D 3.2 CARBON SINK AND EMISSIONS

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Rewilding policies for carbon sequestration under increasing fire risk

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Executive summary

This deliverable evaluates how alternative rewilding and fire-management strategies affect long-term climate mitigation across four Alpine landscapes over an 80-year horizon. The assessment applies the REMAINS simulation framework with harmonized carbon-accounting rules, site-specific age-carbon functions for above- and below-ground stocks, and 15 stochastic runs per site-scenario combination. Four configurations are compared: business as usual (BAU), strict rewilding with stronger fire suppression (StR_S), and two fire-smart configurations (FSR_DP, FSR_DIP).

The central finding is that long-term carbon stock trajectories largely net climate performance. Modelled fire-combustion emissions, while relevant, are generally one order of magnitude smaller than stock variations. By year 80, total carbon stocks range between 7 and 11.5 MtC (or between 158 and 274 tC ha^{-1}), whereas cumulative emissions remain in the order of thousands to tens of thousands of tC. Scenario ranking is therefore primarily driven by how governance settings shape forest area-age dynamics, recovery continuity, and persistence of high-stock classes.

Outcomes are strongly landscape-specific. Three landscapes (1A2a, 1A2b, 1A2c) maintain a positive net balance under most scenarios, whereas 1A1b remains net negative under all configurations, reflecting structural constraints in the most fire-prone context. In normalized terms, StR_S and FSR_DP generally perform close to or above BAU in several sites, while FSR_DIP systematically underperforms relative to BAU across all landscapes. Contrasts against BAU reinforce this pattern: StR_S improves or preserves performance in three landscapes and reaches near parity in one; FSR_DP yields positive effects in three landscapes, with stronger gains in 1A1b and 1A2b. FSR_DIP shows consistent penalties, including large negative deviations in 1A2a and 1A2c. Although FSR_DIP reduces emissions in several cases, these savings are insufficient to offset stock accumulation.

Class-level decomposition confirms a forest-driven carbon system. Broadleaf forest contribute most to the final net gains in all landscapes, conifers contribute positively but to a lesser extent, and non-forest classes play a secondary role with limited influence on final rankings. Consequently, interventions that safeguard forest development and post-disturbance recovery trajectories dominate long-term mitigation outcomes.

From a planning perspective, the results support fire-smart rewilding only when prevention and suppression measures are explicitly designed to protect stock formation, rather than solely to reduce burned area or short-term emissions. A uniform strategy is not supported. Operational targeting should be spatially differentiated, risk-trajectory based, and coupled with adaptive monitoring that tracks both disturbance indicators and stock evolution over time.

Policy implications follow directly. Climate-performance targets should integrate three dimensions: disturbance outcomes, stock outcomes, and recovery continuity. Planning frameworks should designate sink-priority areas, resilience-priority mosaics, and transition corridors with explicit adaptation thresholds. Periodic recalibration of transition dynamics and disturbance responses is necessary to avoid long-term lock-in to structurally low-performance pathways.

Keywords

Rewilding; Alpine space; land-use change; carbon sink; climate change mitigation; forest fire; proforestation; afforestation; adaptive forest governance.

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1. Introduction

1.1 State of the art

Current European rewilding debates are increasingly linked to climate mitigation targets, biodiversity recovery, and long-term ecosystem resilience (Araújo and Alagador, 2024; Pereira et al., 2024; Svenning, 2020). The **EU Nature Restoration Regulation** has accelerated this shift by moving restoration from a voluntary aspiration to a policy domain with measurable obligations, timelines, and monitoring requirements across ecosystems, including forests and mountain landscapes (Hering et al., 2023). In this policy context, rewilding is often proposed as a strategy to increase ecological integrity, support natural dynamics, and rebuild carbon stocks through reduced intervention and longer forest continuity (Perino et al., 2019) For Alpine regions, this framing is highly relevant because large areas are experiencing ongoing land-use change (Anselmetto et al., 2024), demographic pressure in valleys, abandonment of marginal lands, and uneven management intensity across elevation and accessibility gradients.

The policy opportunity is substantial, but so is the implementation challenge. Rewilding can increase woody cover and standing biomass, yet **carbon outcomes depend on disturbance regimes and landscape configuration**. In Europe, wildfire evidence has expanded from a Mediterranean-centered narrative toward a broader continental risk perspective. Recent fire seasons have shown that hot-drought conditions can produce severe fire impacts in areas not historically considered core fire systems (Carnicer et al., 2022). In Alpine and pre-Alpine contexts, this implies that legacy assumptions based on cooler and moister regimes are less reliable for forward planning. Carbon accounting frameworks that ignore this shift risk to overestimate net sink performance under future scenarios.

In mountain systems, the interaction between rewilding and wildfire risk is central. Where rewilding expands or densifies combustible vegetation in fire-prone settings, expected carbon gains may be partly or fully offset by disturbance-related emissions and by post-fire shifts in age structure and species composition. This is why **fire-smart land management** is not a secondary add-on to rewilding policy (Pais et al., 2020). It is part of the core mitigation logic when planning interventions in regions with increasing climate extremes. Scientific literature over the last decade has converged on three robust points that matter for this deliverable. First, **forest carbon sinks are dynamic** rather than stationary. Their magnitude varies through time and is sensitive to climate trends, disturbance pulses, and management choices. Second, disturbances influence both immediate carbon fluxes and long-term stock dynamics. **Wildfire release carbon** directly through fuel combustion, but also reshape future sink capacity by affecting tree mortality, regeneration trajectories, and the likelihood of repeated burning. Third, these impacts are **spatially heterogeneous**. As a results, national average indicators may mask substantial subregional divergence, particularly in topographically complex mountain landscapes.

At the same time, restoration and rewilding policies are motivated by objectives that extend beyond carbon sequestration. They aim to enhance biodiversity, strengthen ecological connectivity, and restore ecosystem functioning (Perino et al. 2019; Svenning 2020). This creates a practical trade-off space for planners: maximizing forest expansion can increase carbon stocks, whereas maintaining or restoring heterogeneous mosaics may reduce wildfire hazard and moderate losses through emissions (e.g., Simões et al., 2023). The “best” configuration therefore depends on local combinations of ignition exposure, landscape flammability, suppression capacity, and socio-ecological objectives. For Alpine planning, this reinforces the need to evaluate rewilding under explicit disturbance coupling rather than under static assumptions.

The Alpine **land-use trajectory** adds a further layer of complexity. Historical transitions have included abandonment and natural succession across many mountain sectors, the persistence of managed patches in more accessible areas, and marked regional differences in pasture dynamics, shrub encroachment, and shifts in forest composition (Anselmetto et al., 2024). These legacies shape present-day baseline conditions, which in turn strongly influence future carbon dynamics and fire regimes. As a result, a policy package that performs well in one landscape may underperform in another characterized by different levels of fragmentation, forest age structures, or class-adjacency configurations.

In this deliverable, two related but distinct pathways of forest expansion and rewilding choices are considered. **Afforestation** refers to the establishment of forest cover on land that was not forest at the reference baseline, typically through natural succession after agricultural or pastoral abandonment or assisted natural regeneration. **Proforestation**, in contrast, involves the continued growth and maturation of existing forests by extending stand development and reducing or halting harvesting pressure, allowing existing stands to accumulate additional biomass and associated carbon pools over time. This distinction is critical for carbon accounting because the two pathways differ in initial carbon stock levels, growth trajectories, disturbance exposure, and expected timing of climate benefit. In Alpine landscapes, both processes can occur simultaneously within the same mosaic, and their relative contributions are strongly influenced by land-use legacies, management constraints, and prevailing fire regimes.

