REWILDING THE ALPS: BALANCING CARBON STORAGE AND FIRE RISK

Reaching net-zero GHG emissions by 2050—and net-negative thereafter—is essential to limit global warming to 1.5°C. The EU must cut emissions from 5.8 Gt CO_2e (2019) to 2.5 Gt by 2030, combining decarbonization with active carbon dioxide removal (CDR). Forests are expected to deliver a significant share of these removals under the EU "Fit for 55" framework.

Rewilding — restoring natural processes where human pressure declines — **is emerging as a promising, nature-based CDR strategy**. It aligns with the EU Biodiversity Strategy for 2030, which aims to increase strictly protected land to at least 10%, providing space for natural dynamics. Across Europe, natural reforestation and proforestation — allowing existing forests to grow naturally without harvesting — are expanding, with millions of hectares of abandoned agricultural and forest land available for rewilding. **Mountain regions, especially the Alps, are at the forefront**. Land abandonment and reduced forest management have led to forest expansion and high biomass accumulation, with forest cover exceeding 75% in many Alpine municipalities. While this enhances carbon storage, it also reshapes habitats and might increase wildfire risk. Reforestation and proforestation can boost carbon sequestration and biodiversity, but poorly planned interventions may amplify fire hazards, particularly under droughts and heatwaves. Large fires, which are expected to increase under global change scenarios, are promoted by fuel accumulation and landscape homogenization, leading to the release of stored carbon and posing significant threats to ecosystems and human communities.

> The central policy challenge is not whether rewilding can contribute to climate neutrality, but how to implement it in ways that are both safe and effective. This requires integrating carbon objectives with biodiversity conservation and fire-smart spatial planning. Expanding forest cover is not inherently the optimal outcome. In fire-prone contexts, the most interventionist rewilding approach does not necessarily yield the greatest long-term climate benefits.

REWILD-FIRE has quantified carbon outcomes of rewilding across the Alps under alternative scenarios, accounting for fire risk, climate change, and socio-economic conditions. This brief distils the findings to guide policies that combine net-zero goals and resilient Alpine landscapes.

ALPINE LAND-USE TRAJECTORIES AND FIRE-SMART REWILDING

Simulations across four large Alpine landscapes (Figure 1), calibrating a modified version of the REMAINS model, revealed long-term patterns over the next 80 years: broadleaf forest consistently expands while shrub cover declines, reflecting progressive reorganization of woody vegetation. These trends hold across all governance scenarios (Table 1), but the magnitude and composition of change are strongly landscape-dependent. Conifer and pasture responses are heterogeneous, highlighting that initial landscape structure constrains outcomes more than scenario design alone.

Forest expansion across the governance scenarios ranges from +0.51% to +5.67% of the initial forest area over 80 years, with the fire-smart + direct + indirect prevention scenario (FSR_DIP) producing the largest gains. However, an increase in forest area alone is not sufficient to enhance carbon stocks or support biodiversity. Unplanned or poorly targeted forest expansion can generate important trade-offs. For example, it may reduce open habitats — such as grasslands, shrublands, and agro-silvo-pastoral systems — that are essential for species of conservation concern and often host high levels of specialized biodiversity. Moreover, the homogenization of landscapes through continuous forest cover can increase fuel continuity, potentially amplifying fire spread and severity. In such contexts, larger forest extent does not necessarily translate into higher long-term carbon stocks, as increased fire risk may lead to greater carbon losses through recurrent high-intensity fires. Fire dynamics therefore play a central role in determining whether forest expansion effectively contributes to climate mitigation and biodiversity conservation: suppression policies, preventive fuel management, and post-fire regeneration dynamics shape both the spatial configuration and the ecological quality of expanding forests. Alpine rewilding can enhance forest cover, carbon storage, and biodiversity, but success depends on spatially explicit, fire-aware planning tailored to local landscape structure, ecological context, and disturbance dynamics.

No single governance scenario proves optimal across the diverse contexts of the Alps. The key implication is not to adopt a universal rewilding model, but to develop landscape-specific strategies that simultaneously account for wildfire risk, carbon sequestration potential, and post-disturbance recovery dynamics. Box 1 translates these findings into actionable recommendations for policy design and spatial planning.
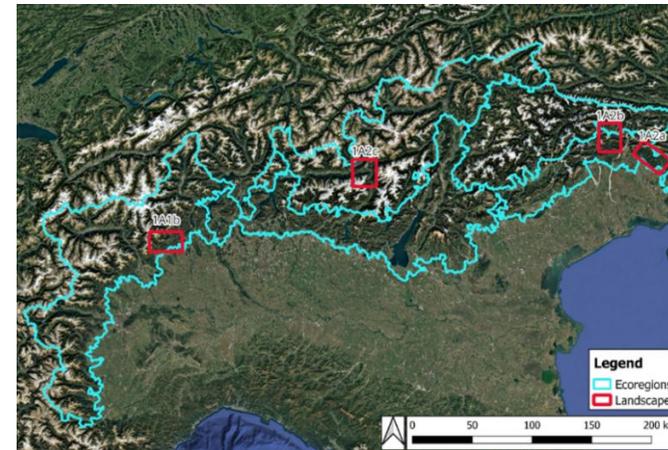

