Dr Nikolaos Fyllas, Department of Biology, NKUA

C Sazeides, E Bintsi-Frantzi, Department of Environment, UAegean

www.carbonfarminghub.eu

Co-funded by the European Union

YOUTH AND LIFELONG LEARNING FOUNDATION

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 2023 1 EL02 KA220 YOU 000158211. It reflects only the author's view and that the European Commission is not responsible for any use that may be made of the information it contains.

How did we (earth-system scientists) realised/proved that Carbon (C) in forest and its dynamics are important?

Back in 2003-2004 Peter Cox and colleagues presented *the first GCM climate change projections that included a dynamic vegetation and an interactive carbon cycle that produced a very significant amplification of global warming over the 21st century. Under ‘business as usual’’ emissions scenario,* CO_2 *concentrations reached about 980 ppmv by 2100, which is about 280 ppmv higher than when these feedbacks were ignored. The major contribution to the increased* CO_2 *arose from reductions in soil carbon because global warming is assumed to accelerate respiration. However, there was also a lesser contribution from an alarming loss of the Amazonian rainforest.*

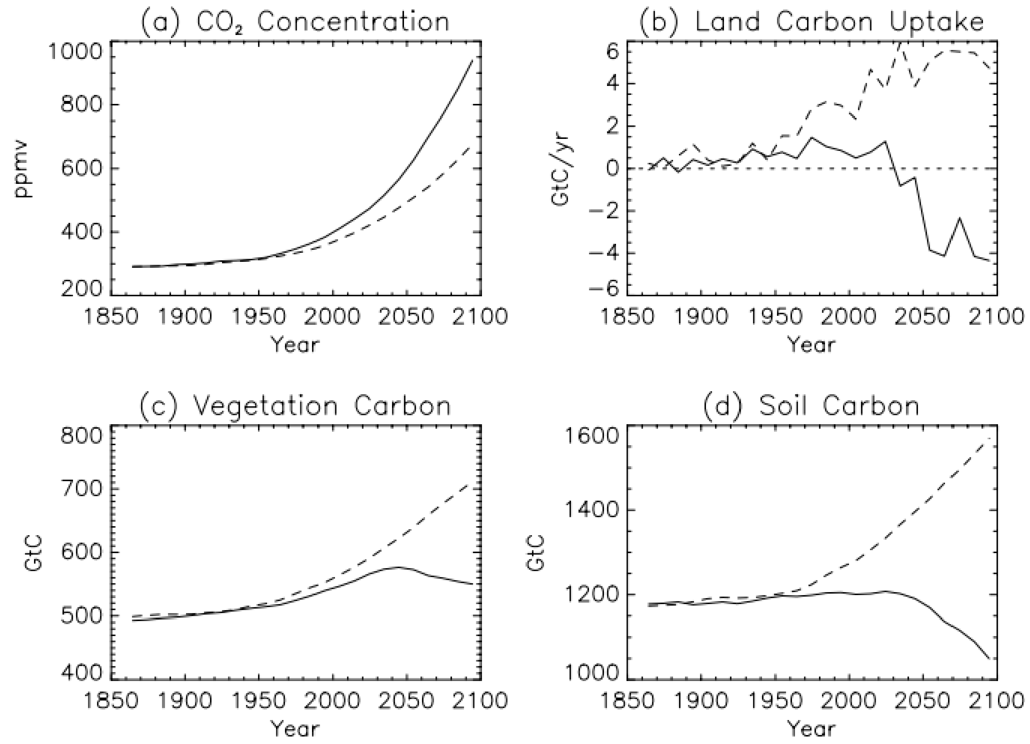


Fig. 1. Impact of climate-carbon cycle feedbacks on projections of (**a**) atmospheric CO_2 concentration, (**b**) global land carbon uptake, (**c**) global vegetation carbon and (**d**) global soil carbon. The continuous line represents the fully coupled climate-carbon cycle run and the dashed line is from the run without climate effects on the carbon cycle

Cox et al. 2004

How did we (earth-system scientists) realised/proved that Carbon (C) in forest and its dynamics are important?

Back in 2003-2004 Peter Cox and colleagues presented *the first GCM climate change projections that included a dynamic vegetation and an interactive carbon cycle that produced a very significant amplification of global warming over the 21st century. Under 'business as usual'' emissions scenario,* CO_2 *concentrations reached about 980 ppmv by 2100, which is about 280 ppmv higher than when these feedbacks were ignored. The major contribution to the increased* CO_2 *arose from reductions in soil carbon because global warming is assumed to accelerate respiration. However, there was also a lesser contribution from an alarming loss of the Amazonian rainforest.*

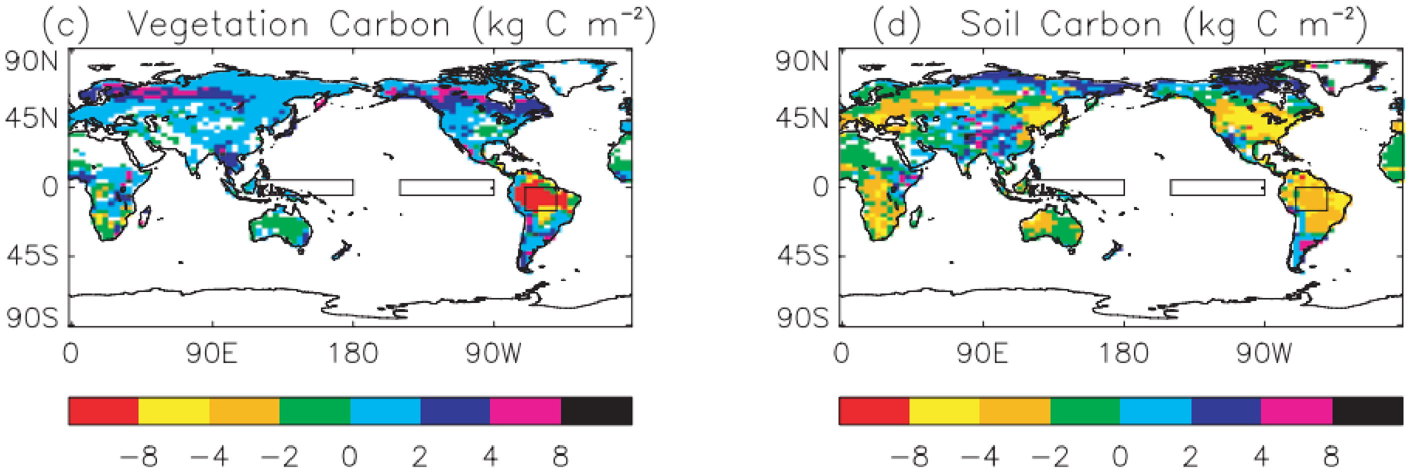


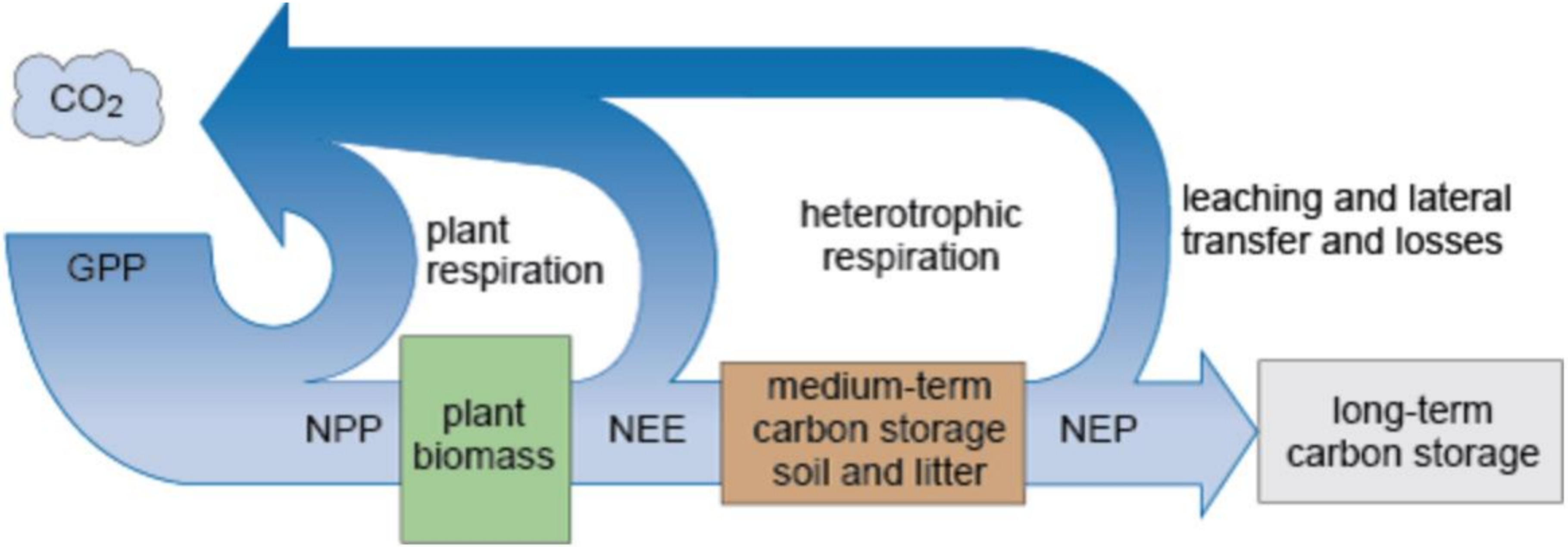
Fig. 4. Maps of changes in climate and land carbon storage over the 21st century from the fully coupled climate-carbon cycle projections. (**a**) Screen temperature, (**b**) precipitation, (**c**) vegetation carbon and (**d**) soil carbon. These maps were calculated as the differences between the means for the 2090s and the 1990s. Only areas for which the projected change is greater than 95% significant (according to a paired student t-test) are shown. In each map the box over South America represents the definition of Amazonia for the purposes of this study (70° W–50° W, 15° S–0° N), while the boxes over the Pacific show the NINO3 region (150° W–90° W, 5° S–5° N), and the western Equatorial Pacific region as used in Fig. 5 (120° E–180° E, 5° S–5° N)

