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Abstract EGU26
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Fine-scale Environmental Filtering and Seed Limitation Shape Early Post-fire Regeneration in Mediterranean *Pinus halepensis* Forests

Atzeni F.[1], Taccaliti F.[2], Marangon D.[2], Lingua E.[2]

[1] Marche Polytechnic University — Department of Agricultural, Food and Environmental Sciences
[2] University of Padova — Department of Land, Environment, Agriculture, and Forestry

EGU26 GENERAL ASSEMBLY

UAV & LiDAR | Random Forest | SHAP Analysis | Post-fire Restoration

Why Here? Why Now?

Mediterranean pine forests are burning more often and more severely. Where will the next generation of trees establish, and where won't it?



The site

Spotorno, Liguria (NW Italy)
Pinus halepensis forest
Burned: 2006 + 2015

Salvage logged both times



The data

RTK GNSS: 329 seedlings mapped
UAV: orthomosaic
LiDAR: DTM + CHM
↓
Microtopographic features



The approach

Spatial point pattern analysis
GLM + GAM
Random Forest
Trained with ecological informed pseudo-absences
↓
5x5 m^2 suitability map

Key Findings — click to explore

Environmental filtering + seed limitation drive regeneration.
No plant–plant interactions.

① Spatial pattern

K_{inhom} & g_{inhom}:
no biotic interactions

Hotspots
(NW ridges)
Vs
coldspots
(drainage lines).

tap to explore

② Multivariate Exploration

PCA
+
angular clustering
MIC
+
dCor matrices

tap to explore

③ TWI & HLI dominate

TWI: strong negative
(moisture)
HLI: positive
(heat load)
Sharp ecological
thresholds

tap to explore

④ Seed limitation

Probability drops
steeply
beyond ~40 m from
surviving adult pines

tap to explore

⑤ 5 m suitability map

Ecologically informed
machine learning
(AUC 0.895)
vs random
(AUC 0.653)
↓
Precision restoration
tool

tap to explore

All figures: Atzeni et al. (2025, in prep.) · Data: UAV + LiDAR (Spotorno, 2024–2025) · R packages: spatstat, randomForest, fastshap, terra, mgcv

Result 1 — Spatial Pattern of Regeneration

Hotspots, coldspots, no biotic interactions

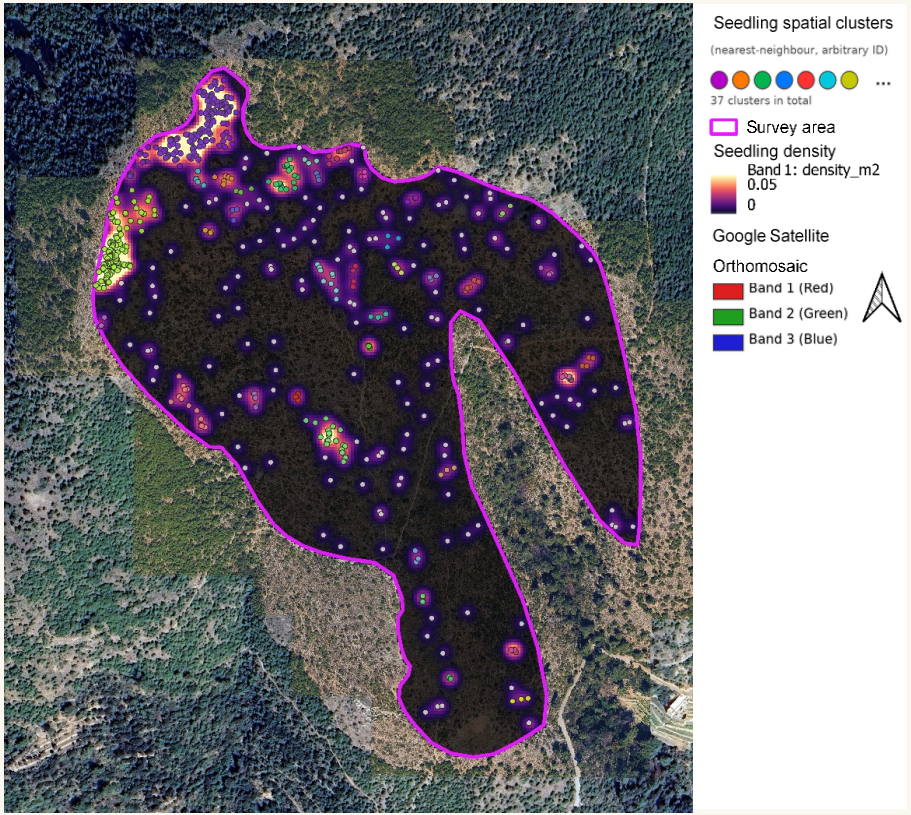


Fig. 2: Kernel-smoothed seedling intensity (hotspots: NW ridges; coldspots: drainage lines)

© Atzeni et al. (2025) — field data & analysis: Atzeni et al.