This provides the rationale for a **coupled modelling approach**. Integrating land use change, forest dynamics, landscape flammability, the fire regime, and post-fire recovery enables the analysis to move beyond simple measures of "forest area gained" and to estimate net outcomes as a balance between carbon stock accumulation and disturbance-related emissions. The framework explicitly incorporates scenario levers such as suppression rules, direct and indirect prevention measures, and rewilding allocation logic. In short, the current state of knowledge supports a policy-relevant conclusion: in Alpine systems, rewilding can contribute to climate mitigation, but its effectiveness critically depends on where and how it is implemented in relation to fire dynamics and historical landscape trajectories.

1.2 Objectives and research questions

This deliverable estimates carbon sink and fire-induced emissions under alternative rewilding scenarios in four representative Alpine landscapes, using the existing REMAINS scenario framework and multi-run stochastic outputs (see Deliverables 1.1, 2.2 and 3.1). The general objective is to quantify **net carbon balance** as:

Net balance = landscape carbon gain − cumulative fire emissions

evaluated over the simulation period and at the policy-relevant endpoint (year 80), incorporating uncertainty from ensemble runs.

Specific objectives are:

- Quantify carbon stock trajectories by landscape, scenario, and simulation year, using class- and age-dependent carbon functions for forested cells (calibrated in Deliverable 2.1) and fixed class coefficients for non-forest classes.
- Quantify cumulative fire emissions by class, incorporating class-specific non-forest emission factors and pool-based forest combustion factors (litter, duff, deadwood).
- Compare each policy scenario against business as usual (BAU) in each landscape, carrying run-level uncertainty through all summary metrics.
- Decompose net outcomes by land-cover class to identify which transitions and class compositions drive gains or losses.
- Interpret carbon outcomes in the context of initial landscape structure, governance design, and observed historical land-use pathways.

Research questions are:

1. Which scenario configurations deliver the largest positive net carbon outcomes relative to BAU at year 80?
2. To what extent is gross carbon-stock gain offset by cumulative fire emissions under each governance strategy?
3. Are the effects consistent across landscapes, or are they strongly context-dependent due to differences in initial composition, fragmentation and fire-proneness?
4. Which land-cover classes contribute most to final net balance, and how does this vary among scenarios?
5. Do fire-smart mechanisms (direct and indirect prevention) meaningfully alter long-term net carbon, beyond their influence on burned area?

1.3 Relation to previous deliverables

This deliverable is designed as the carbon-accounting synthesis of the project workflow established in the previous reports. The first key input is the historical land-use baseline established in **Deliverable 1.1**, which provides the empirical reference for interpreting simulated trajectories. This baseline documents recent changes in four Alpine landscapes, identified dominant transitions, and clarifies how class harmonization was handled before simulation. These elements are essential because carbon stocks and emissions outcomes are interpreted not in isolation, but relative to observed land-use pathways and landscape specific legacies. Additionally, the four governance configurations analysed in this report are directly inherited from Deliverable 1.1 without conceptual modification, ensuring that carbon comparisons remain fully consistent with the policy experiments already implemented.

Deliverable 2.1 provides the empirical carbon-accounting foundation for this report. It establishes the measurement framework linking land-cover conditions (class and age) to carbon pools and stock factors for both afforestation and proforestation, applying harmonized assumptions across the study areas and explicit accounting for class-level differences. This baseline is essential for Deliverable 3.2 as simulated trajectories must to be translated into carbon quantities using site-specific allometric equations, coefficients and pool logic that are fully consistent with the project's field-informed accounting framework.

The modelling framework outlined in **Deliverable 2.2** defines the structure and logic of the simulation system. REMAINS is a coupled, spatially explicit model in which annual landscape trajectories emerge from the interaction of: (i) land-cover transition demand and probabilities, (ii) neighbourhood-based allocation and spatial aggregation, (iii) fire-risk and spread processes, (iv) scenario-specific suppression and prevention rules, and (v) post-fire regeneration and recovery routines. This complete architecture underpins the carbon estimation in Deliverable 3.2: yearly class and age states drive carbon stock calculations, while yearly burned patterns determine emissions. Both components are then integrated to generate net balance metrics at the run, scenario, and landscape levels.

Finally, **Deliverable 3.1** provides the fire-simulation framework on which the emissions' estimates in Deliverable 3.2 are based. Its defines how fire risk, ignition, spread, suppression, and post-fire state updates are represented within REMAINS, including the scenario-specific controls that influence fire behaviour over time. This framework is critical for carbon-emission accounting because cumulative losses are not imposed externally; they emerge dynamically from the interaction of simulated fires with evolving land-cover mosaics and management rules. In this sense, Deliverable 3.1 supplies the disturbance engine, while Deliverable 3.2 quantifies the carbon consequences of these simulated fire pathways and integrates them with carbon stock trajectories to produce a comprehensive net balance metric.

2. Study areas, scenarios, and input data

2.1 Spatial and temporal domain

The analysis covers four Alpine case-study landscapes — 1A1b (Northwestern Alps), 1A2a (Pre-Alps), 1A2b (Dolomiti and Carnia), 1A2c (Northeastern Alps) — each simulated under four governance scenarios representing alternative governance strategies that combine rewilding objectives with fire-management logic:

- **Business As Usual (BAU)** represents the reference pathway, following baseline management and historical suppression practices. It serves as counterfactual for all scenario comparisons.
- **Strict Rewilding + strengthened suppression (StR_S)** increases rewilding intensity under stricter conservation rules and stronger suppression settings. Expected outcomes include potential carbon stock gains from reduced intervention and wildfire protection, but with possible risk of higher fuel continuity in some areas and the emergence of negative feedbacks on burned area.
- **Fire-Smart Rewilding + Direct Prevention (FSR-DP)** combines rewilding with direct fire-prevention measures (e.g., firebreak suppression in the fire module) and intermediate suppression levels between BAU and StR_S. Expected outcomes include moderated fire spread and emissions where direct prevention is effective, while retaining rewilding-driven carbon gains.
- **Fire-Smart Rewilding + Direct + Indirect Prevention (FSR-DIP)** adds pre-configuration of landscape fuels and cover around prevention structures to the direct-prevention framework. Expected outcomes include stronger long-term control of fire-related losses, potentially with trade-offs in local carbon stock trajectories depending on how indirect prevention alters cover.

A full description of the scenarios is provided in Deliverable 1.1. For each landscape-scenario combination, REMAINS was run as a stochastic ensemble with 15 independent iterations, and outputs were analysed over an **80-year horizon** using regular simulation time steps. The computational domain is raster-based, with each pixel representing **0.09 ha**. Since class coefficients and emission factors are expressed in **tC ha^{-1}**, all pixel-level values are converted to carbon per pixel using the formula: tC per pixel = tC ha^{-1} × 0.09.

Carbon accounting is conducted at the pixel level and then aggregated to run, scenario, and landscape scales. Accordingly, the final reporting units in this deliverable are:

- **landscape** × **scenario** × **run** × **time** – for trajectory diagnostics, and
- **landscape** × **scenario** (mean and distribution across runs) – for policy interpretation, including comparisons against BAU at year 80.