Cox et al. 2004

Co-funded by
the European Union

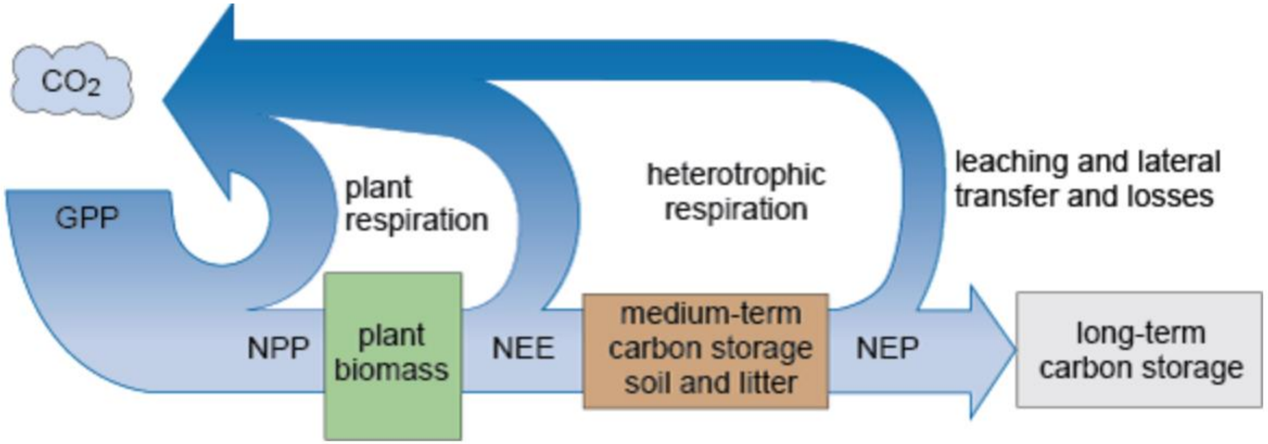
Back to the basics (from ecosystem ecology)

Forests sequester carbon by capturing carbon dioxide (CO_2) from the atmosphere and transforming it into biomass through photosynthesis. Sequestered carbon is then accumulated in the form of biomass, deadwood, litter and in forest soils. Release of carbon from forest ecosystems results from natural processes (respiration and oxidation) as well as deliberate or unintended results of human activities (i.e. harvesting, fires, deforestation).



https://archive.ipcc.ch/ipccreports/sres/land_use/index.php?idp=24

Back to the basics (from ecosystem ecology)



Gross Primary Productivity (GPP) denotes the total amount of carbon fixed in the process of photosynthesis by plants in an ecosystem

Net Primary Productivity (NPP) denotes the net production of organic matter by plants in an ecosystem, i.e. GPP - autotrophic respiration (Ra), NPP= GPP - Ra

Net Ecosystem Productivity (NEP) denotes the net accumulation of organic matter or carbon by an ecosystem – i.e. NPP - the decomposition rate of dead organic matter (heterotrophic respiration, Rh). NEP = NPP – Rh

Net Biome Productivity (NBP) denotes the net production of organic matter in a region containing a range of ecosystems and includes, in addition to heterotrophic respiration, other processes leading to loss of living and dead organic matter (harvest, forest clearance, and fire, etc.)

Co-funded by
the European Union

https://archive.ipcc.ch/ipccreports/sres/land_use/index.php?idp=24

How can we estimate C storage & fluxes ?

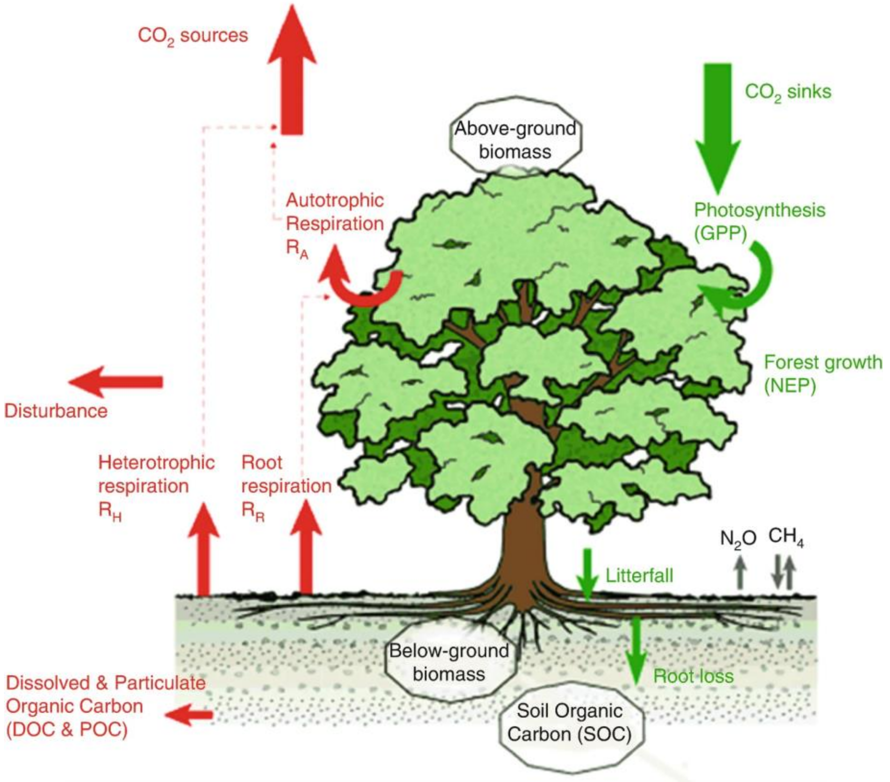
- **Inventory-based estimation**
- **Satellite-based estimation**
- **Process-based estimation**
- **Eddy-flux tower (just for fluxes)**
- **Fused methods of the above**

Co-funded by
the European Union

https://archive.ipcc.ch/ipccreports/sres/land_use/index.php?idp=24

Inventory-based methods

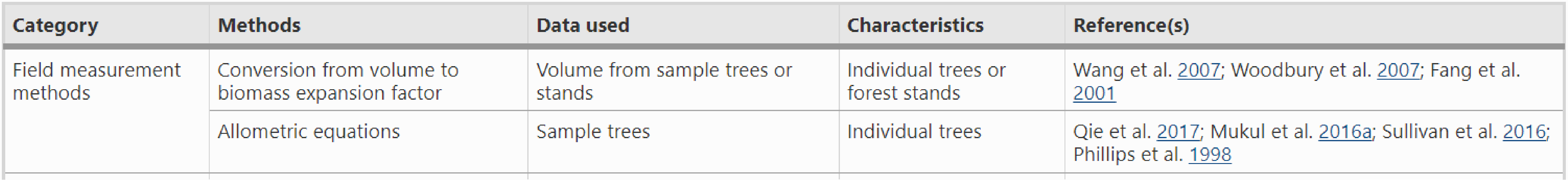
These are the most traditional (and probably most accurate) methods that use field measurements in (permanent) monitoring plots. The biomass (usually only aboveground) of individual trees and other biometric variables are measured to provide allometric equations that predict biomass (B) as a function of a suite of independent variables. Then C is a portion of B.



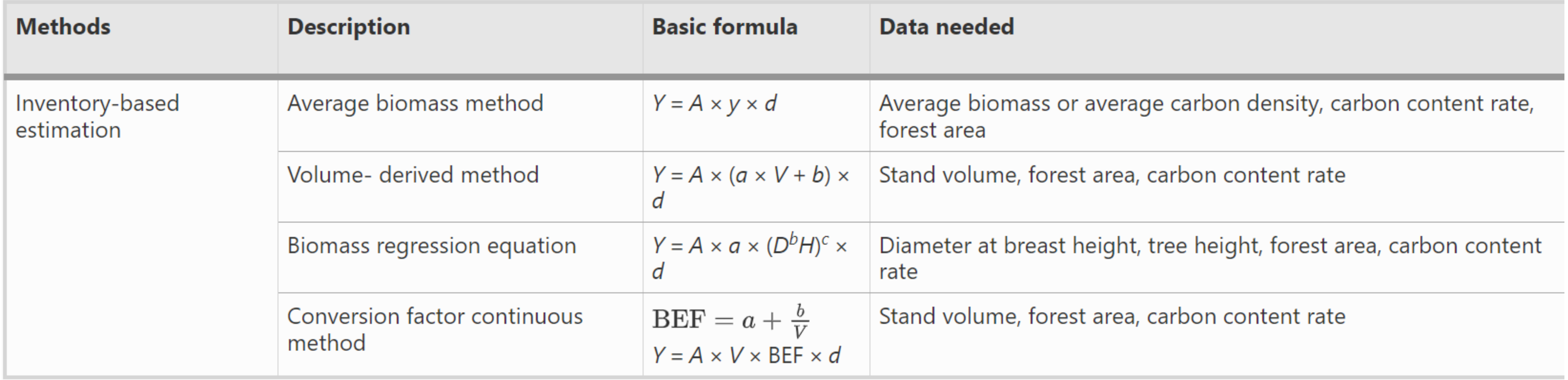
Makul et al. 2020

Inventory-based methods

There are different variants of inventory-based methods to estimate C stocks, for example:



Category	Methods	Data used	Characteristics	Reference(s)
Field measurement methods	Conversion from volume to biomass expansion factor	Volume from sample trees or stands	Individual trees or forest stands	Wang et al. 2007; Woodbury et al. 2007; Fang et al. 2001
	Allometric equations	Sample trees	Individual trees	Qie et al. 2017; Mukul et al. 2016a; Sullivan et al. 2016; Phillips et al. 1998



