Best practices for the management of low-elevation Mediterranean pine forests to optimize carbon and water balance in the context of climate change

Developed in the framework of the project "Management of Mediterranean pine forest for optimizing carbon and water balance under climate change" (PineOptim) (2024-2025)

Carbon Sequestration

Resilience to Drought

Adaptive management

The "PineOptim" project is implemented within the framework of the action of H.F.R.I. "Funding of Basic Research (Horizontal Support of all Sciences)" of the National Recovery and Resilience Plan "Greece 2.0", funded by the European Union – NextGenerationEU (HFRI Project Number: 016258).

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The challenges under the climate change regime

The low-elevation Mediterranean pine forests, and especially the ecosystems of Aleppo pine (*Pinus halepensis*) and Brutian pine (*Pinus brutia*), have a high ecological and socio-economic value. They make a substantial contribution to carbon sequestration and biodiversity conservation.

Climate change intensifies drought and increases temperatures, placing significant pressure on the water balance of pine forests and reducing their resilience.

At the same time, the more frequent and severe occurrence of forest fires threatens the structure, function, and long-term sustainability of Mediterranean pine forests.

The **PineOptim** project evaluates and proposes forest management practices that enhance the water and carbon balance in low-elevation pine forests. Through systematic ecological monitoring, it identifies best practices that support forests' adaptation to climate change and enhance their potential to mitigate its impacts.

This brochure brings together the scientific results of the project, providing evidence-based and actionable guidelines for researchers and students, forest and environmental policymakers, and forest managers in the public and private sectors.

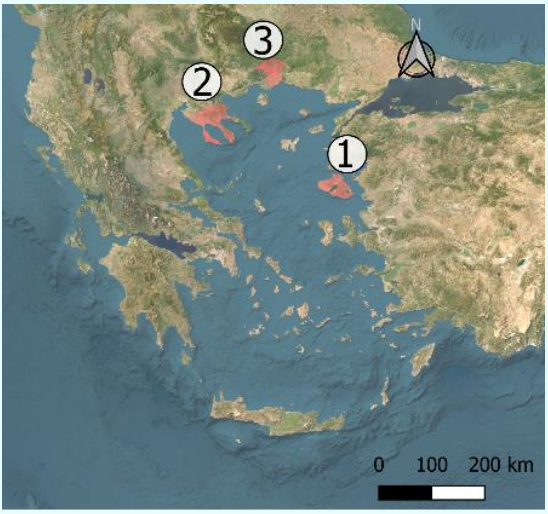
Methodology of PineOptim

The overall objective of the **PineOptim** project was to propose management practices that **optimize carbon sequestration** and **water use efficiency** in low-elevation pine forests, under current and **expected climate conditions**. The methodology included:

- Development of a common, harmonized monitoring protocol.
- Collection and analysis of field data on carbon and water fluxes.

Applied to:

1. Natural *P. brutia* forests of Lesvos: different post-fire age and no management interventions.
2. A natural coastal forest of Aleppo pine in Sani, Chalkidiki: removal of the understory - overstory of different densities.
3. Peri-urban forest of *P. brutia* in Xanthi: Different thinning intensity of the overstory.



- Evaluation of the effect of alternative management practices on the productivity of the Brutian and Aleppo pine ecosystems.
- Development of a model for estimating ecosystem productivity and fire risk under different climate change scenarios.

Methodology of PineOptim

Continuous monitoring in the field:
Use of low-cost and easy-to-use sensors by non-specialized personnel to measure tree growth and microclimatic soil and air parameters.

Field sampling and measurements:

- Biometric data for the estimation of biomass on the overstory and understory vegetation.
- Measurements of photosynthesis, water potential, and moisture content in needles and twigs.
- Measurements of soil respiration, decomposition of the forest floor, and biomass accumulation through litterfall.

Modeling:
A mechanistic model was used that simulates the carbon fluxes in each tree. The model was fed with all the above-mentioned data to estimate productivity at the ecosystem level and was validated against actual carbon and water fluxes data from an Eddy covariance tower The validated model was used to produce simulations under different climate and forest management scenarios.

Key concepts

Net Ecosystem Productivity – NEP *

NEP expresses the amount of carbon captured or released annually by an ecosystem, such as a forest.