Figure 1. Alpine Ecoregions and Landscapes used for the REWILD-FIRE project.

BOX 1 - Operational implications for policy and planning

- **Adopt spatially differentiated strategies rather than a single rewilding model**, as scenario performance varies markedly across Alpine landscapes.
- **Assess rewilding based on net long-term carbon performance rather than forest expansion alone**, since greater forest cover does not necessarily translate into superior climate outcomes.
- **Integrate fire prevention and forest growth objectives instead of addressing them separately**, because fire regimes and forest expansion interact in shaping long-term emissions and carbon stocks.
- **Safeguard recovery trajectories in fire-prone landscapes**, as recurrent disturbances can erode long-term biomass accumulation and compromise climate benefits.
- **Implement adaptive monitoring to periodically recalibrate interventions**, recognizing that landscape responses and the relative effectiveness of alternative strategies may shift under increasing climate pressures.

EMPIRICAL INSIGHTS ON CARBON SEQUESTRATION FROM AFFORESTATION AND PROFORESTATION IN THE ALPS

Empirical data collected across the Alps using standardized methods to quantify carbon stocks following natural reforestation of abandoned agricultural-pastureland and proforestation confirm that both natural reforestation and proforestation can deliver substantial carbon sequestration, but outcomes vary by site, successional stage, and ecological context. More specifically, afforestation provides consistent aboveground carbon gains, while soil carbon recovery is context-dependent. In fact, tree density averaged ~1,300 trees/ha; mortality peaked 30–35 years after abandonment, then declined; aboveground carbon stocks increased linearly with time since abandonment at 1.7–3.2 tC ha^{-1} yr^{-1} across all ecological regions; soil carbon accumulation was slower and heterogeneous, 0.2 tC ha^{-1} yr^{-1} on average, higher on former cropland than grassland; total ecosystem carbon rose steadily, reaching up to 3.3 tC ha^{-1} yr^{-1} in the most productive regions.

Proforestation also enhances carbon storage, but is more spatially heterogeneous and depends on stand structure and environmental constraints. In this case, tree density remained similar between managed and unmanaged stands, but average diameter, basal area, and deadwood increased over time; aboveground carbon stocks — including deadwood — grew progressively, with significant accumulation after ~60 years in some regions; soil carbon responses were region-specific; mid-successional stands showed variable gains, sometimes plateauing depending on ecological conditions; total ecosystem carbon was influenced more by ecoregion and stand structure than by time alone. These results, underline the fact that climate strategies should prioritize spatially explicit assessments, focusing on high-productivity sites while considering ecological heterogeneity, land-use history, and structural characteristics.

FIRE-SMART REWILDING AND CLIMATE MITIGATION: INSIGHTS FROM LANDSCAPE SIMULATION MODELING

REWILD-FIRE explored the interplay between fire risk, rewilding strategies, and carbon sequestration across the four Alpine landscapes under the governance scenarios outlined in Table 1. The results span an 80-year horizon, shedding light on carbon stock dynamics, fire-related emissions, and the integrated net carbon balance, revealing key insights into the trade-offs involved in balancing rewilding with fire risk mitigation. The total carbon stock at year 0 varied across landscapes and its trajectories over the course of 80 years diverged significantly depending on both the landscape and governance scenario:

➢ Lombardia (1A2c) showed the strongest increase in carbon stocks, with Fire-smart Rewilding + Direct + Indirect Prevention (FSR_DIP) resulting in slightly reduced accumulation compared to the other scenarios, but still positive.

➢ North-western Alps (1A1b) exhibited a carbon stock decline across all scenarios, with FSR_DIP worsening the situation.

➢ Pre-Alps (1A2a) showed positive growth in all scenarios, but FSR_DIP resulted in the lowest carbon stock accumulation.

➢ Dolomiti and Carnia (1A2b) also saw moderate growth, but FSR_DIP resulted in the smallest increase compared to other scenarios.