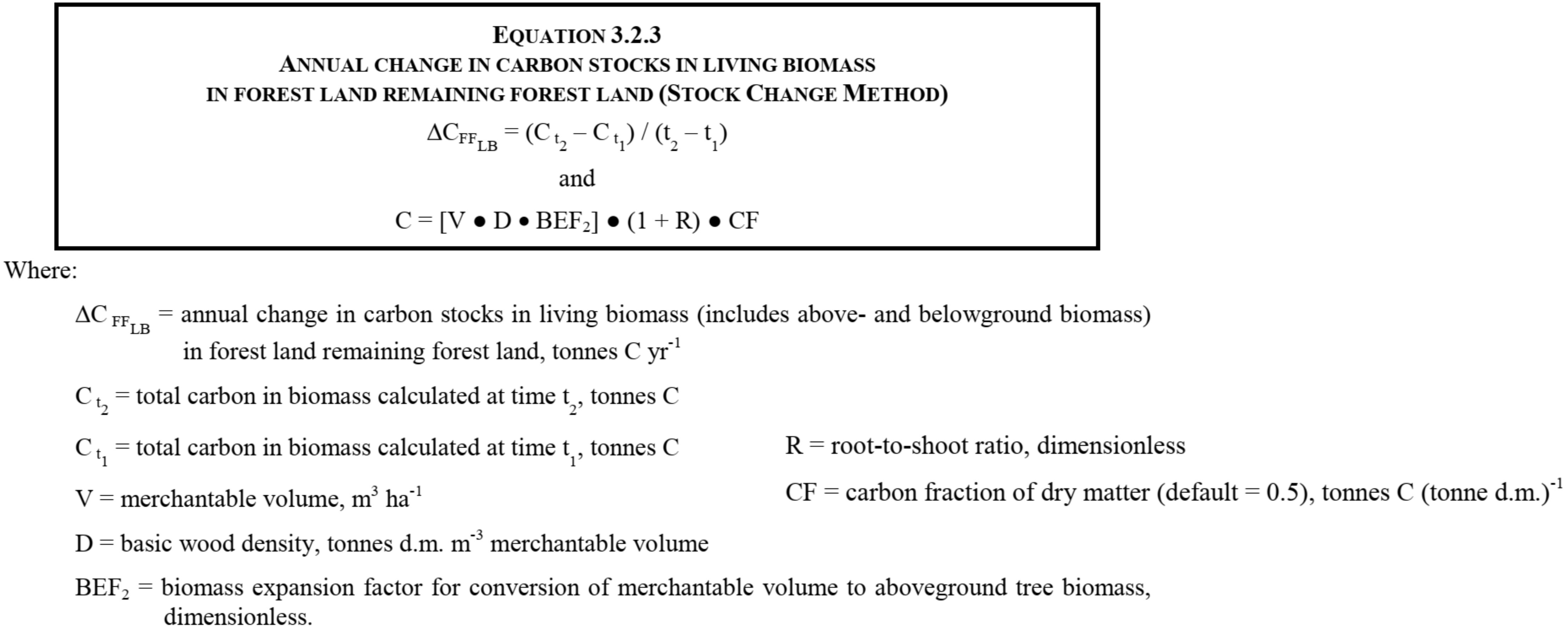
Methods	Description	Basic formula	Data needed
Inventory-based estimation	Average biomass method	$Y = A \times y \times d$	Average biomass or average carbon density, carbon content rate, forest area
	Volume- derived method	$Y = A \times (a \times V + b) \times d$	Stand volume, forest area, carbon content rate
	Biomass regression equation	$Y = A \times a \times (D^b H)^c \times d$	Diameter at breast height, tree height, forest area, carbon content rate
	Conversion factor continuous method	$\mathrm{BEF} = a + \frac{b}{V}$ $Y = A \times V \times \mathrm{BEF} \times d$	Stand volume, forest area, carbon content rate

Co-funded by
the European Union

Makul et al. 2020

Inventory-based methods

Once we have estimates at two points in time (t_1 & t_2) then:



EQUATION 3.2.3
ANNUAL CHANGE IN CARBON STOCKS IN LIVING BIOMASS
IN FOREST LAND REMAINING FOREST LAND (STOCK CHANGE METHOD)

$$\Delta C_{FF_{LB}} = (C_{t_2} - C_{t_1}) / (t_2 - t_1)$$

and

$$C = [V \bullet D \bullet BEF_2] \bullet (1 + R) \bullet CF$$

Where:

$\Delta C_{FF_{LB}}$ = annual change in carbon stocks in living biomass (includes above- and belowground biomass) in forest land remaining forest land, tonnes C yr^{-1}

C_{t_2} = total carbon in biomass calculated at time t_2, tonnes C

C_{t_1} = total carbon in biomass calculated at time t_1, tonnes C

V = merchantable volume, $m^3\ ha^{-1}$

D = basic wood density, tonnes d.m. m^{-3} merchantable volume

BEF_2 = biomass expansion factor for conversion of merchantable volume to aboveground tree biomass, dimensionless.

R = root-to-shoot ratio, dimensionless

CF = carbon fraction of dry matter (default = 0.5), tonnes C (tonne d.m.)$^{-1}$

https://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/Chp3/Chp3_2_Forest_Land.pdf

Inventory-based methods

The Lesvos pine forest example:

Using the permanent forest plot network of the UAegean, we can estimate the annual gain and loss of biomass

These forest monitoring plots have been established along a post-fire chronosequence (to explore the effects of stand structure on C fluxes) and alone an elevation gradient (to explore the effects of microenvironmental conditions on C fluxes).

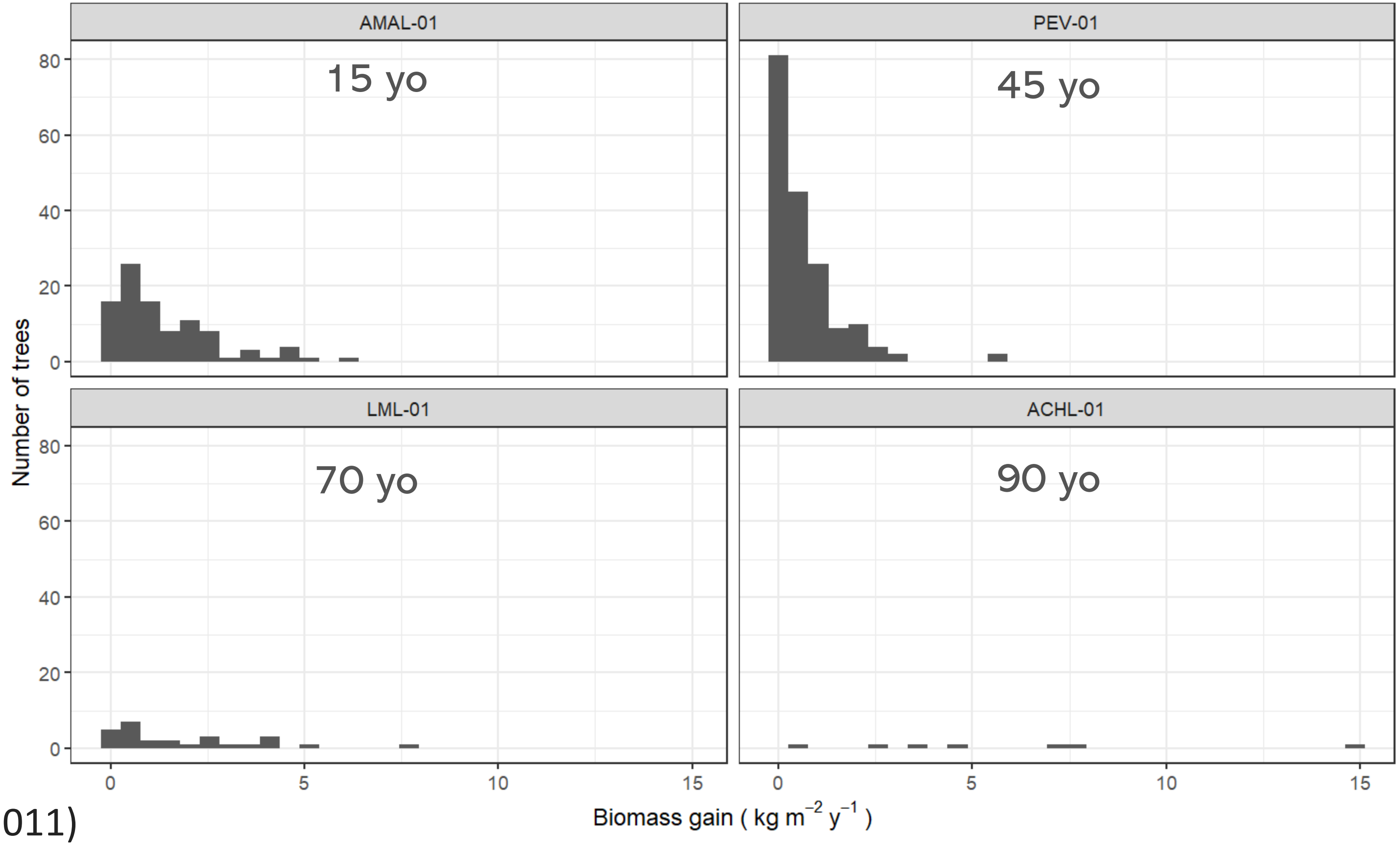
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2024 Maxar Technologies
Image © 2024 Airbus

Inventory-based methods

The Lesvos pine forest example:

Using the permanent forest plot network of the UAegean, we can estimate the annual gain and loss of biomass

These plots summarise annual biomass gains between 2019 and 2022



$lnB = 6.212 + 1.774\ln(D)$ (Ziannis et al. 2011)