Key observations

- **Hotspots** in NW sector and interior ridges near surviving adult pines.
- **Coldspots** in drainage lines and depressions, almost no recruits.
- Most seedlings coincide with warm, moderately sloping microsites.

Point pattern analysis

- Kinhom(r) and ginhom(r) remain within Monte Carlo envelopes of the inhomogeneous Poisson null model.
- No aggregation or inhibition at any scale (1–80 m).
- Clusters are made by environmentally driven intensity variation, NOT plant–plant facilitation.

Result 2a — Predictor Structure: MIC & dCor Matrices

Three ecological axes identified

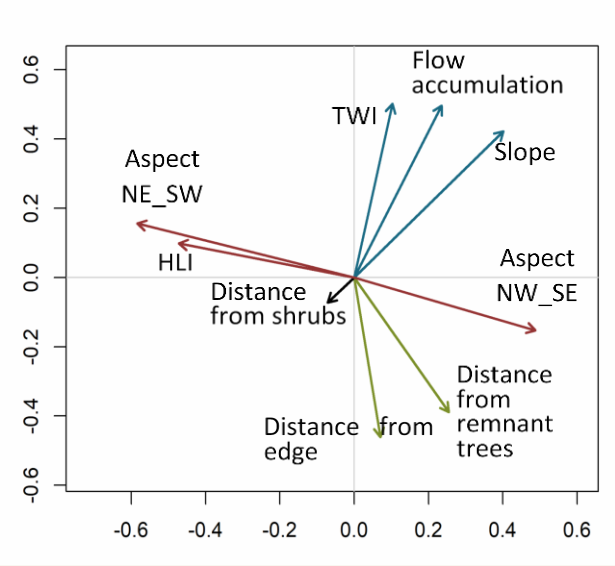


Fig. 4a — PCA biplot (PC1 28.8%, PC2 23.4%)

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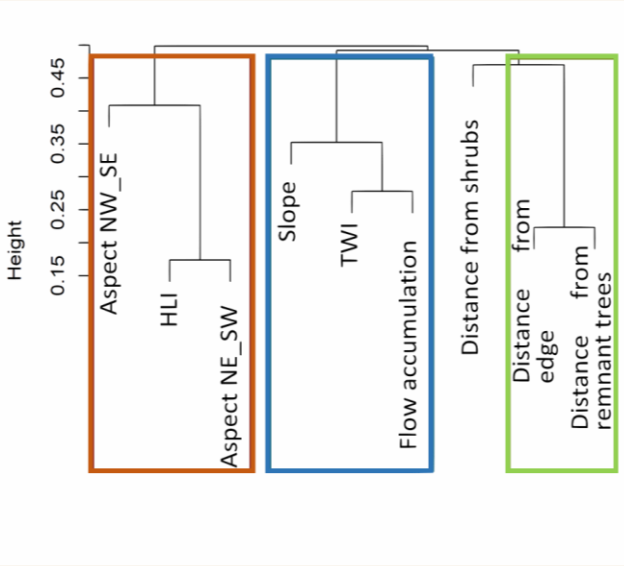


Fig. 4b — Angular-distance hierarchical clustering

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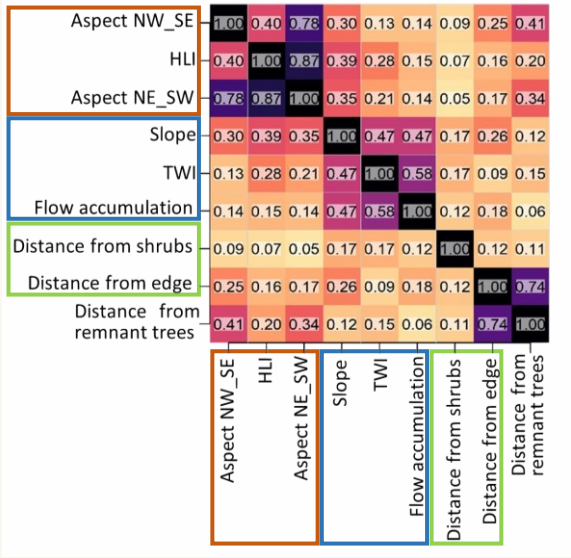