Integrated Fire Index – IFI *

The IFI ~~indicator~~ estimates the potential risk of a fire ignition based on the microclimatic conditions of the understory vegetation, the density and moisture content of the vegetation, as well as meteorological factors. IFI values range from 1 to 5, with 1 indicating a low risk of fire ignition and 5 indicating a high risk. The index does not refer to the fire's spatial spread and extinguishment.

Local climate change scenarios

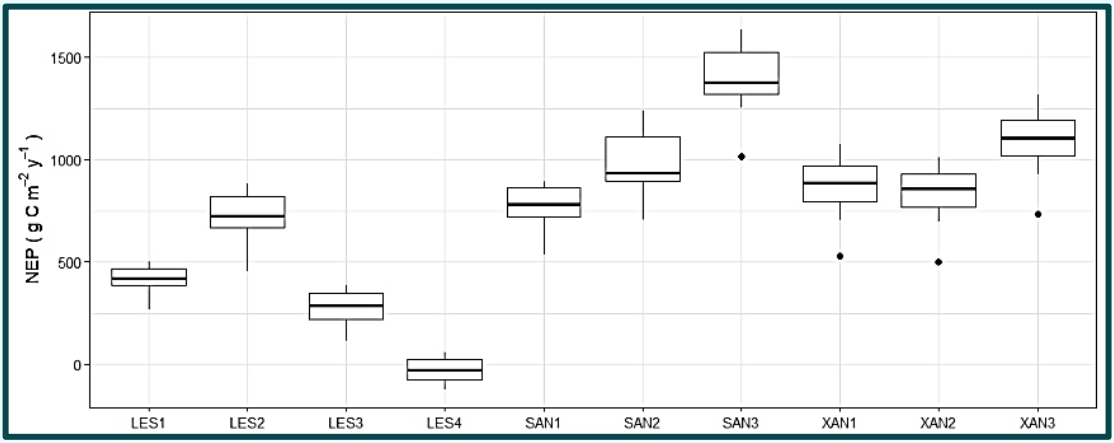
SSP2 4.5 (Moderate scenario): If the current increasing trend in greenhouse gas concentrations continues until 2050 and is leveled thereafter, an increase in mean annual temperature of 1.8–2.3 °C and an increase in annual precipitation of approximately 2–12% are projected by the end of the century.

SSP5 8.5 (Pessimistic scenario): If the combustion of fossil fuels and the continuous increase in greenhouse gas concentrations persist, an increase in mean annual temperature of 4.0–4.7 °C and a decrease in annual precipitation of approximately 15–20% are projected by the end of the century.

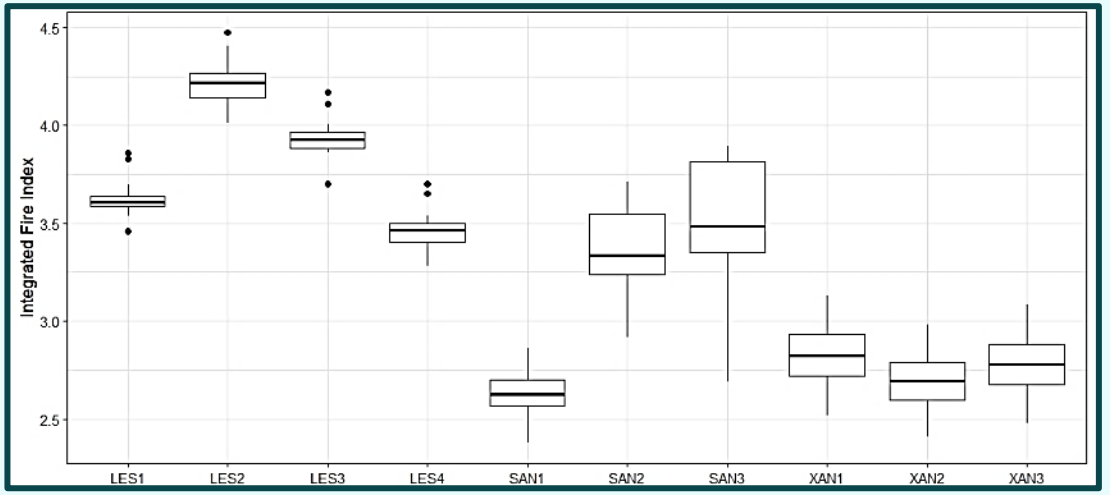
** The NEP and IFI results of the present guidelines derive from the simulations of the model developed within the project.*