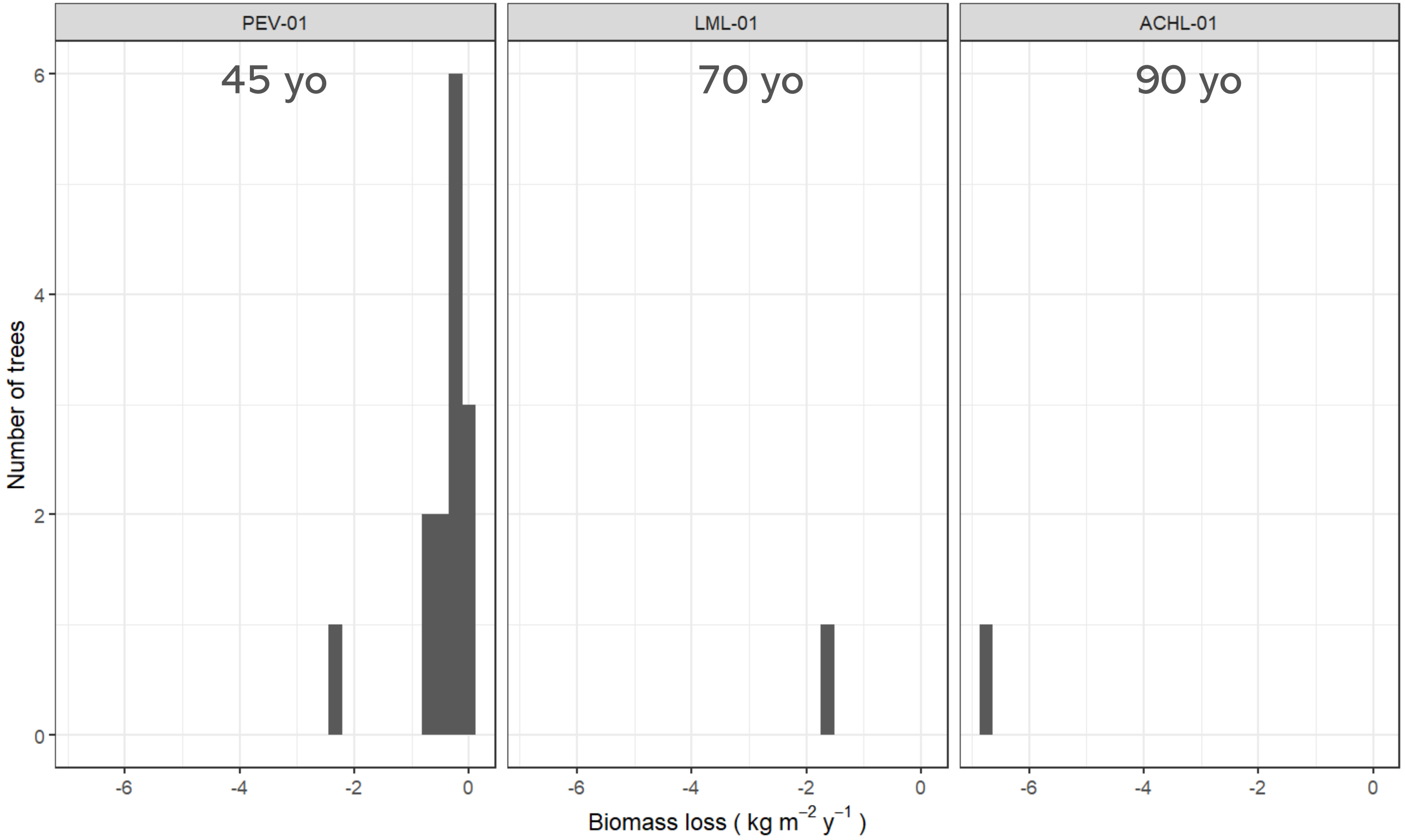
Co-funded by
the European Union

Inventory-based methods

The Lesvos pine forest example:

Using the permanent forest plot network of the UAegean, we can estimate the annual gain and loss of biomass

These plots summarise annual biomass losses between 2019 and 2022



Inventory-based methods

The Lesvos pine forest example:

Using the permanent forest plot network of the UAegean, we can estimate the annual gain and loss of biomass

Results indicate that above ground biomass growth (ABG) is stronger in younger plots

+ but soil fluxes are not included in these calculations

Plot	Gain (kg m^{-2} y^{-1})	Loss (kg m^{-2} y^{-1})	Δbiomass (kg m^{-2} y^{-1})
AMAL (15 yo)	0.148		0.148
PEV (40 yo)	0.130	0.006	0.124
LML (70 yo)	0.056	0.002	0.054
ACHL (90 yo)	0.046	0.008	0.038

Co-funded by
the European Union

Satellite-based methods

The basic idea is to train a statistical model of biomass B or volume V with data coming from satellite data flows. The basic satellite data flows currently used are:

- Optical remote sensing data (for example sentinel images)
- Synthetic aperture radar (SAR) data,
- Light detection and ranging (LiDAR) data

Each data flow has its pros and cons

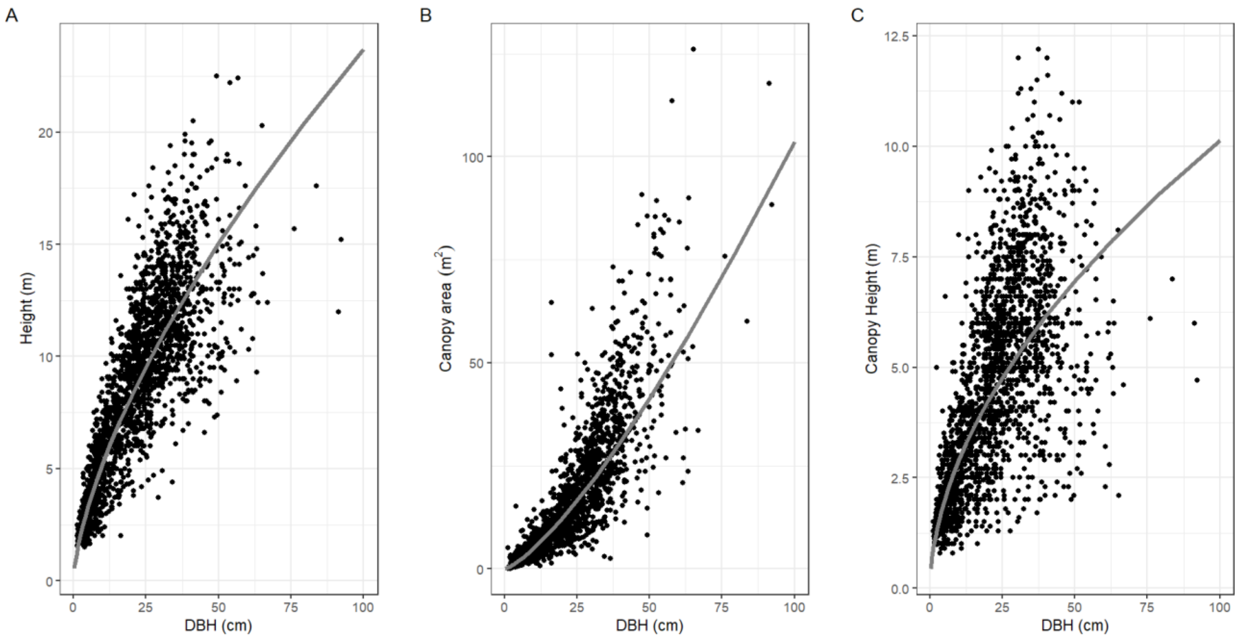
Co-funded by
the European Union

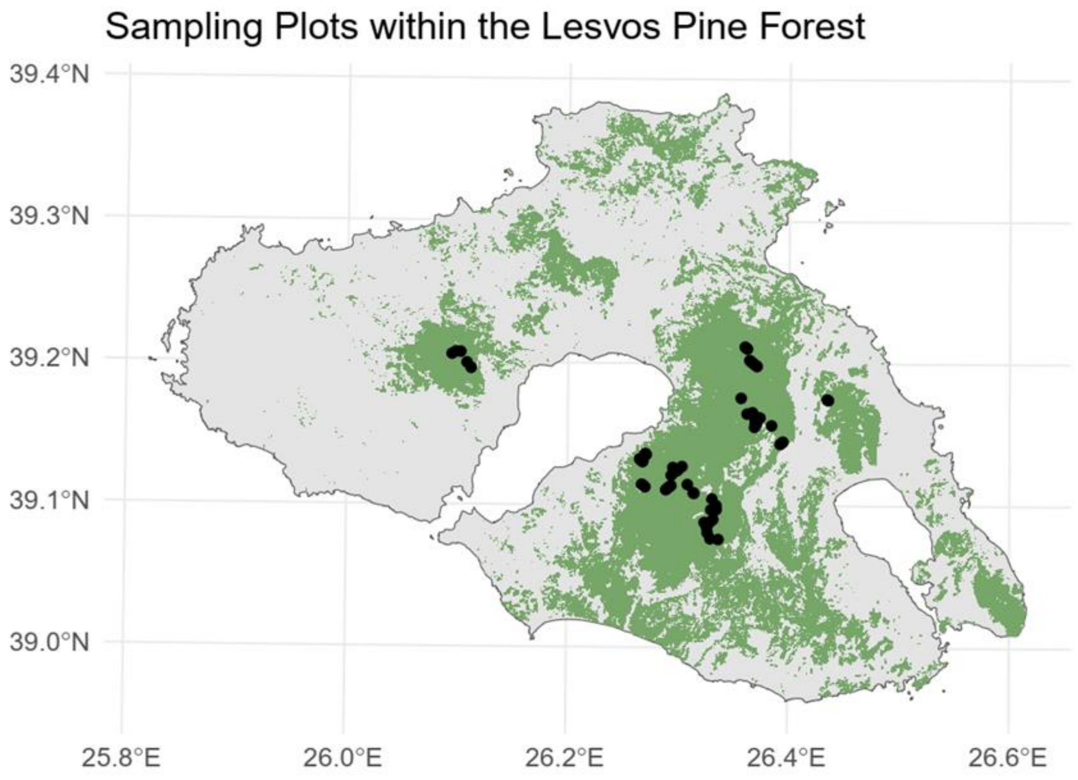
Satellite-based methods

The Lesvos pine forest example:

→ 80 square 30x30 m plots, each tree identified and measured, LAI and litter biomass measured *in situ.*

Allometric equations for *P. brutia*




Sampling Plots within the Lesvos Pine Forest

Satellite-based methods

The Lesvos pine forest example:

We trained random forest models to predict various stand level variables such as stem density, average D, H, litter biomass and total aboveground biomass using topographic, geological and RS indices.