2.2 Study landscapes and their ecological/planning relevance

As previously mentioned, four landscapes were selected to represent contrasting Alpine socio-ecological mosaics, differing in forest composition, open-land fractions, topography, and disturbance regimes:

1. **Northwestern Alps** (**Piemonte**) – **1A1b**
2. **Pre-Alps** (**Friuli Venezia Giulia**) – **1A2a**
3. **Dolomiti and Carnia** (**Friuli Venezia Giulia**) – **1A2b**
4. **Northeastern Alps** (**Lombardia**) – **1A2c**

In this deliverable, these landscapes are treated as contrasting Alpine archetypes: mixed montane mosaic (1A1b), broadleaf-dominated prealpine system (1A2a), steep and connected mixed-forest system (1A2b), and high-elevation fragmented mosaic (1A2c). Together, they span a meaningful range of planning conditions relevant for rewilding and fire-risk governance (see full description provided in Deliverable 1.1). From a carbon perspective, these differences are significant because baseline composition and spatial configuration shape both carbon stock accumulation potential and fire-related losses. Landscapes with larger existing forest shares can achieve rapid gains through continued stand development, whereas landscapes with extensive open or transitional areas may relay more heavily on succession and afforestation pathways. From a fire perspective, landscape flammability influences cumulative emissions and post-fire effects.

2.3 Simulation outputs used for carbon accounting

Carbon stocks and emissions were calculated using three families of REMAINS output:

1. **Land-cover type (LTC) maps** at each simulation time step and run. These rasters provide the class identity of each pixel and form the basis for assigning class-specific carbon stock factors (for non-forest classes) and for identifying forested pixels for age-based carbon stock equations calibrated in Deliverable 2.1. All calculations use a harmonized 9-class land-cover system: urban, crop, pasture, broadleaf, conifer, sparse, shrub, barren, and water.

2. **Wildfire maps** by run and time step. Burned pixels are identified from 5-year wildfire rasters and used to compute step-wise emissions. Cumulative emissions are then obtained by temporal aggregation from year 0 to each analysis year.
3. **Age/state data** (land dataframe outputs). These provide per-pixel land-cover state and age or time-since-change variables used to estimate forest stock with site-specific age functions and to classify forest pixels according to pathway logic (proforestation vs. afforestation conditions, as defined in the carbon module).

The accounting workflow integrates these three data sources at each run-time snapshot, calculates pixel-level carbon stock and stepwise emissions, and aggregates the results to landscape totals and scenario summaries.

For carbon stock accounting:

- **urban, barren, and water** are set to zero in the current parameterization;
- **non-forest vegetated classes** use fixed class coefficients;
- **forest classes** are modelled with age-dependent equations using site-specific parameters.

Aggregated landscape totals are obtained by summing pixel values. Net carbon indicators are calculated both over the simulation period and at the endpoint, using the formula:

$$\text{Net balance}(t) = \text{Landscape stock}(t) - \text{Cumulative fire emissions}(0 \rightarrow t)$$
$$\text{Net balance}_{80} = [\text{Stock}_{80} - \text{Stock}_{0}] - \text{Cumulative fire emissions}_{0\rightarrow 80}$$

3. Modelling methods and carbon accounting framework

3.1 Summary of methods for field sampling and measurement of ecosystem carbon

Deliverable 2.1 provides the empirical foundation for parameterizing carbon accounting in the simulated landscapes. The field campaign was structured around **afforestation** and **proforestation chronosequences** in the four Alpine ecoregions of the project (1A1b, 1A2a, 1A2b, 1A2c), using harmonized protocols across all partners.

Sampling targeted ecosystem pools relevant to both carbon stock estimation and fire-related carbon dynamics, including: living trees (aboveground and roots), shrubs, grass, standing deadwood, stumps, lying deadwood (coarse, fine, very fine), litter, and soil (organic and mineral horizons). For afforestation, field plots were arranged along chronosequences representing increasing time since abandonment (TSA). For proforestation, stands were stratified by management history, with three plots per stand positioned geometrically to reduce within-site spatial bias. Plot centers were georeferenced using sub-metric GNSS, and vegetation/soil measurements followed standardized templates to ensure comparability among institutions and ecoregions.

Aboveground tree biomass was estimated from dendrometric measurements using allometric equations and converted to carbon with standard carbon fractions. Dead biomass was converted using conifer- and broadleaf-specific carbon fractions from the literature, while litter and very fine woody debris were quantified using dedicated fuel-class weighing protocols.

Soil organic carbon was determined from core-based soil bulk density and CHN carbon concentration, with separate consideration of organic and mineral horizons.

The total ecosystem carbon stock was finally derived as the sum of all the above-mentioned carbon pools.

The Deliverable 2.1 dataset thus provide the empirical basis for model-based carbon dynamics in subsequent analysis.

3.2 Carbon stock, emissions, and net equations and pool assumptions

After REMAINS simulation runs, carbon accounting was applied at the pixel level and then aggregated to landscape/scenario/run/year summaries. The accounting framework follows the harmonized land cover classes used in the simulation workflow and distinguishes between forest and non-forest carbon dynamics.

For **forest pixels** (broadleaf and conifer), total ecosystem carbon stock $C_{forest}(t)$is estimated using age-dependent equations developed in Deliverable 2.1 for each ecoregion. These equations integrate aboveground biomass, roots, soil, litter, herb/shrub layer, and deadwood into a single stock function ($tC\ ha^{-1}$). Two families of equations are used:

- **Proforestation equation:** applied when the pixel was already forested at year 0 and remained unburned up to time t.
- **Afforestation equation:** applied otherwise, i.e., newly forested pixels or those affected by fire history.

This classification is reconstructed from the initial landscape state combined with cumulative fire occurrence at the pixel level. The age variable is derived from the simulation state (`tsch`), with class starts interpreted as $[0, 6, 12, 18, 28, 64]$ years for the corresponding age bins. Using the initial year for each age bin produces a conservative underestimation of absolute carbon stocks, but preserves accuracy for relative comparisons — across sites, rewilding scenarios, and between initial and endpoint of the simulation.

Equations did not differentiate between conifer and broadleaf forests. Forest carbon stock was parameterized using site-specific linear age functions ($tC\ ha^{-1}$), with separate coefficients for proforestation and afforestation trajectories:

$$C_{pro}(age) = a_{pro} + b_{pro} \cdot age$$
$$C_{aff}(age) = a_{aff} + b_{aff} \cdot age$$

where `age` is time since abandonment / transition (using the REMAINS age-state variable).

Site (ecoregion)	Proforestation equation $\mathbf{C_{pro}(tC\ ha^{-1})}$	Afforestation equation $\mathbf{C_{aff}(tC\ ha^{-1})}$
1A2a	$271 + 0.673 \cdot age$	$92.2 + 2.31 \cdot age$
1A2b	$202 + 0.385 \cdot age$	$101 + 1.93 \cdot age$

1A2c	$210 + 1.42 \cdot \text{age}$	$111 + 3.30 \cdot \text{age}$
1A1b	$154 + 1.30 \cdot \text{age}$	$69.8 + 1.58 \cdot \text{age}$

For **non-forest classes**, fixed carbon stock factors (tC ha^{-1}) are applied by class, encompassing all carbon pools (biomass and soil). Cropland and pasture values are drawn from Tier1 estimates provided in the **2006 IPCC Guidelines for National Greenhouse Gas Inventories** for cold temperate wet climates. Sparse and shrubland classes are parameterized through synthetic comparison with these classes.