These results underscore that carbon accumulation trajectories are not solely determined by the prevalence of fire events, but rather by how governance strategies — particularly those influencing forest age and management practices — shape long-term forest growth. While FSR_DIP did reduce carbon emissions through fire prevention, it frequently failed to maintain the carbon stock accumulation that more moderate approaches, like Fire-smart Rewilding + Direct Prevention (FSR_DP), were able to sustain in fire-prone landscapes.

Scenario	Key features	Fire suppression	Rewilding allocation	Management notes
Scenario 1: Business As Usual (BAU)	No dedicated rewilding policy; baseline land-use trends continue	Historical suppression only	None; forests, pastures, agriculture follow existing management/abandonment patterns	Forest: 30% actively managed (150 m road buffer), 85% unmanaged; Pasture/sparse: 10% managed; Agriculture: full aging/abandonment
Scenario 2: Strict Rewilding + Fire-control (StR_S)	Enforces 10% strict protection quota; allocation starts in protected areas	Increased suppression (+0.4 vs BAU)	Allocation prioritizes protected areas; expands to buffers if needed; no fire-smart prevention	Management reduced inside protected areas to increase proforestation; potential fire-fighting trap due landscape flammability exceeding fire suppression
Scenario 3: Fire-smart Rewilding + Direct Prevention (FSR_DP)	10% rewilding target combined with firebreak networks; lower-risk locations prioritized	Increased suppression (+0.2 vs BAU)	Excludes high-flammability pixels; fixed exclusion layer (~5% outside protected areas)	Forest management aligns with BAU (30%); rewilding does not involve management in protected areas; direct prevention modifies spread logic via firebreaks
Scenario 4: Fire-smart Rewilding + Direct + Indirect Prevention (FSR_DIP)	Builds on FSR_DP with indirect prevention through fuel/land-cover reorganization	Increased suppression (+0.2 vs BAU)	Targeted in low-risk zones, including outside protected areas; mosaic-agriculture buffers added	Forest management increased to 40% in eligible zones; rewilding does not involve management in protected areas; firebreak corridors potentiated by the mosaic of crops over 5% of the flammable area

Fire-smart rewilding can enhance climate mitigation by balancing fire risk management and forest maturation, promoting long-term carbon storage. Successful strategies reduce high-severity fire risk, maintain recovery continuity, and avoid cycling through low-stock phases. However, overemphasizing fire prevention decreases its leverage on overall burnt area and can limit forest growth, leading to a negative net carbon balance despite reduced emissions.

While fire emissions contribute to the carbon dynamics, their impact is secondary to the long-term effects of forest stock accumulation. In other words, they were insufficient, on their own, to offset the carbon gains from robust stock accumulation. This suggests that fire suppression alone, even when it results in lower emissions, is not always the most effective strategy for climate mitigation.

The simulation outcomes reinforce that the real challenge lies in managing carbon stocks while considering the interaction of disturbance regimes, forest age, and post-fire recovery pathways. The net carbon balance at year 80, which combines carbon stock changes and fire emissions, was used as the primary metric to assess the effectiveness of each governance scenario. Across landscapes, the balance showed clear patterns: in 1A2c, the most favorable landscape, Strict Rewilding + Fire-control and Fire-smart Rewilding + Direct Prevention scenarios achieved the best net carbon balance, with Fire-smart Rewilding + Direct + Indirect Prevention underperforming despite reduced fire emissions. In 1A1b, the net carbon balance remained negative for all scenarios, with Fire-smart Rewilding + Direct + Indirect Prevention amplifying this deficit. Normalized net carbon balance per hectare per year further emphasized these differences. Of

particular interest was how Fire-smart Rewilding + Direct + Indirect Prevention consistently showed a lower net carbon balance compared to all the others across all landscapes, particularly in fire-prone areas. This reinforces the trade-off inherent with such a scenario: while it may reduce fire-related emissions, it often limits long-term forest growth and resilience, leading to weaker carbon outcomes in the long run. A significant finding was that forest classes, particularly broadleaf forests, were the primary drivers of net carbon outcomes across landscapes. These forests dominate carbon sequestration over time, especially as they mature. Non-forest land covers, including cropland and pasture, played a secondary role, contributing positively when fire risk was low but having limited impact overall.

This result underscores the importance of focusing on forest structure and maintain an even-spread of age-classes in fire-prone landscapes for long-term climate mitigation: fire-smart strategies that balance fire risk management with forest growth and age-class preservation are most effective.