Simulation Results

Carbon sequestration and fire ignition risk under current conditions



Net Ecosystem Productivity (NEP) across all study stands of the PineOptim project during the period 2013–2025 under current management practices



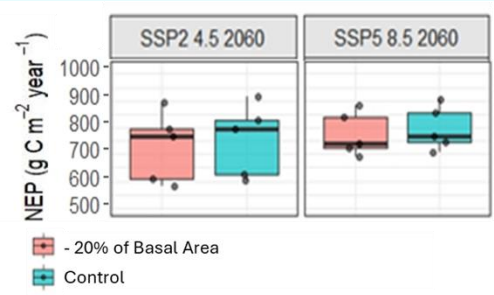
Integrated Fire Index (IFI) across all study stands of the PineOptim project during the dry–hot season (June–September, 2013–2025) under current management practises

LES1: 20 post-fire years
LES2: 46 post-fire years
LES3: 78 post-fire years
LES4: 92 post-fire years
(*no management interventions*)

SAN1: No intervention, low understory & overstory density
SAN2: Understory removal
SAN3: No intervention, high understory & overstory density

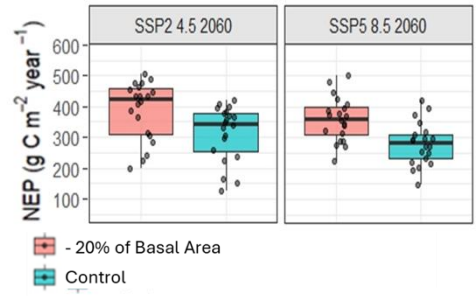
XAN1: No overstory thinning
XAN2: Moderate overstory thinning
XAN3: Intensive overstory thinning

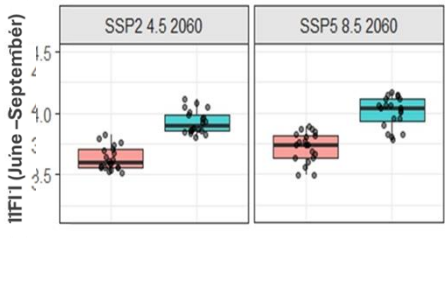
Lesvos – Simulation Results of NEP and IFI
(overstory thinning & climate scenarios)



LES2:
46 years after fire

Estimated Net Ecosystem Productivity (NEP) and Fire Ignition Risk Index (IFI) in 2060 for 46-year-old Aleppo pine stands in Lesvos, **if moderate overstory thinning (removal of 20% of basal area)** is applied instead of the current absence of management interventions, based on the moderate (SSP2 4.5) and pessimistic (SSP5 8.5) climate scenarios.





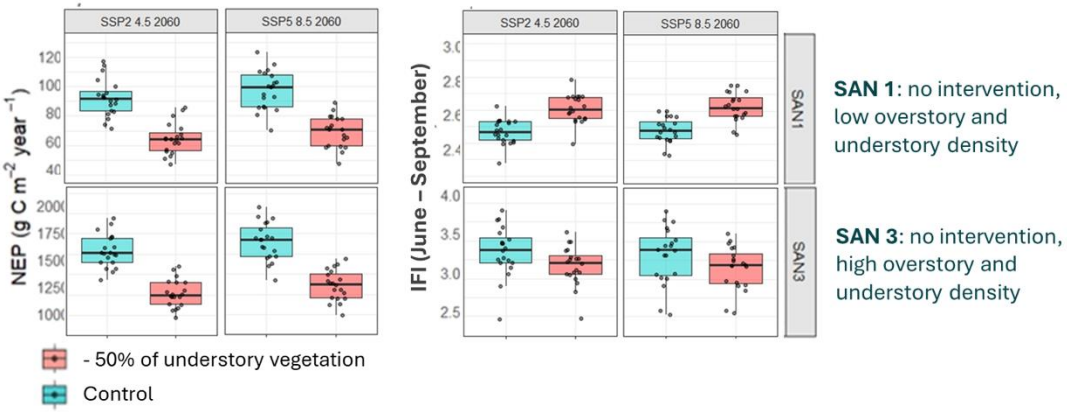
LES3:
70 years after fire

Estimated Net Ecosystem Productivity (NEP) and Fire Ignition Risk Index (IFI) in 2060 for approximately 70-year-old Aleppo pine stands in Lesvos**, if intensive overstory thinning (removal of 40% of basal area)** is applied instead of the current absence of management interventions, based on the moderate (SSP2 4.5) and pessimistic (SSP5 8.5) climate scenarios.