- cropland = 85 tC ha^{-1}
- pasture = 80 tC ha^{-1}
- sparse = 100 tC ha^{-1}
- shrubland = 90 tC ha^{-1}
- urban, water, barren = 0 tC ha^{-1}

For **non-forest fire emissions**, class-specific burnable biomass values are applied each time a pixel burns, with emissions calculated for aboveground and dead biomass pools but excluding soil carbon:

- cropland = 5 tC ha^{-1}
- pasture = 5 tC ha^{-1}
- sparse = 20 tC ha^{-1}
- shrubland = 10 tC ha^{-1}
- urban, water, barren = 0 tC ha^{-1}

Forest emissions are computed from combustible pools including litter, duff and deadwood. Emissions from tree biomass (above- and belowground) are not calculated separately, as these are already captured by the change in stock between consecutive time steps for burned pixels. Soil carbon emissions are considered negligible. Deadwood is accounted for both in the change in stock following fire-induced consumption, and also explicitly here as an emission source, to reflect the fact that consumption during combustion is generally higher than live tree biomass.

$E_{forest} = 0.5 \cdot (B_{litter} \cdot CF_{litter} + B_{duff} \cdot CF_{duff} + B_{deadwood} \cdot CF_{deadwood})$, with 0.5 as biomass-to-carbon conversion and class-specific combustion factors, estimated synthetically:

- litter $CF = 0.75$
- duff $CF = 0.30$
- deadwood $CF = 0.30$ for broadleaf, 0.60 for conifers

and biomass values derived from the most updated version of the Italian database of forest fuels (Ascoli et al., 2020), averaged over all broadleaf and conifer forest measurements recorded in the three study regions (Piemonte, Lombardia, Friuli Venezia Giulia).

- broadleaf: litter 3.9 tC ha^{-1}, duff 9.1 tC ha^{-1}, deadwood 6.4 tC ha^{-1}
- conifer: litter 6.8 tC ha^{-1}, duff 16.9 tC ha^{-1}, deadwood 7.7 tC ha^{-1}

All per-hectare stocks/emissions are multiplied by **pixel area = 0.09 ha** before aggregation.

The primary accounting outcomes are:

- **Stock at time** t: $S(t) = \sum_{i=1}^{N_{pix}} C_i(t) \cdot 0.09$
- **Cumulative fire emissions**: $F(0 \rightarrow t) = \sum_{\tau=1}^{t} \sum_{i=1}^{N_{pix}} E_{i,\tau} \cdot 0.09$
- **Net carbon balance at year** t: $Net(t) = S(t) - F(0 \rightarrow t)$
- **Net final carbon gain**: $\Delta C_{net}(t) = [S(t) - S(0)] - F(0 \rightarrow t)$

The deliverable-level policy indicator at year 80 is computed as the difference between each scenario and BAU (non-BAU minus BAU), with ensemble summaries aggregated across stochastic runs.

3.3 Methods implementation and reproducibility

The implementation follows an end-to-end reproducible R workflow, structured into deterministic preprocessing and stochastic-ensemble postprocessing blocks. First, input harmonization aligns the initial landscape state (year 0), per-step land-cover rasters, per-step wildfire rasters, run-time state tables (`land cover type`, `time since change`, `cell.id`).

A consistent **cell indexing convention** (row-major order from upper-left) ensures that rasters, tables, and initial conditions map one-to-one for every pixel across years and runs. Class names and codes are reconciled prior to carbon accounting, including numeric and string variants, to ensure consistency across datasets.

Second, run-level accounting is executed for each site × scenario × run × time:

- determine per-pixel forest status at year 0,
- update cumulative burn history,
- assign proforestation vs afforestation equations for forest pixels,
- apply non-forest stock factors,
- compute annual and cumulative fire emissions,
- aggregate to landscape totals and LCT-specific totals.

Third, ensemble statistics summarize uncertainty from replicated stochastic runs:

- mean, SD, selected quantiles (e.g., P10–P90 or P25–P75),
- time-series envelopes for stock, cumulative emissions, and net balance,
- endpoint contrasts at year 80 vs BAU.

This architecture ensures that uncertainty rising from stochastic fire and land-cover transitions is propagated into policy-relevant carbon metrics, while maintaining run-level traceability for diagnostics and scenario comparison. For transparency and reproducibility, outputs are stored at both **run-level** (full trajectories) and **scenario-level** (central tendency and spread across stochastic runs), including total values as well as class-specific contributions to the net carbon balance.

4. Results

4.1 Gross carbon stock changes (Year 0-80)

When total carbon stock is analysed independently, the four landscapes exhibit two distinct baseline conditions and two distinct long-term responses (Figure 1). At year 0, 1A2a (Pre-Alps) has the largest initial stock (9.95 MtC), followed by 1A2b (Dolomiti and Carnia; 7.80 MtC), 1A2c (North-eastern Alps; 7.78 MtC), and 1A1b (North-western Alps; 7.56 MtC). Over 80 years, trajectories diverge markedly by site and scenario.

In **1A2c (North-eastern Alps, Lombardia)**, total carbon stock growth is the strongest and most consistent. BAU, StR_S, and FSR_DP converge around 10.31-10.35 MtC at year 80, reflecting gains of approximately 2.53-2.58 MtC from the initial condition. FSR_DIP remains lower at 9.69 MtC, but still shows substantial accumulation (+1.91 MtC). This indicates a highly favourable growth context, where most scenario logics sustain strong carbon build-up, while FSR_DIP moderates — but does not reverse — the positive trajectory.

In **1A2a (Pre-Alps, Friuli Venezia Giulia)**, total carbon stock increases under all scenarios, but scenario differences are more pronounced at the endpoint. BAU reaches the highest stock (11.45 MtC), StR_S is nearly identical (11.44 MtC), FSR_DP is slightly lower (11.41 MtC), and FSR_DIP is distinctly lower (10.93 MtC). In absolute terms, gains range from +1.51 MtC (BAU) to +0.99 MtC (FSR_DIP). The main pattern is that carbon accumulation remains positive across all scenarios, but scenario design determines how much of that potential is realized.

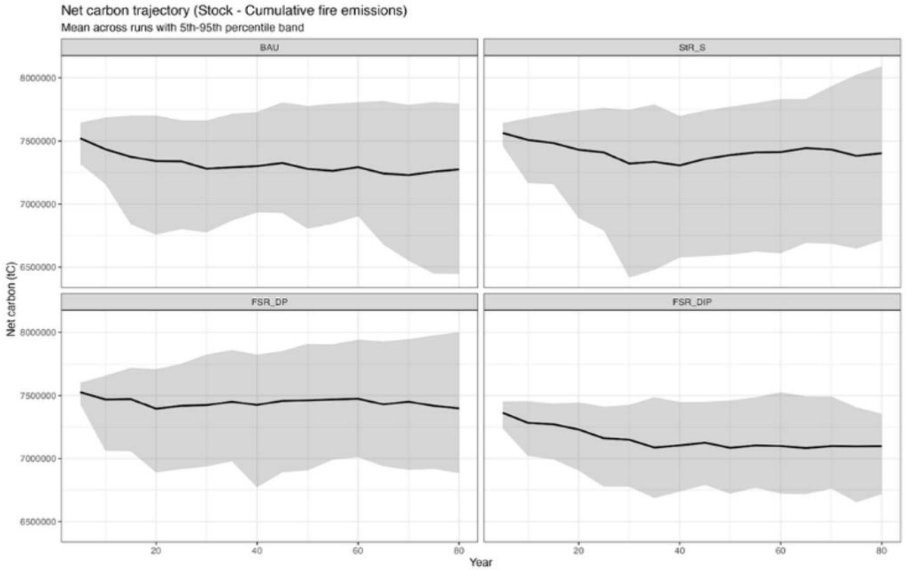
In **1A2b (Dolomiti and Carnia, Friuli Venezia Giulia)**, carbon stock increases are moderate. BAU reaches 8.27 MtC (+0.47 MtC), StR_S 8.36 MtC (+0.56 MtC), FSR_DP 8.32 MtC (+0.52 MtC), while FSR_DIP is substantially lower at 7.98 MtC (+0.18 MtC).