→Optical data performed better for biomass variables

→LIDAR data performed better for stand structure variables

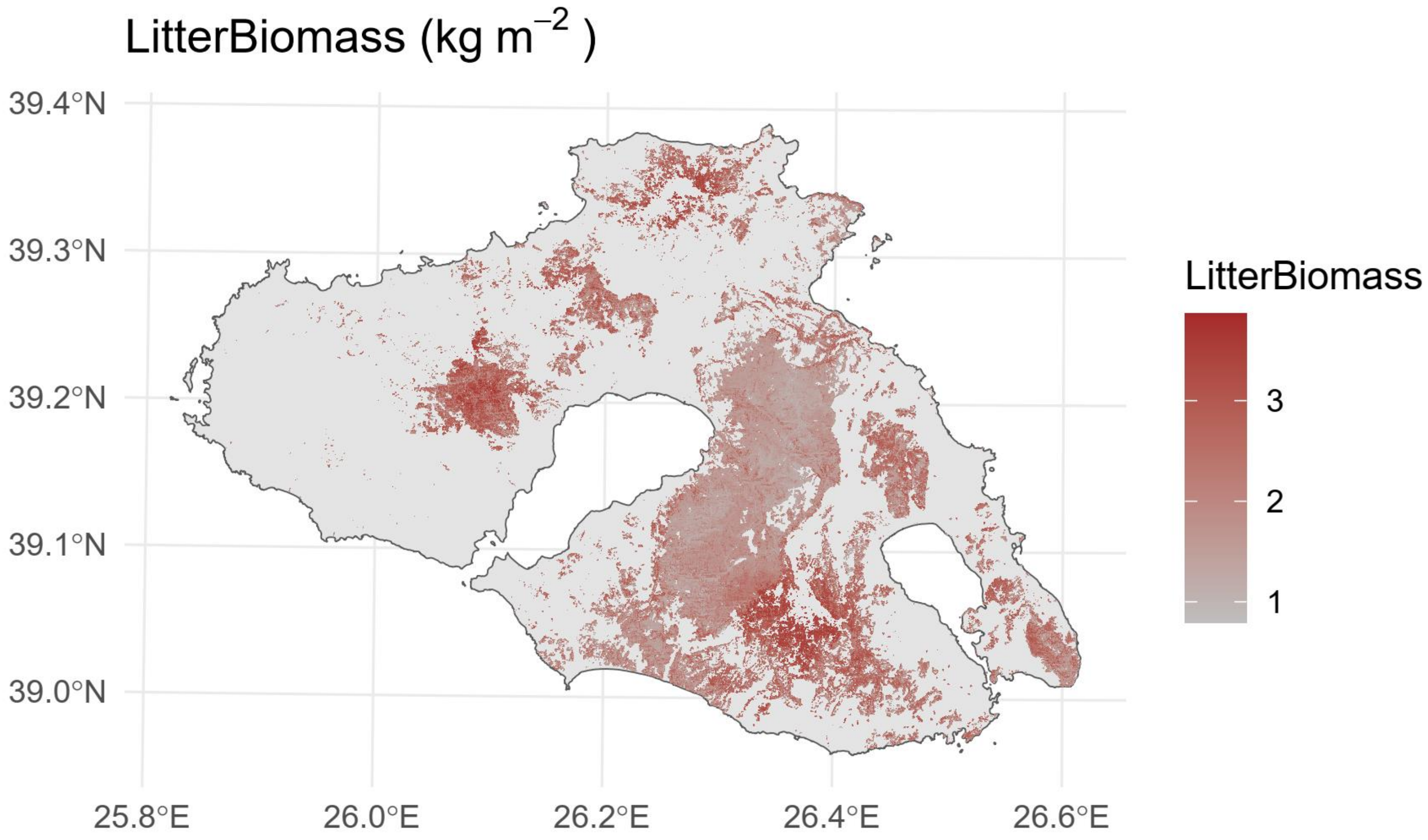
	N	DBH	Height	Hcrown	Canopy Area	Litter Biomass	Biomass
Optical RS Data							
intercept	-8.250	38.165	8.731	0.738	73.540	-2.958	-8.388
Geology:Sediments							
Geology:Volcanic	-3.934	6.258	3.206	1.855	10.730	0.605	1.527
Slope%			0.038			0.011	0.043
Elevation		0.015		-0.002		0.002	0.003
HLI				-2.655	-23.817	1.497	
NDVI	26.616	-30.202		9.436	-57.399	3.915	26.231
R^2	0.087	0.107	0.179	0.439	0.167	0.470	0.600
RMSE	5.716	7.950	2.568	1.367	10.032	0.606	2.165
LIDAR RS Data							
intercept	18.196	-2.627	-0.626	-0.068	-6.749	1.076	3.096
Geology:Sediments							
Geology:Volcanic					10.600		-2.120
Slope%				0.015		0.009	
Elevation	0.025	-0.028	-0.012	-0.005	-0.033		
HLI							
PAI (GEDI)		-7.251		1.341			
Cover (GEDI)	27.829				-56.914	0.644	16.191
Height (GEDI)	-1.915	2.849	0.906	0.296	3.968		
R^2	0.302	0.378	0.679	0.741	0.358	0.076	0.467
RMSE	4.538	6.297	1.670	0.877	8.637	0.606	2.189

Co-funded by
the European Union

Satellite-based methods

The Lesvos pine forest example:

We then used the model to upscale for the whole pine forest of the island.

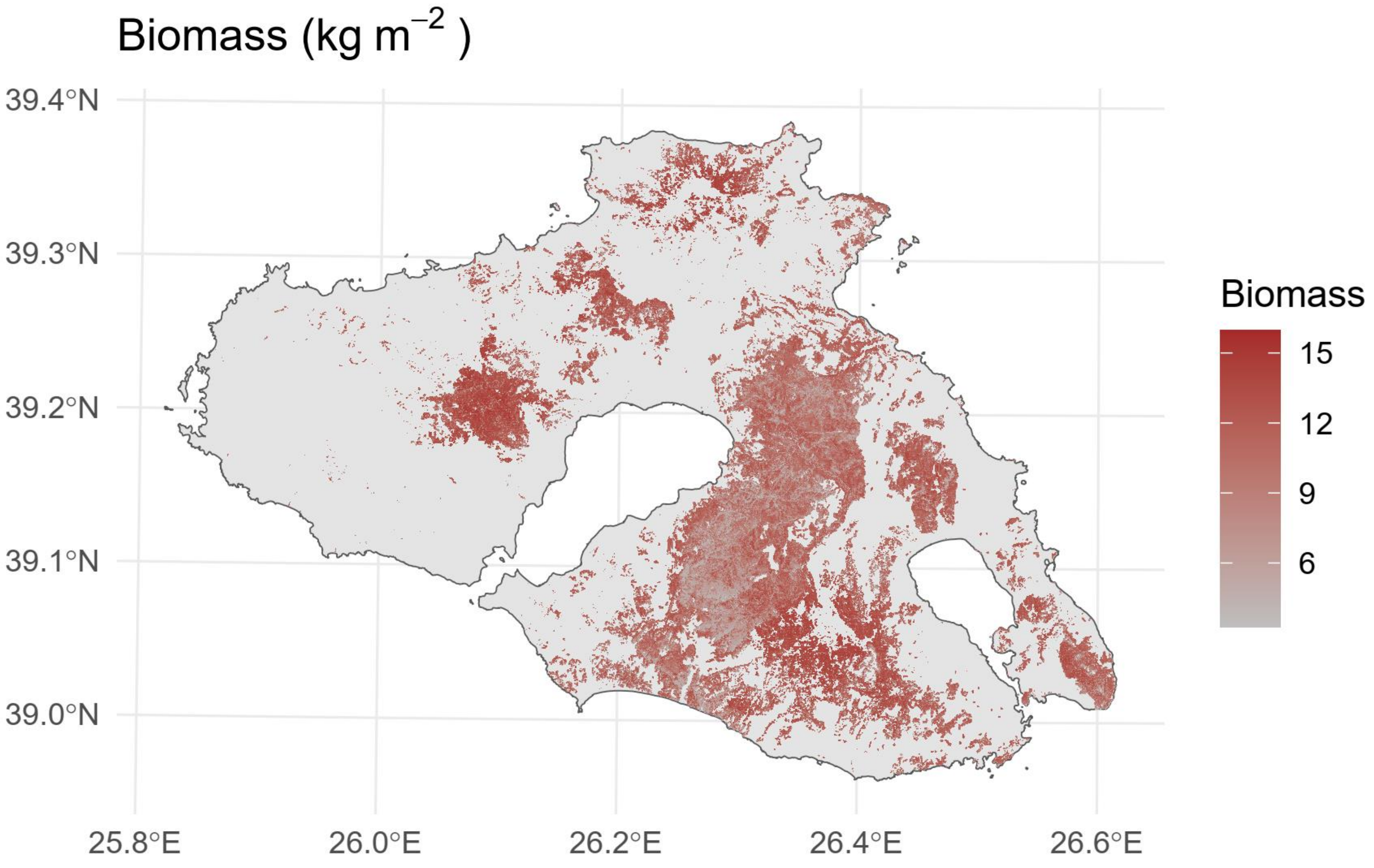


Co-funded by
the European Union

Satellite-based methods

The Lesvos pine forest example:

We then used the model to upscale for the whole pine forest of the island.