Fig. 5 — Distance Correlation (dCor) matrix

© Atzeni et al. (2025) — Atzeni et al. (2025) · energy pkg (Székely & Rizzo, 2017)

Radiation axis	Moisture-morphometry axis	Proximity axis
HLI · Aspect NW_SE · Aspect NE_SW	TWI · Flow accumulation · Slope	Dist. to seed trees · Dist. to edge

Shrubs were too homogeneously distributed to generate detectable microhabitat gradients at the scale of analysis.

Result 2b — GLM & GAM: Environmental Drivers

Four predictors · consistent ecological relationships

TWI

Topographic Wetness Index

▼ Negative (p < 0.001)

Regeneration drops steeply at TWI > 4.8–4.9
Hollows & drainage lines = persistent coldspots
Beyond wetness: rilling + sediment loss destabilise seedbed
(Lucas-Borja et al., 2019; Shakesby, 2011)

HLI

Heat Load Index

▲ Positive (p < 0.001)

Probability rises sharply above HLI ~0.84–0.86
Warm, SW-facing, well-drained slopes
Favours rapid early growth in short favourable windows
(Marcolin et al., 2019; Marzano et al., 2013)

Dist. to adult pines

Distance to seed trees

▼ Negative (p < 0.001)

Neutral effect at ~35–40 m from nearest adult pine
Strongly negative beyond ~60 m
Obligate seeder: seed shadow templates post-fire recovery
(Nathan et al., 2000; Leverkus et al., 2014)

Dist. to shrubs

Garigue shrub proximity

— Non-significant

Not significant in any GLM or GAM formulation
Homogeneous garigue distribution limits microhabitat contrasts
Distance-to-centroid may miss canopy geometry effects
(Gómez-Aparicio, 2009)

Result 3 — Random Forest

Ecologically informed PA vs. random PA · 70/30 split × 100 repeats

Informed pseudo-absence strategy

- True absences undefined in early post-fire settings
- Unfavorability score = high TWI + low HLI + large dist. to pines (from GLM/GAM)
- Spatial balance: 25 blocks (5×5 grid), PA from 80th–60th percentile of local unfavorability
- n = 329 balanced (presence = PA)

Metric	Informed PA	Random PA
AUC	**0.895 ✓**	0.653
ACC	**0.821 ✓**	0.607
SEN	**0.785 ✓**	0.648
SPE	**0.864 ✓**	0.571

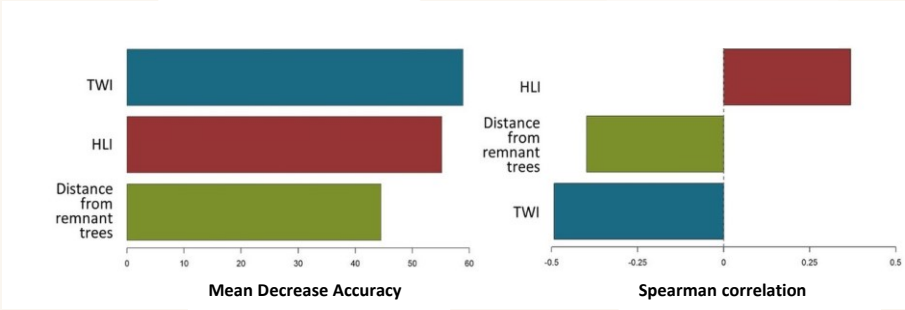


Fig. 7 — Permutation importance (MDA) & Spearman correlation — best RF (informed PA)

© Atzeni et al. (2025) — Atzeni et al. (2025) · randomForest package (Breiman, 2001; Liaw & Wiener, 2002)

Variable ranking (best RF):