1A1b (North-western Alps, Piemonte) is the only landscape where total stock declines relative to year 0 in every scenarios. BAU ends at 7.33 MtC (-0.23 MtC), StR_S at 7.46 MtC (-0.10 MtC), FSR_DP at 7.45 MtC (-0.10 MtC), and FSR_DIP at 7.15 MtC (-0.40 MtC). These results confirm that 1A1b is the most constrained landscape for long-term carbon stock recovery in the current setup, with FSR_DIP amplifying the downward trajectory. A possible interpretative caveat for 1A1b is that the age-carbon relationship adopted from Deliverable 2.1 may already reflect disturbance legacies in the calibration plots used for the Piemonte landscape. If so, the simulated age resets associated with disturbance could compound an already disturbance-conditioned stock trajectory, potentially amplifying the apparent decline in total carbon stock. This possibility cannot be verified with the available data and should therefore be treated as a methodological caution rather than as a demonstrated explanation.

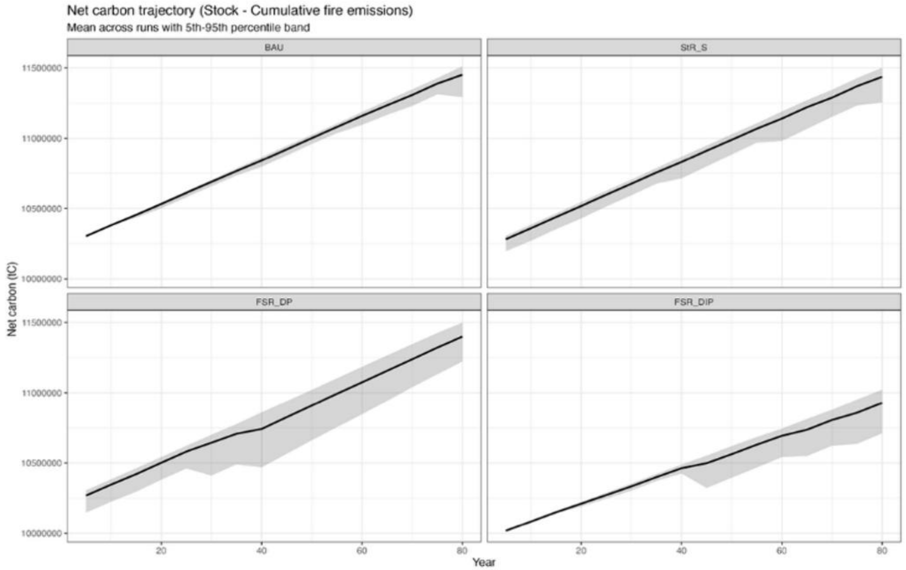
Across all sites, a clear ranking emerges: FSR_DIP consistently yields the lowest total carbon stock at year-80, while BAU, StR_S, and FSR_DP are generally closer, with their relative positions varying by site. These differences in total carbon stock are driven primarily by how scenario rules influence long-term accumulation pathways, rather than by fire outcomes alone.

Figure 1 (previous page) – Gross carbon stock changes in the four landscapes. The grey area indicates a 95% confidence interval from the 15 simulation runs for each landscape x scenario.

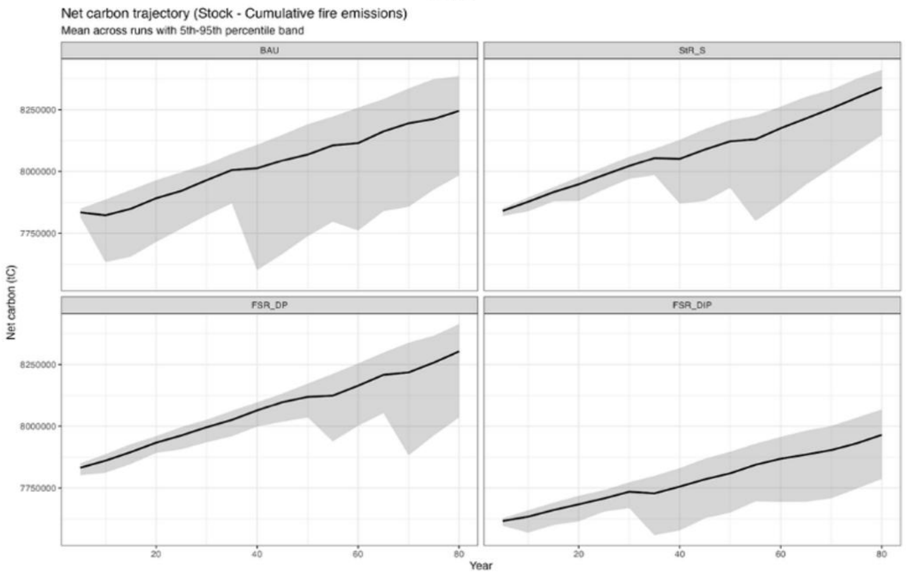
1A1b



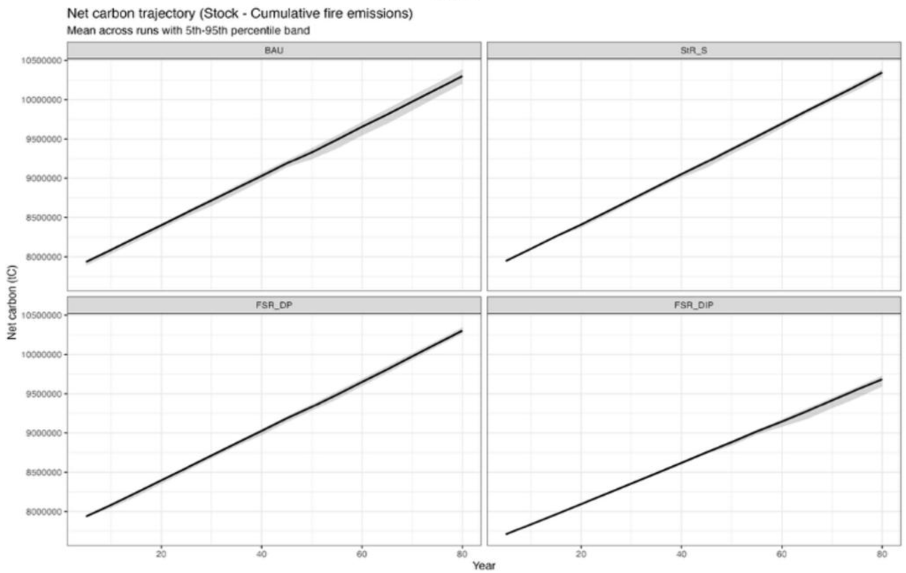
1A2a



1A2b



1A2c



4.2 Cumulative non-forest and forest floor emissions (Year 0–80)

Cumulative emissions in this deliverable include **non-forest fire-combustion emissions** from cropland, pasture, sparse vegetation, and shrubland (using fixed factors in tC ha^{-1}), and **forest combustion emissions** from litter, duff, and deadwood. They **do not include direct combustion of live-tree biomass**, which is captured indirectly through carbon stock resulting from fire-induced reductions in forest age classes. Soil carbon emissions are considered negligible. In this framework, most long-term fire impact on forest biomass are represented indirectly via post-fire age resets and trajectory modifications in stock accumulation.