Satellite-based methods

The Lesvos pine forest example:

Now, as this is a near real time prediction, we can use the model to estimate differences between points in time

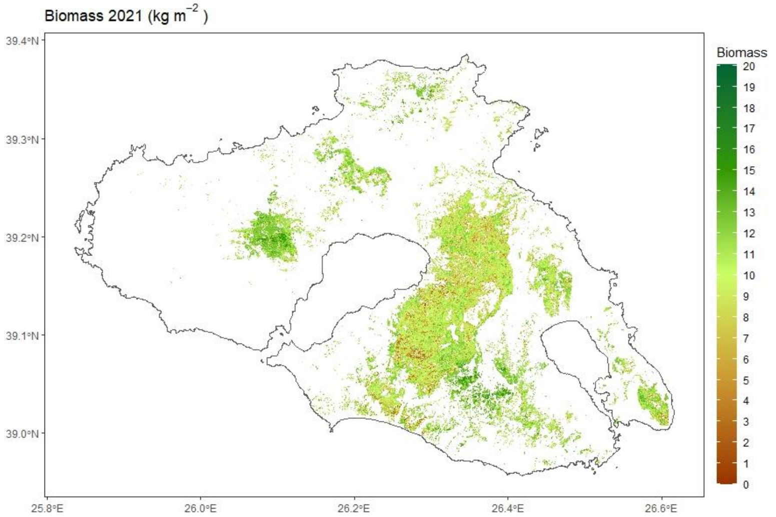
Η φωτιά στη Λέσβο μέσα από 20 συγκλονιστικές φωτογραφίες και βίντεο -Οι φλόγες έφθασαν στην παραλία

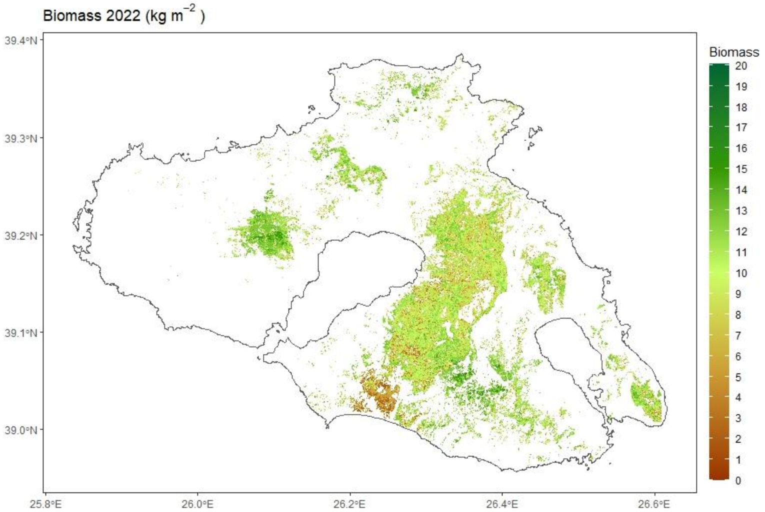
Φωτιά στα Βατερά Λέσβου

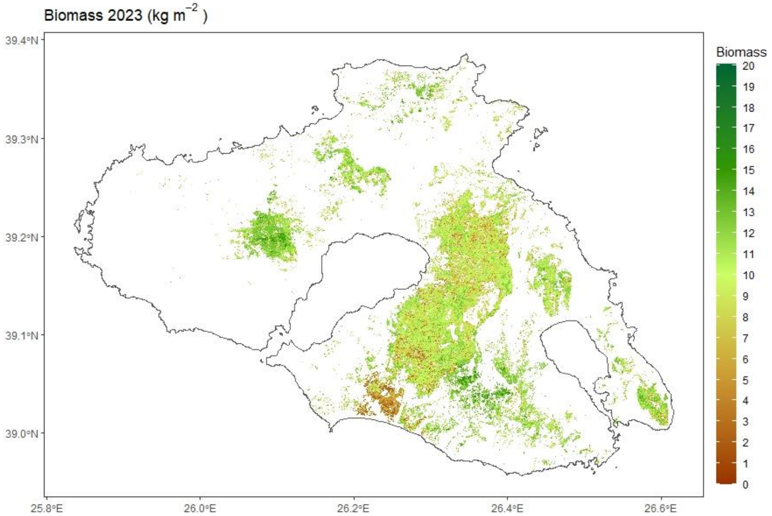
NEWSROOM IEFIMERIDA.GR
23/07/2022 19:12

Μαίνεται από το πρωί του Σαββάτου η φωτιά που ξέσπασε στην περιοχή Βατερά της Λέσβου, με τον καπνό μάλιστα να φθάνει μέχρι τις Κυκλάδες

ΡΟΗ ΕΙΔΗΣΕΩΝ







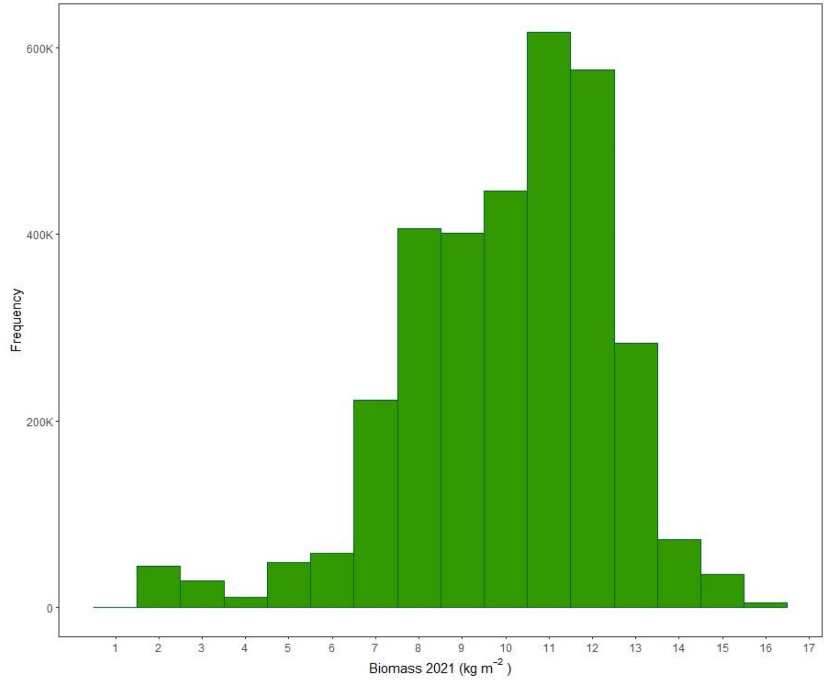
Satellite-based methods

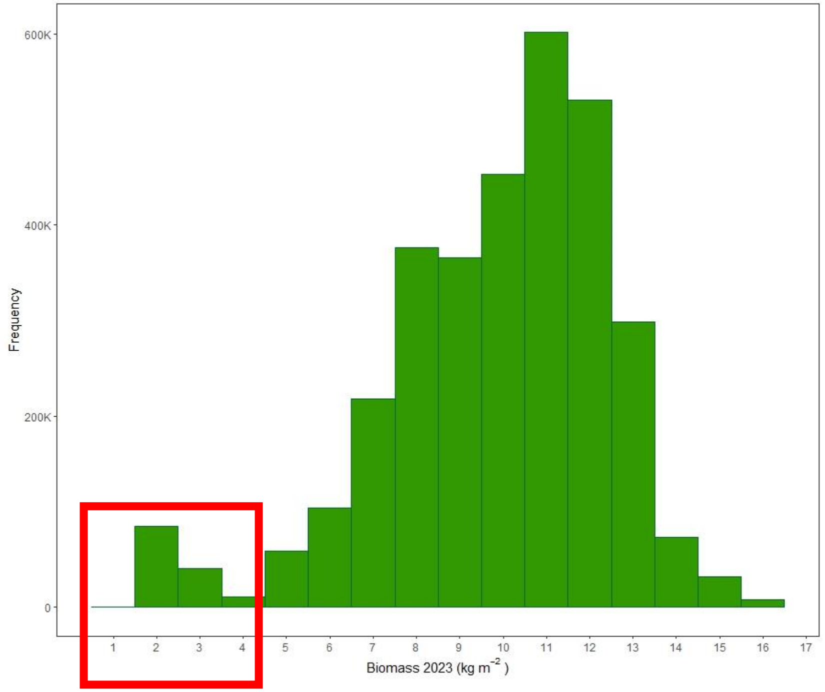
The Lesvos pine forest example:

Now, as this is a near real time prediction, we can use the model to estimate differences between points in time

and estimate carbon storage or release

For example, the average (aboveground) C stock across the island was reduced from ~ 10.0 to 9.8 kg m^{-2} mainly due to the 2022 wildfire.





2022 Vatera forest wildfire

Process-based methods

These methods are based on the development of process-based models that simulate vegetation dynamics from first principles . Data from inventory and satellite methods can be fused into these approaches to initialize/constrain/validate them.

Process-based models can be applied from the plot to the regional scale and also have the ability to make longer-term projections, including for example climate change effects on forest function and dynamics.

Local scale models, parameterized with local species traits data provide in general more accurate predictions.

Co-funded by
the European Union

Process-based methods

The Lesvos pine forest example:

During the years we have developed two process-based forest models, parameterized for the dominant tree species found in Greece.

A forest-gap dynamics model (Fyllas et al. 2007), parameterized with annual tree-ring width data.

A physiological- and individual- based model (Fyllas et al. 2014), parameterized with photosynthetic response curves.