In the studied stands of Lesvos:

- ✓ Under both climate scenarios, moderate thinning at around 45 years of age enhances fire protection without negatively affecting carbon sequestration.
- ✓ Intensive thinning at around 70 years of age increases long-term carbon sequestration by approximately 25% and at the same time reduces the fire ignition risk by approximately 8% (mean values across both climate scenarios).

Sani, Chalkidiki – Simulation Results of NEP and IFI
(understory removal & climate scenarios)



Estimated Net Ecosystem Productivity (NEP) and Fire Ignition Risk Index (IFI) in 2060 for Aleppo pine stands in Sani, Chalkidiki, **if 50% understory removal is applied in stands with low or high overstory and understory density**, based on the moderate (SSP2 4.5) and pessimistic (SSP5 8.5) climate scenarios

In the studied stands in Sani, Chalkidiki:

- With low overstory and understory density, removal of 50% of the understory vegetation is expected to lead to:

✓ A decrease in carbon sequestration of approximately 30% (mean values across both climate scenarios).

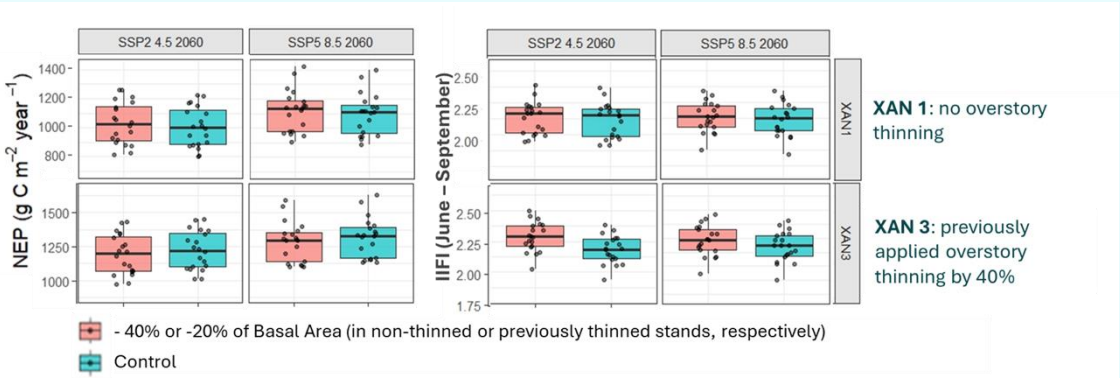
✓ An increase in fire ignition risk of approximately 5% (mean values across both climate scenarios).

- With high overstory and understory density, removal of 50% of the understory vegetation is expected to lead to:

✓ A decrease in carbon sequestration of approximately 25% (mean values across both climate scenarios).

✓ A decrease in fire ignition risk of approximately 5% (mean values across both climate scenarios).

Xanthi – Simulation Results of NEP and IFI
(overstory thinning & climate scenarios)



Estimated Net Ecosystem Productivity (NEP) and Fire Ignition Risk Index (IFI) in 2060 for Aleppo pine stands in Xanthi, **if 40% overstory thinning is applied to a stand with no previous thinning (XAN1) or 20% thinning is applied to a stand that underwent 40% thinning 10 years ago (XAN3)**, based on the moderate (SSP2 4.5) and pessimistic (SSP5 8.5) climate scenarios.

In the studied areas in Xanthi, under both climate scenarios:

- Strong overstory thinning (40% of basal area) in a stand with no previous thinning is expected to lead to:

✓ A slight increase in carbon sequestration (approximately 3% on average across both climate scenarios).

✓ No change in fire ignition risk.

- Repetition of overstory thinning, even moderate (20% reduction of basal area), within a 10-year period, is expected to lead to:

✓ A decrease in carbon sequestration.

✓ No significant change in fire ignition risk.