TWI — *most important · strong negative*

HLI — *2nd · positive effect*

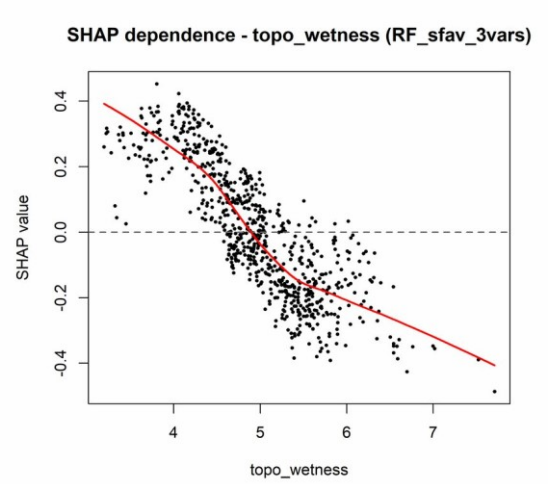
Dist. to pines — *3rd · moderate negative*

Tap to see SHAP dependence plots →

Result 3b — SHAP Dependence Plots

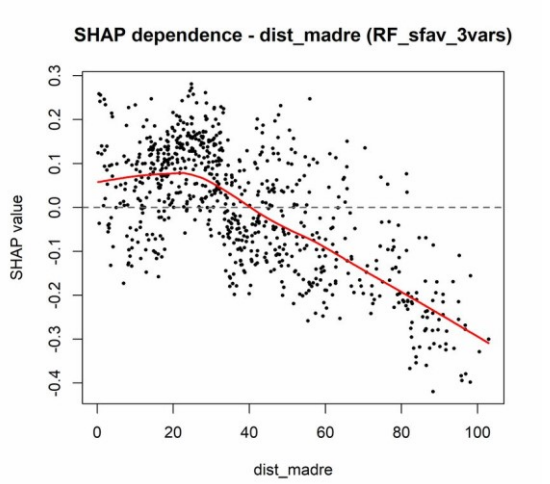
fastshap package · nsim = 100 · class-1 predicted probability

TWI (Topographic Wetness)



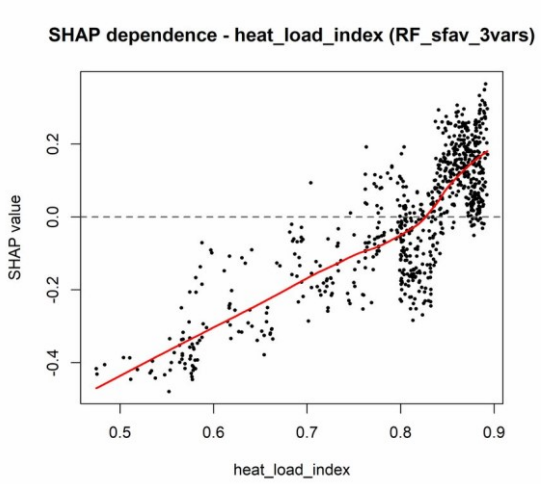
Positive SHAP at low TWI (3.5–4.5)
Sharp drop crossing zero ~4.8–4.9
Strongly negative at TWI ≥ 6

Distance to remnant pines



Slightly positive below ~30 m
Crosses zero at ~35–40 m
Strongly negative beyond ~60–80 m

HLI (Heat Load Index)



Strongly negative at HLI < 0.65
Crosses zero near HLI ~0.80
Positive and rising above HLI 0.86

SHAP values = additive contribution of each predictor to model probability · fastshap package · Atzeni et al. (2025)