Co-funded by
the European Union

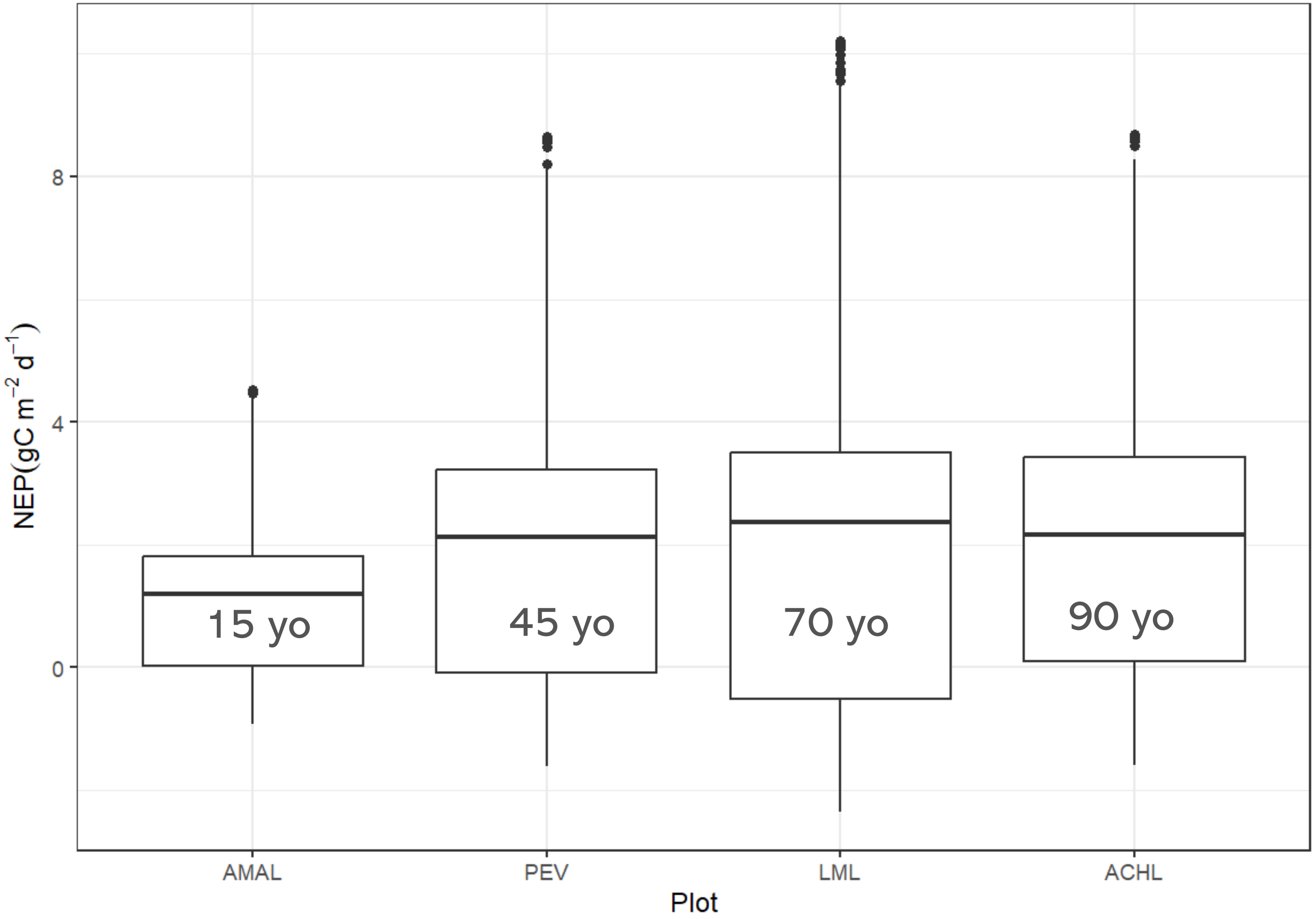
Process-based methods

The Lesvos pine forest example:

These models can be used to explore how forest stands absorb carbon for example:

along post-fire gradients.

These simulations indicate that mature (~70 yo) pine stands are probably absorbing C at the fastest rate.



Co-funded by
the European Union

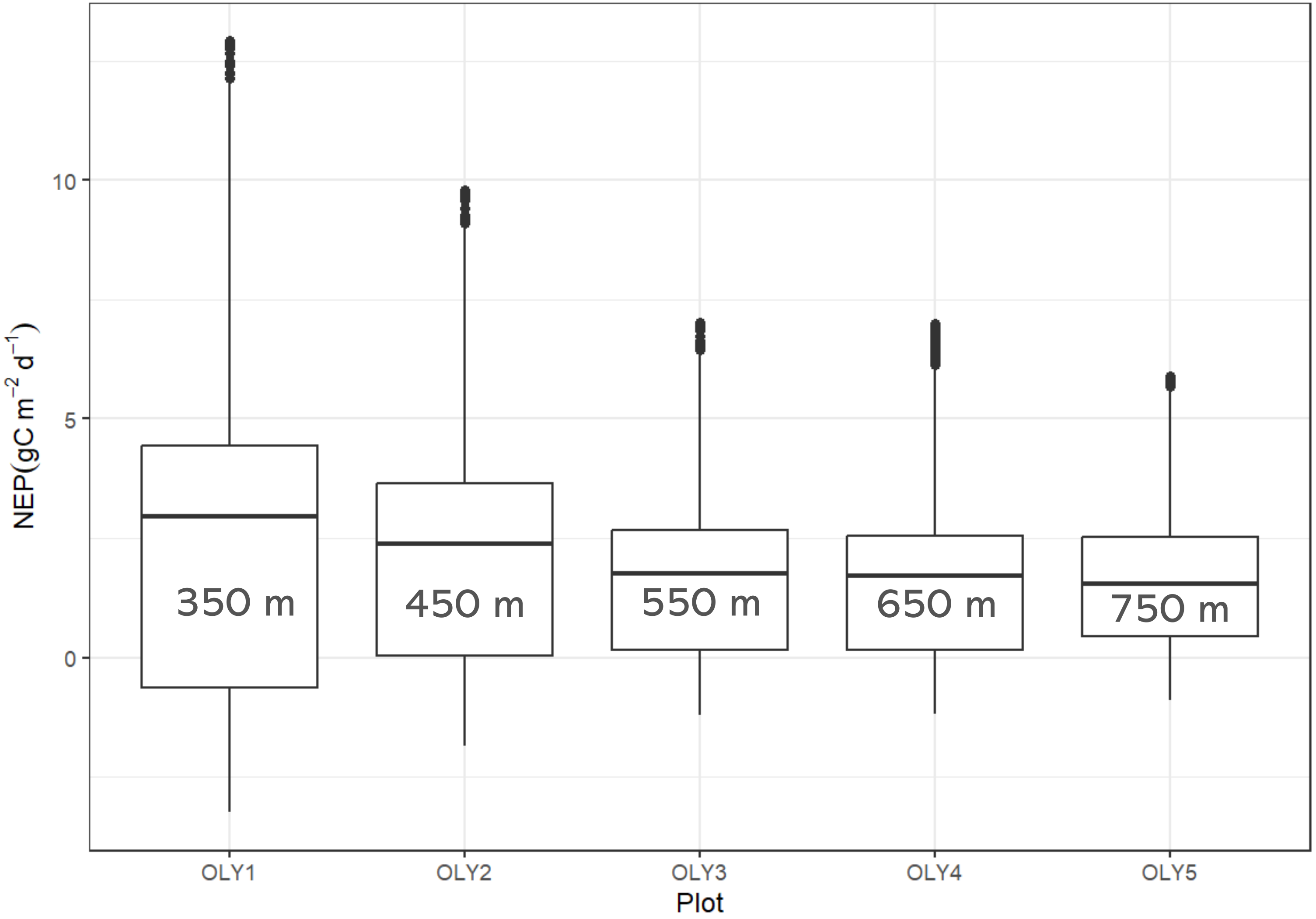
Process-based methods

The Lesvos pine forest example:

These models can be used to explore how forest stands absorb carbon for example:

along elevation gradients.

These simulations indicate that with the Lesvos pine forest, microclimate variability does not substantially affect C storage



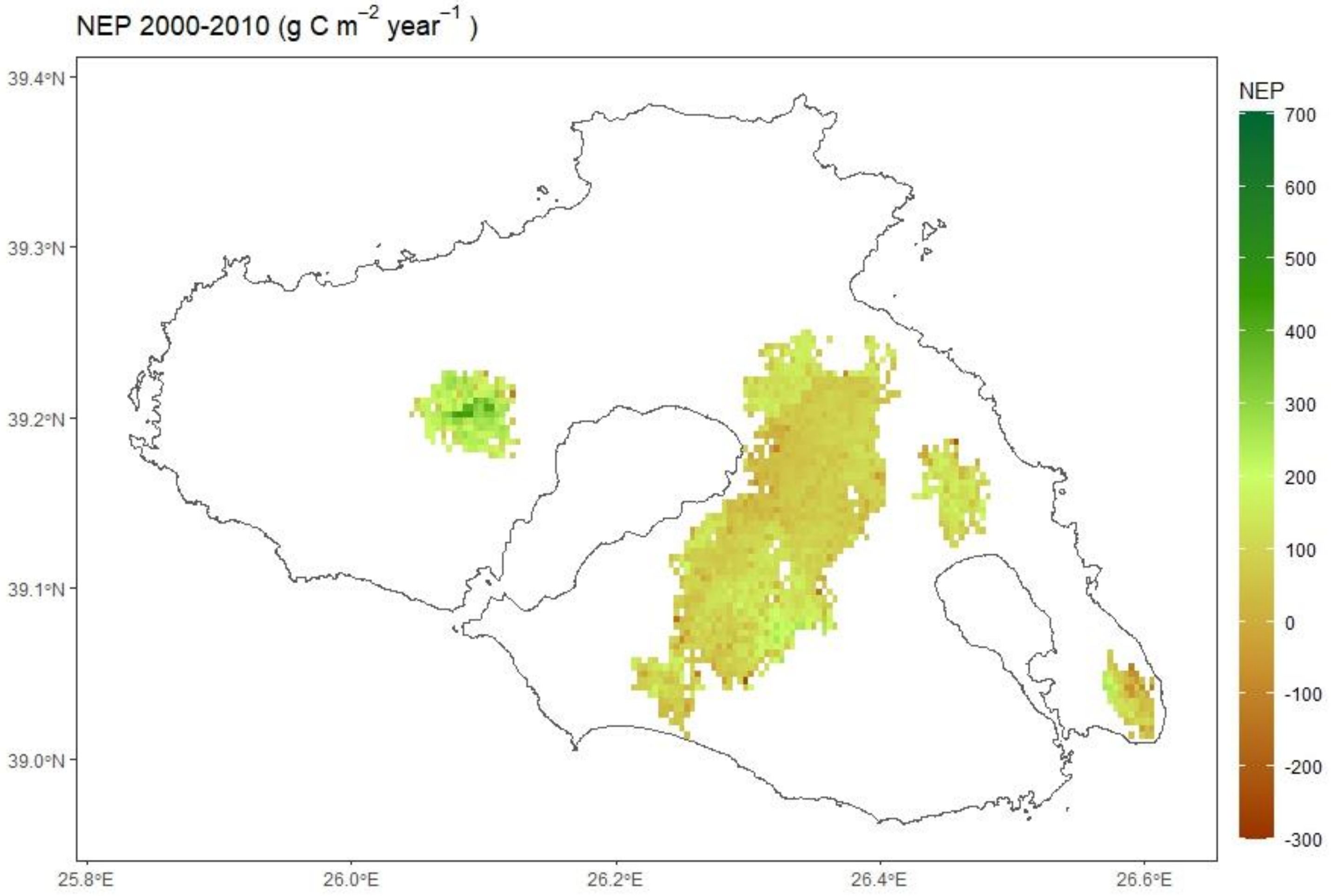
Co-funded by the European Union

Process-based methods

The Lesvos pine forest example:

These models can be applied at the regional scale (whole island), identifying areas that are hotspots of C storage

These simulations follow a **baseline climate scenario**, assuming a no fire – no harvesting scenario.