Best Practices

(For low-elevation pine stands originating from natural post-fire regeneration, without management interventions)

Proposed best management practices to increase carbon sequestration and reduce fire ignition risk:

- **Moderate thinning (up to 20% of basal area) between 20 and 40 years of age,** mainly to reduce competition and enhance fire protection.
- **Strong selective thinning (up to 40% of basal area) after 45 years, and no later than around 70 years of age,** to allow the establishment of native broadleaf species.
- **Regeneration thinning after 70 years of age** to promote natural regeneration of the stands.

Note: These recommendations apply on the condition that the stands are protected from grazing.

LES1: 20 post-fire years

LES2: 46 post-fire years

LES3: 78 post-fire years

LES4: 92 post-fire years

Best Practices

(For natural coastal pine forests, where understory removal of evergreen broadleaf species is applied for fire protection)

Proposed best management practices to increase carbon sequestration and reduce fire ignition risk:

- **Understory removal should not exceed 50% of understory ground cover,** as higher percentages lead to a strong reduction in carbon sequestration potential.
- **In stands with sparse overstory, 50% understory removal should be avoided,** because this practice not only reduces ecosystem productivity but also increases fire ignition risk due to changes in the microclimatic conditions.
- **Reforestation with pine** (using seeds from the local area) where natural regeneration is low, due to adverse climatic conditions.

SAN1:
No intervention, low understory & overstory density

SAN2:
Understory removal

SAN3:
No intervention, high understory & overstory density

Best Practices

(For managed peri-urban pine forests originating from plantations, where moderate or intensive overstory thinning has already been applied)

Proposed best management practices to increase carbon sequestration and reduce fire ignition risk:

- **Strong thinning (40% of overstory basal area),** because the development of an understory of native broadleaf species increases ecosystem productivity, and therefore carbon sequestration, without increasing fire ignition risk.
- **Thinning should not be repeated within a period shorter than 10 years.**
- The ultimate goal should be natural forest regeneration and the **creation of broadleaf or mixed broadleaf–conifer forests, depending on local conditions.**

10 years post-intervention

XAN1: No overstory thinning

XAN2: Moderate overstory thinning

XAN3: Intensive overstory thinning

Summary

Mediterranean pine forests are under increasing pressure, as climate change intensifies xerothermic conditions and the frequency and severity of wildfires. The results of the **PineOptim** project show that the contribution of these ecosystems to mitigating the impacts of climate change is critically influenced by the management practices applied.

Management of low-elevation Mediterranean pine forests should not focus solely on fire protection or carbon sequestration, but rather on **balancing ecosystem productivity, fire protection, and long-term sustainability**. An integrated approach, **based on combined evaluation of indicators such as NEP and IFI and the use of models**, supports evidence-based decision-making for the long-term sustainability of low-elevation Mediterranean pine forests.

The monitoring protocols developed (Eleftheriadou et al., 2026), along with the proposed best practices emerging from the **PineOptim** project, provide a framework to support climate-adapted management of low-elevation Mediterranean pine forests.

Climate-adapted management is required, using appropriate indicators and models, along with the implementation of contemporary management plans.

Eleftheriadou, N., Mantzari, E. D., Kiorapostolou, N., Sazeides, C. I., Xanthopoulos, G., Markos, N., Spyroglou, G., Bintsi-Frantzi, E., Gouvas, A., Dimitrakopoulos, P. G., Fotelli, M. N., Radoglou, K., & Fyllas, N. M. (2026). An Integrated Monitoring Protocol to Study the Effects of Management on the C Sequestration Potential of Mediterranean Pine Ecosystems. Methods and Protocols, 9(1), 18. https://doi.org/10.3390/mps9010018

Management of Mediterranean pine forest for optimizing carbon and water balance under climate change

Forestry and Management of the Environment and Natural Resources

Department of Environment

Forest Research Institute

Sazeides CI, Kiorapostolou N, Eleftheriadou N, Mantzari ED, Xanthopoulos G, Bintsi-Frantzi E, Gouvas A, Sinodinos, AD, Fyllas NM, Fotelli MN, Dimitrakopoulos PG, *Spyroglou G,* Markos N, Milios E, Kitikidou K, & Radoglou K (2025). *Best practices for the management of low-elevation Mediterranean pine forests to optimize carbon and water balance in the context of climate change*. Available online: https://pineoptim.fmenr.duth.gr/

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PineOptim

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