> **Net carbon balance is trajectory-dependent. Fire-smart strategies are not automatically climate-positive; their success hinges on whether they preserve or enhance long-term carbon stock formation while reducing fire risk. The simulations highlight that more suppression is not a sufficient success criterion. Effective landscape management requires integrated targets that combine fire outcomes, carbon stock trajectories, and recovery continuity.**

When the entire Italian Alpine Convention area is considered, the model advocates for a layered rewilding strategy rather than a uniform approach across the entire region. It highlights a broad Strict Rewilding + Fire-control (St_R) backbone where conditions are favorable for spontaneous rewilding, complemented by a narrower Fire-smart Rewilding + Direct Prevention (SR_DP) set targeting areas with higher fire risk, and a very selective Fire-smart Rewilding + Direct + Indirect Prevention (FSR_DIP) subset in regions where afforestation and risk patterns warrant integrated fire prevention measures.

Spatially, the optimal rewilding choices reveal a clear longitudinal gradient across the Italian Alpine arc, with scenario propensity increasing from the patchy western zones to more continuous and expansive structures in the central-eastern sectors. This gradient is present across all three scenario families, though with varying intensity, continuity, and fragmentation.
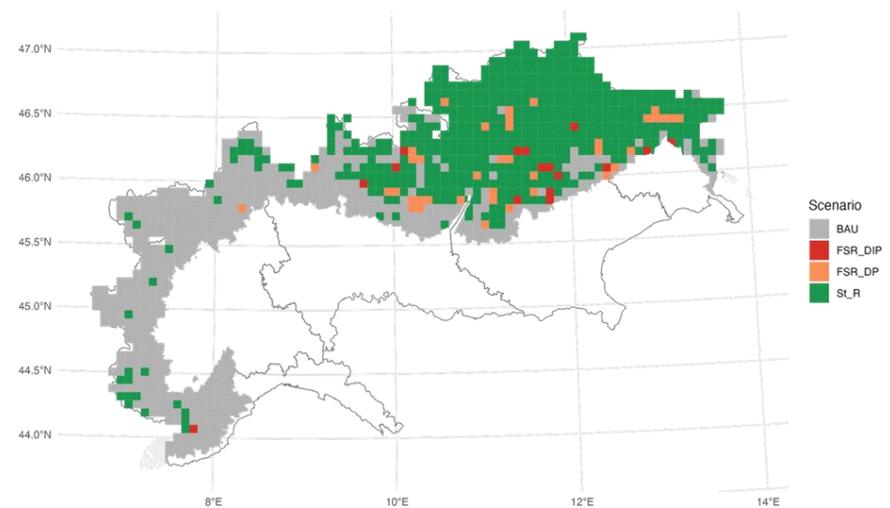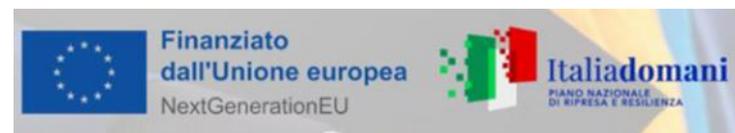

Figure 2. Best rewilding alternative in the Italian Alpine space.

FINAL POLICY RECCOMANDATIONS

REWILD-FIRE findings point to the need for a more nuanced approach to rewilding in fire-prone landscapes—one that balances fire risk management with long-term forest growth, ensuring that carbon sequestration benefits are maximized while minimizing the risk of catastrophic fires in the future. Because no single scenario consistently outperforms the others across all Alpine contexts, the findings support a landscape-specific approach to rewilding — one that simultaneously accounts for wildfire risk, carbon dynamics, and post-disturbance recovery processes:

➢ **Differentiate rewilding strategies by landscape type**. Public authorities should avoid applying a single rewilding model across the Alps and instead tailor interventions to local fire regimes, vegetation dynamics, and land-use trajectories.
➢ **Evaluate policies through multiple performance indicators**. Strategy assessment should encompass forest-cover change, carbon-stock dynamics, burned area, and post-disturbance recovery in order to capture trade-offs and synergies among climate and ecological objectives.
➢ **Prioritize fire-prevention measures where rewilding increases fuel continuity**. In landscapes experiencing shrub encroachment and forest expansion, targeted fire-smart interventions should accompany rewilding to mitigate the risk of large carbon losses.
➢ **Strengthen long-term recovery after disturbance**. Planning should minimize the likelihood of repeated fires in regenerating areas and maintain conditions conducive to sustained forest regeneration and biomass accumulation.
➢ **Continuously update strategies through adaptive monitoring**. Rewilding plans should be periodically revised based on monitoring data and scenario-based evaluation, rather than treated as fixed, long-term prescriptions.