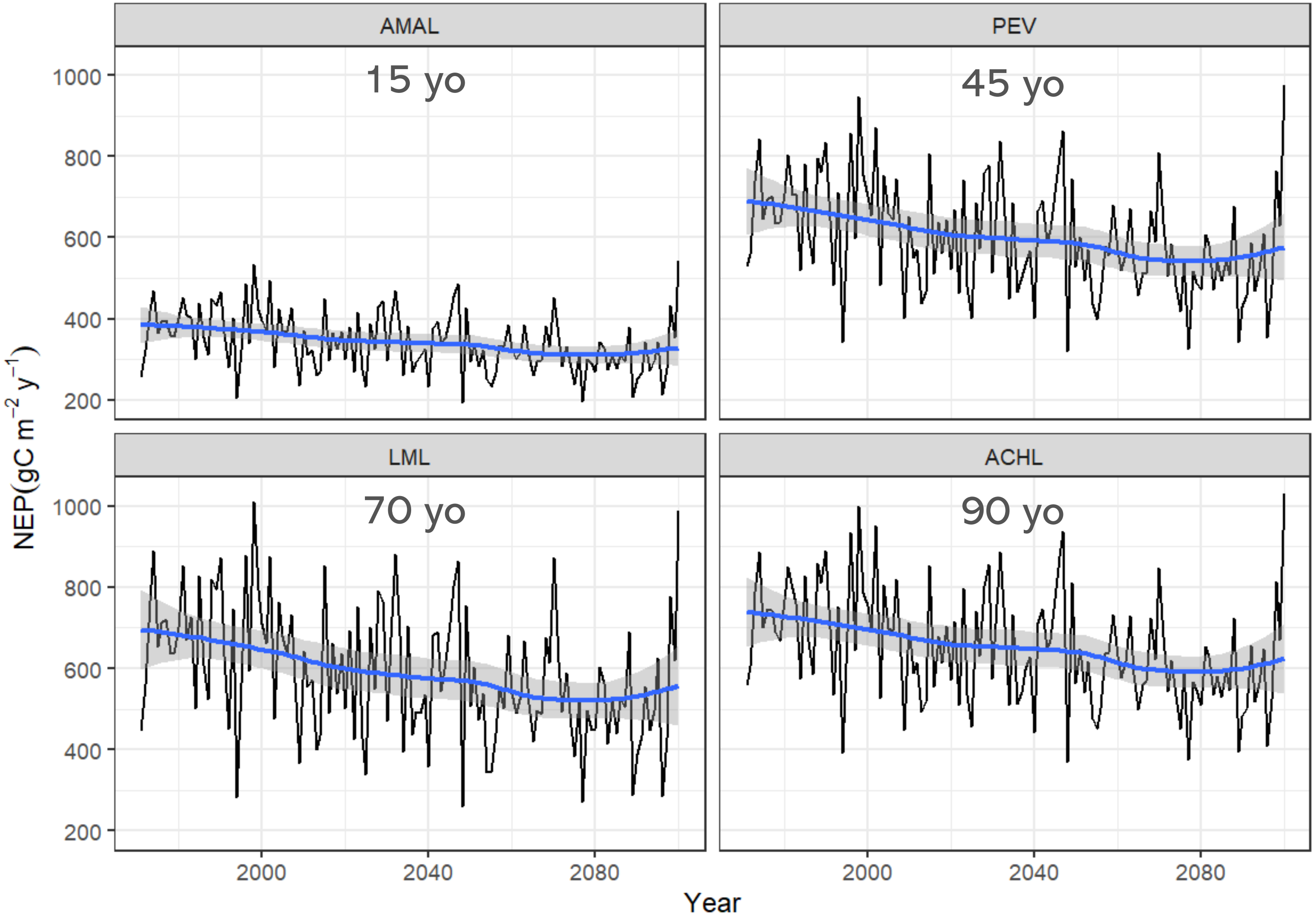


Process-based methods

The Lesvos pine forest example:

And they can also be applied to project the effects of climate change on the pine forest storage capacity

These simulations follow an **RCP 4.5 climate change scenario**, assuming a no fire – no harvesting scenario



Co-funded by the European Union

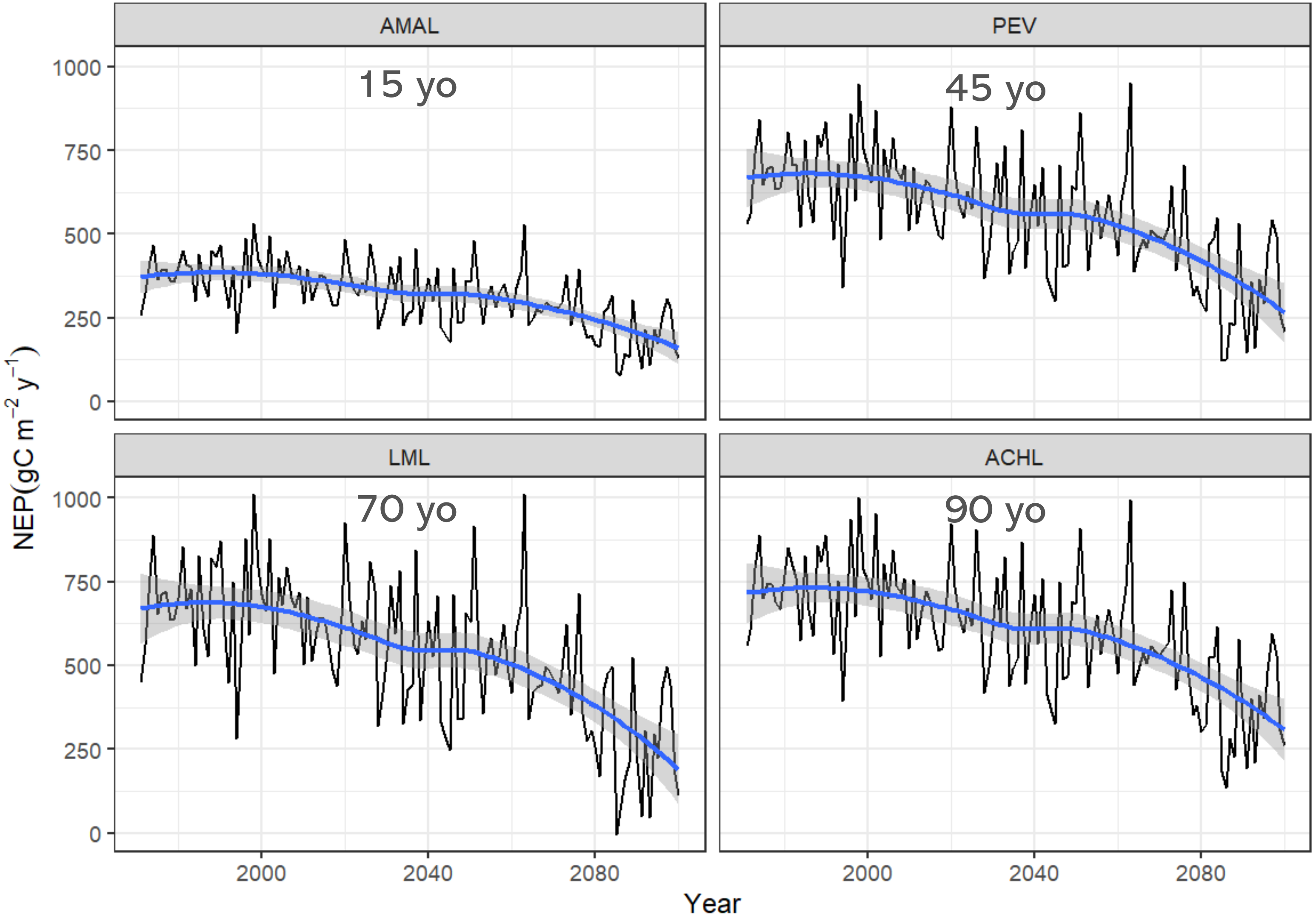
Process-based methods

The Lesvos pine forest example:

And they can also be applied to project the effects of climate change on the pine forest storage capacity

These simulations follow an **RCP 8.5 climate change scenario**, assuming a no fire – no harvesting scenario

→ Diminishing capacity of these ecosystems to capture C with increasing CC severity



Co-funded by the European Union

Some concluding remarks

- A range of methods available to estimate C storage and fluxes
- Pros and cons depending on the level of accuracy required and scale of implementation
- Tips: Know your species (ecological and ecophysiological traits)

  Know your forest (permanent monitoring plots provide crucial info)
- Look also underground (Soil C storage and dynamics very important)
- Try to take into account disturbances (fires) and management (harvesting)
- Please remind yourself that C storage is not the only service provided by ecosystems

Co-funded by
the European Union

Thank you for your attention

nfyllas@biol.uoa.gr

YOUTH AND LIFELONG LEARNING FOUNDATION

Co-funded by the European Union

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 2023 1 EL02 KA220 YOU 000158211. It reflects only the author's view and that the European Commission is not responsible for any use that may be made of the information it contains.