Across all landscapes and scenarios, cumulative fire emissions are much smaller than total carbon stocks and even smaller than many stock gains between year 0 and 80. Total carbon stocks reach **millions of tC** (about 7 to 11.5 MtC by year 80), while cumulative emissions are in the **thousands to tens of thousands of tC**. This order-of-magnitude difference is critical for interpretation: emissions influence net balance, but scenario ranking are primarely driven by differences in long-term carbon stock accumulation.

At site level, the largest cumulative emissions occur in **1A1b (Northwestern Alps – Piemonte)**, the most fire-prone landscape, where scenario means range from about **55.5 to 58.0 thousand tC** (BAU 55,451; StR_S 55,650; FSR_DP 57,992; FSR_DIP 56,773 tC). While these emissions are substantial relative to other sites, they remain far below total-stock magnitudes and below the largest stock changes observed across scenarios.

In **1A2b (Dolomiti and Carnia – Friuli Venezia Giulia)**, cumulative emissions are intermediate, with distinct scenario effects: BAU is highest at **26,416 tC**, StR_S lowest at **18,140 tC**, FSR_DP at **20,775 tC**, and FSR_DIP at **17,571 tC**. In this landscape, prevention-oriented settings reduce total combustion more clearly than in 1A1b.

In **1A2c (Northeastern Alps – Lombardia)**, cumulative emissions are lower overall: BAU **9,131 tC**, StR_S **6,641 tC**, FSR_DP **5,819 tC**, FSR_DIP **5,826 tC**. The two fire-smart scenarios converge to similarly low values, indicating strong containment of modelled combustion across the landscape.

The lowest cumulative emissions are observed in **1A2a (Pre-Alps – Friuli Venezia Giulia)** under BAU and StR_S (BAU **2,746 tC** and StR_S **3,667 tC**, respectively), while FSR_DP and FSR_DIP are higher but still low in absolute terms (**6,897** and **6,099 tC**, respectively). This confirms that, in some landscapes, absolute emission totals remain limited across all scenario logics.

Comparing scenarios, a consistent pattern emerges in three sites (1A2b, 1A2c, and partly 1A2a) where prevention-oriented configurations reduce or keep emissions at lower levels relative to BAU. However, lower cumulative emissions do not automatically translate into better net carbon outcome at year 80, because net balance also depends on stock dynamics. In this model structure, and with these parameterizations, differences in cumulative emissions are often too small to offset large differences in stock accumulation trajectories. Therefore, cumulative emissions should be interpreted as one component of the carbon outcome, not as a standalone proxy for carbon performance.

4.3 Net carbon balance

The primary endpoint indicator for this deliverable is the **net carbon balance at year 80**, calculated at the run level and then summarized by scenario and landscape. This metric integrates long-term carbon stock dynamics and fire-combustion losses in a single quantity:

$$\mathrm{NetBalance}_{80} = (\mathrm{Stock}_{80} - \mathrm{Stock}_{0}) - \mathrm{CumEmis}_{0\to 80}$$

where: $\mathrm{Stock}_{80} - \mathrm{Stock}_{0}$is the total carbon gain (or loss) over 80 years, and $\mathrm{CumEmis}_{0\to 80}$is cumulative fire-combustion emissions over the same period.

At the landscape scale, results exhibit marked heterogeneity (Table 1). In **1A2c (Northeastern Alps – Lombardia**), the net carbon balance is strongly positive across all scenarios, with the highest values in StR_S and FSR_DP. Mean balances are: BAU 2,525,002 tC, StR_S 2,571,657 tC, FSR_DP 2,528,100 tC, FSR_DIP 1,908,493 tC**.** This reflect a high inherent accumulation potential, only partially reduced by FSR_DIP scenario.

In **1A2a (Pre-Alps – Friuli Venezia Giulia)**, all scenarios are also positive, but their separation is more pronounced: BAU 1,503,928 tC, StR_S 1,489,497 tC, FSR_DP 1,451,687 tC, FSR_DIP 980,818 tC. The first three scenarios are closely clustered, while FSR_DIP is substantially lower.

In **1A2b (Dolomiti and Carnia – Friuli Venezia Giulia)**, net carbon performance is intermediate and more sensitive to scenario design: BAU 444,043 tC, StR_S 538,887 tC, FSR_DP 501,519 tC, FSR_DIP 163,465 tC. Here StR_S is the top performer, while FSR_DIP exhibits a clear reduction in net benefit.

In **1A1b (Northwestern Alps – Piemonte)**, the net carbon balance is negative across all scenarios: BAU −281,903 tC, StR_S −152,251 tC, FSR_DP −158,881 tC, FSR_DIP −458,246 tC. This landscape is the most constrained in the simulation set, with FSR_DIP further amplifying the deficit.

Table 1. Net carbon balance at year 80 (tC, mean across 15 runs)

Site	BAU	StR_S	FSR_DP	FSR_DIP
1A1b	-281,903	-152,251	-158,881	-458,246
1A2a	1,503,928	1,489,497	1,451,687	980,818
1A2b	444,043	538,887	501,519	163,465
1A2c	2,525,002	2,571,657	2,528,100	1,908,493

Uncertainty across the 15 runs is notable. In the most variable case (1A1b), scenario distributions are wide and can occasionally cross zero though mean values remain directionally consistent. In contrast, 1A2c shows much lower variability relative to the mean signal, reflecting robust positive trajectories. These differences in spread highlight that scenario effects are landscape-dependent, both in magnitude and in the degree of certainty.

To enhance comparability across landscapes with different size, net carbon balance at year 80 was also normalized per hectare per year:

$$\mathrm{Net\ sink}_{80,\ \mathrm{ha,yr}} = \frac{\mathrm{NetBalance}_{80}}{\mathrm{Area}_{\mathrm{ha}} \times 80}$$

where $\text{NetBalance}_{80} = (\text{Stock}_{80} - \text{Stock}_0) - \text{CumEmis}_{0\rightarrow 80}$. This indicator expresses the average annual net carbon effect per unit area over the full simulation horizon (Table 2).

Table 2. Net carbon sink in tC ha^{-1} yr^{-1} (mean across 15 runs)

Site	BAU	StR_S	FSR_DP	FSR_DIP
1A1b	-0.078	-0.042	-0.044	-0.127
1A2a	0.449	0.445	0.434	0.293
1A2b	0.128	0.155	0.144	0.047
1A2c	0.707	0.720	0.708	0.534

Interpretation of the normalized per-ha values aligns with the absolute-tC analysis (Figure 2):

- **1A1b** remains negative under all scenarios, with the largest deficit in **FSR_DIP**.
- **1A2a, 1A2b, 1A2c** remain positive overall.
- **StR_S** achieves the highest net balance in **1A2b** and **1A2c**.
- **FSR_DIP** is systematically lower than BAU, StR_S, and FSR_DP in all landscapes.