Result 4 — Ecological Suitability Map → Restoration

Best RF (informed PA)
applied to full 5 × 5 m raster stack

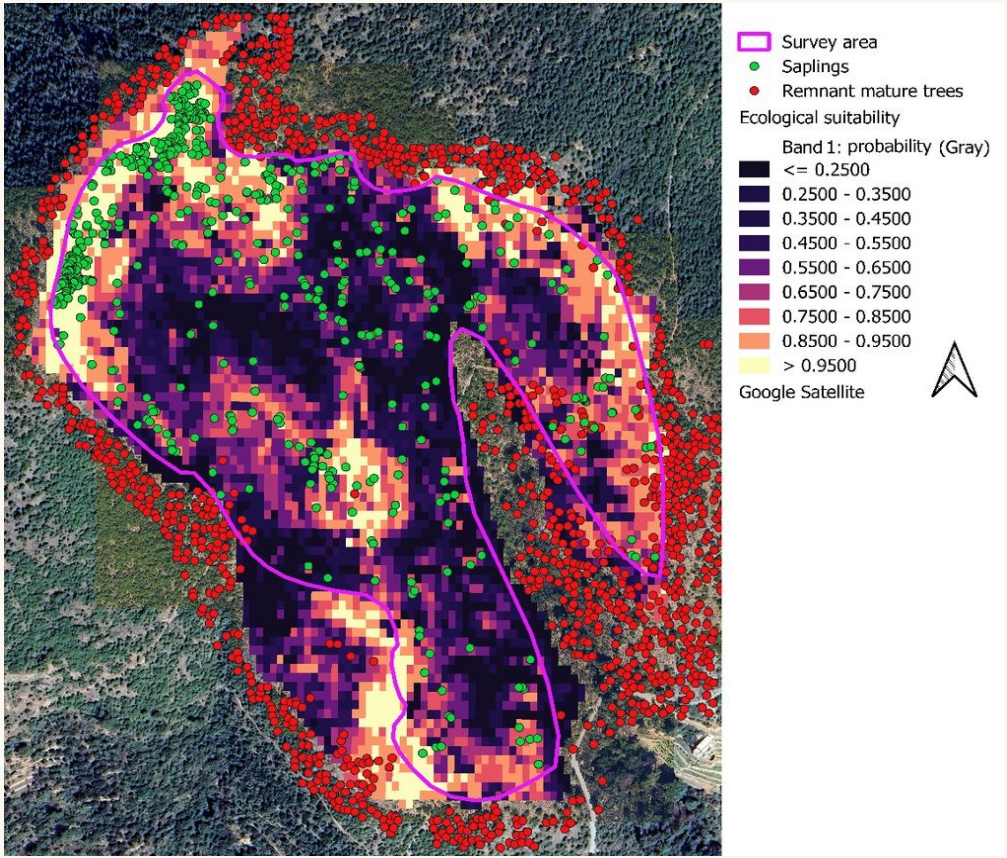


Fig. 8 — Suitability map · saplings (green) and remnant pines (red) overlaid

Precision Forest Restoration

Hotspots (warm + near pines)

Passive regeneration already succeeding.
→ protect remaining seed trees, avoid further disturbance

Coldspots — seed-limited

Suitable microsite but too far from seed source
→ targeted planting / sowing · or seed tree retention

Coldspots — hydrological (high TWI)

Soil instability + waterlogging in hollows
→ microsite preparation or moisture-tolerant species

Transferable framework

UAV + LiDAR + informed RF scalable to other Mediterranean burned slopes at 5 m precision

Conclusions

1. Environmental filtering — not plant–plant interactions — drives regeneration spatial structure (Kinhom + ginhom within Poisson envelopes)

2. TWI and HLI are primary microsite controls with sharp ecological thresholds (TWI break ~4.8; HLI crossing zero ~0.80)

3. Seed limitation is critical: probability declines sharply beyond ~40 m from surviving adult pines (obligate seeder dynamics)

4. Ecologically informed pseudo-absences substantially improve RF discrimination (AUC 0.895 vs. 0.653 with random absences)

5. The 5 m suitability map provides an operational, transferable planning tool for precision-based post-fire restoration in Mediterranean landscapes

Limitations: single 12 ha site · single snapshot · UAV/LiDAR detection uncertainties | Future: multi-site, long-term monitoring, sensitivity analyses

Thank You · Questions?

Contact

Francesco Atzeni

f.atzeni@pm.univpm.it

PhD · Marche Polytechnic University · D3A

Co-authors: F. Taccaliti, D. Marangon, E. Lingua

University of Padova · TESAF

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Key message

TWI, HLI and distance to surviving adult pines drive post-fire regeneration.

Ecologically informed ML → actionable suitability maps for precision-based restoration.

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Image & data credits

All figures (Fig. 1–8): Atzeni et al. (2025, in prep.) · Basemaps: Google Satellite (Google LLC) · R packages: spatstat (Baddeley et al., 2015), mgcv (Wood, 2017), randomForest (Breiman, 2001; Liaw & Wiener, 2002), fastshap, terra (Hijmans, 2023), minerva (Reshef et al., 2011), energy (Székely & Rizzo, 2017).

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