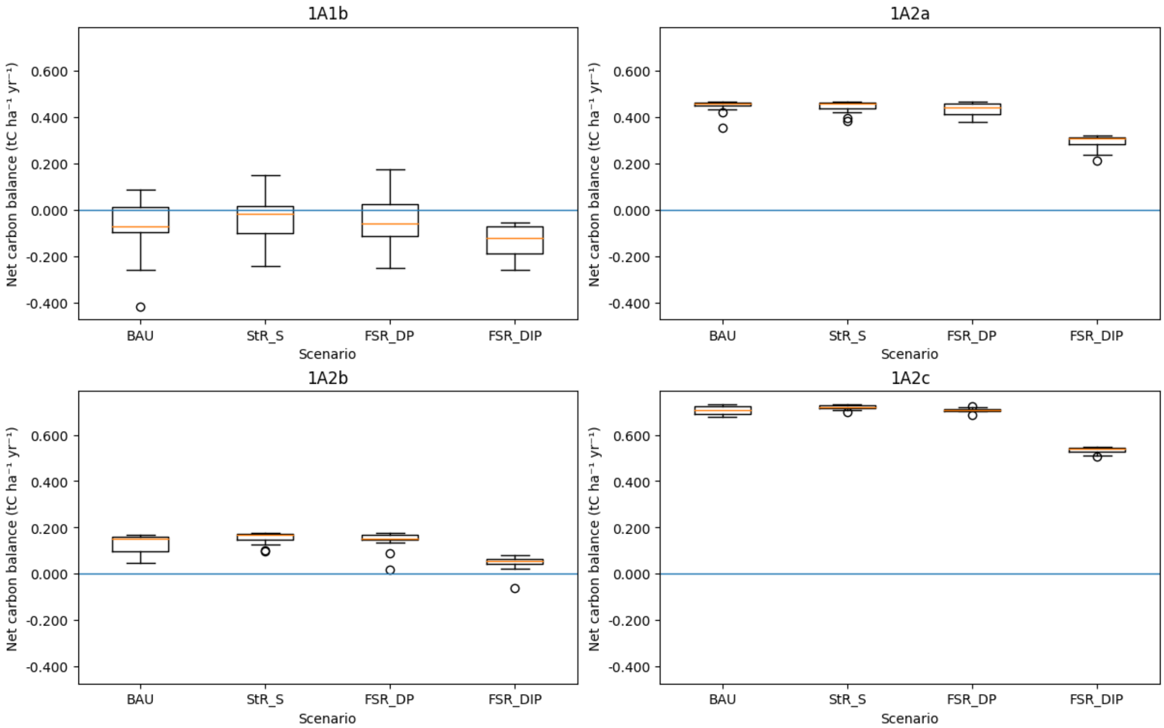


Figure 2 – Normalized net carbon balance (tC ha^{-1} yr^{-1}) across the four landscape and scenario at the end of the simulation (year 80).

Finally, to quantify the policy effect, each scenario was contrasted against BAU at year 80:

$$\Delta\text{Net}_{80}^{\text{scenario-BAU}}$$

StR_S improved or maintained BAU outcome in three landscapes (1A1b, 1A2b, 1A2c), and was near-parity in 1A2a. **FSR_DP** showed positive gains in three landscapes, with modest benefit in 1A2c and stronger gains in 1A1b and 1A2b. **FSR_DIP** was consistently below BAU across all landscapes, with particularly large penalties in 1A2a and 1A2c (Table 3).

Table 3. Scenario contrasts of net carbon balance (cumulative tC over the whole landscapes and 80 yeas of simulation)

Landscape	StR_S – BAU	FSR_DP – BAU	FSR_DIP – BAU
1A1b	+110,515	+123,023	-176,094
1A2a	-14,431	-52,241	-523,110
1A2b	+94,844	+57,709	-280,181
1A2c	+46,879	+3,640	-615,140

In unitary terms, FSR_DIP decreases net carbon balance between 0.05 and 0.17 tC ha^{-1} $year^{-1}$ relative to BAU. At the endpoint, the most robust positive policy signal came from **StR_S**, while **FSR_DIP** was consistently unfavorable under the tested parameterization. This underperformance is driven primarily by the stock component (Figure 3). In several landscapes, FSR_DIP reduced emissions relative to BAU, but the reductions were too small to offset the losses in stock accumulation. In other words, emission savings exists but are secondary compared with long-term structural effects on carbon accumulation pathways.

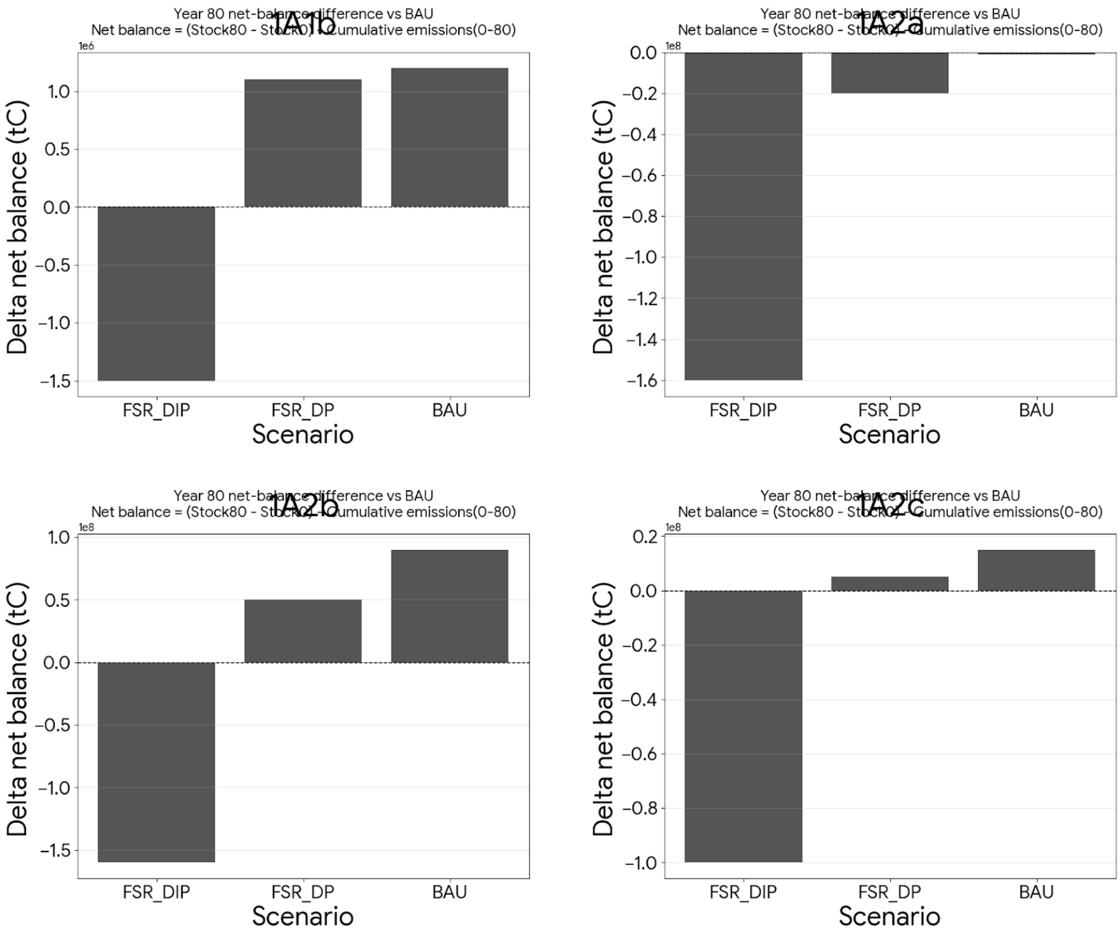


Figure 3 – Difference in net carbon balance between fire-smart rewilding scenarios and BAU at the end of the simulation (year 80 – average values over 15 iterations). Net balance = Stock80 – Stock0 – Cumulative emissions yeas 0-80.

4.4 Contribution of land cover classes

At year 80, the net carbon balance is overwhelmingly driven by **forest classes**, with broadleaf forest as the dominant contributor in every landscape. Class-level analysis shows:

- broadleaf (LCT 4) is the main source of net carbon gain.
- conifer (LCT 5) contribute positively but typically to a smaller share.

This pattern reflects the modelled age-stock relationships and the fact that much of the long-term stock signal is carried by forest age trajectories — in short, the final net outcome is primarily a forest-structure outcome.

Non-forest classes play a secondary but sometimes meaningful role. Cropland and pasture can contribute positively where they persist in mosaics, particularly if their area remains stable and fire pressure is moderate. Shrub and sparse classes contribute less, both because of lower per-hectare stock and limited or dynamic spatial extent. Urban, water, and barren classes are negligible under the adopted accounting factors, so they do not materially influence scenario ranking.

This decomposition clarifies scenario differences: the gap at year 80 is mostly explained by how governance rules shape forest area-age pathways and modulate fire-mediated forest losses over time. Large compensatory effects from non-forest classes are generally absent. Therefore, scenarios that preserve or enhance favorable forest trajectories perform better, whereas scenarios that constrain long-term forest accumulation show lower net carbon balance even if they reduce some combustion.

Overall, the simulations depict a forest-led carbon system: positive net outcomes are possible and often substantial, but their magnitude depends on landscape-specific management decisions that affect disturbance exposure, post-disturbance recovery pathways, and the persistence of productive forest trajectories over decades.

5. Discussion

Across the four Alpine landscapes, a clear and robust result emerges: the year-80 carbon outcome is driven primarily by forest dynamics, not by direct non-forest fire emissions. In all sites, the dominant signal comes from forest area, age structure, and forest-type transitions over time, while non-forest components act mainly as secondary modifiers. The direct "emissions" term remains much smaller in magnitude than total carbon stocks and long-term stock changes. Consequently, small differences in forest stock accumulation trajectories can determine the final net balance, even when annual fire-related emissions behave as expected. This is central for interpretation and for policy messaging: **reducing fire events is necessary, but alone it does not guarantee a larger net sink at 80 years if the strategy simultaneously limits long-term stock growth potential.**

A second robust finding is **asymmetric scenario performance**. The FSR_DIP pathway is consistently penalized relative to BAU in year-80 contrasts, across all sites. By contrast, StR_S and FSR_DP show site-dependent effects: they improve over BAU in some landscapes and underperform in others. This indicates that **policy effectiveness is conditional — it depends**

on initial landscape structure, site-specific fire regimes, and the interaction of governance rules with land-cover transitions over long time horizons.

The mechanism can be understood as a coupled system with three main drivers. First, **the initial state matters**. Each landscape begins with a specific composition of forest classes, non-forest mosaics, and age structures. This baseline determines whether the landscape has strong sink potential (i.e., capacity to accumulate additional stock by ageing) or is already approaching a slower-growth phase. In landscapes with ample sink headroom and stable succession, net gains are achievable. In contrast, landscapes with fragile mosaics or constrained recovery pathways, can be locked into lower-growth trajectories if governance logic is overly aggressive, unintentionally limiting long-term accumulation.

Second, **the scenario logic matters**. Rewilding and governance choices influence fire incidence and shape post-disturbance transitions, including age resets and class-level pathways. Since carbon stock equations vary by land-cover state and age class, the same burned pixel can undergo a structural shift in its carbon trajectory, altering long-term accumulation and ultimately affecting the landscape-level net balance.

Third, **there is a fire-land feedback**. Fire modifies land-cover transitions and age structure, which in turn influence future fuel arrangement, continuity, and fire susceptibility. Over long simulations, this feedback accumulates. A scenario may reduce short-term emissions but still yield a weaker net carbon sink if it produces a landscape configuration that limits long-term growth. Conversely, strategies that allow some controlled disturbance in a resilient mosaic can better preserve long-term sink function than purely suppression-centric pathway. In this context, FSR_DIP likely crosses a threshold where the negative effects on forest trajectories outweigh the benefits of avoided emissions, whereas StR_S and FSR_DP remain closer to a balance point, with initial local conditions largely determining whether outcomes are positive or negative.

Therefore, **does fire-smart rewilding improve climate mitigation relative to BAU?** It can improve mitigation relative to BAU when fire-smart design preserves or enhances long-term forest stock formation. This happens where interventions:

- reduce high-severity loss,
- maintain recovery continuity, and
- avoid repeated transitions into lower-stock pathways.

In such cases, avoided disturbance and sustained growth reinforce each other, producing a positive net effect. Conversely, mitigation can fail when the intervention package reduces fire but constrains forest structural development, repeatedly routing areas through low-stock phases. Here, the avoided direct emissions are insufficient to compensate for weaker long-term stock accumulation, turning the net effect negative, as observed for FSR_DIP in year-80 contrasts.

Maximizing closed-forest expansion may increase gross carbon stock in benign regimes, but in fire-prone systems it can also increase fuel continuity and reduce functional heterogeneity, raising long-term risk. A well designed **fuel management mosaic** can limit fire spread and severity, stabilize recovery pathways, and protect high-value sink cores. The **optimal mitigation pathway** is combines:

- dense, high-productivity forests where fire risk is manageable, and
- resilient mosaic buffers where fire propagation risk is high.

For planning, this shifts focus from area targets to trajectory targets: maintain sink-dominant cores and protect transition corridors that keep post-fire recovery on high-stock pathways.

Under **increased fire activity and warmer conditions**, unplanned forest expansion that increases continuity without fire risk mitigation can make landscapes more vulnerable to episodic stock setbacks. Future pathways require active shaping of structure and composition, not just passive continuation of past trends. Once a landscape enters a low-performance transition regime, recovering previous sink trajectory can take decades, making early targeting and adaptive correction far more effective than late compensation.

Operationally, the deliverable supports five priorities:

- **Plan interventions according to ecological risk patterns, not administrative borders.** Management strategies should reflect how different areas respond to land-cover change and wildfire dynamics, even when these areas cross municipal or regional boundaries.

- **Track carbon and fire outcomes together.** Monitoring should combine indicators of wildfire occurrence and severity with indicators of carbon storage and recovery, because fire control alone does not show whether climate objectives are being achieved.

- **Use a portfolio of management options rather than a single fixed strategy.** Decision makers should keep both precautionary and more adaptive pathways available, with clear criteria for when to maintain, strengthen, or revise each approach.

- **Prioritize actions that support long-term ecosystem recovery.** Interventions should reduce the risk of repeated disturbance in areas with high carbon value and help maintain regeneration processes that allow forests to recover and remain resilient over time.

- **Update strategies regularly as new evidence becomes available.** Planning should include periodic review of land-cover dynamics, carbon trends, and disturbance responses, so that management assumptions can be adjusted before ineffective approaches become embedded in long-term policy.

6. Conclusions and recommendations

The central conclusion is that net climate mitigation is trajectory-dependent. In these simulations, direct fire emissions are relevant for accounting, but they are not the dominant driver of year-80 net balance. The primary determinant is whether management and disturbance jointly sustain high cumulative forest stock formation.

A second key finding is that fire-smart strategies are not automatically climate-positive. Their effectiveness depends on whether they reduce disturbance while preserving favorable land-cover and age-class pathways.

At the policy scale, this means that **"more suppression" alone is a sufficient success criterion**. Effective landscape-based climate mitigation requires integrated targets that combine: fire outcomes, stock trajectory outcomes, and recovery continuity outcomes.

At planning scale, managers should adopt spatially differentiated design, defining: **sink-priority cores**, **resilience-priority mosaics**, and **transition corridors**, each with explicit management intent and monitoring thresholds.

Further development should focus on refining the accuracy and realism of the REMAINS model framework, by (1) improving transition realism after fire and management interaction (likely the most sensitive part of the mechanism); (2) refining class-specific stock equations and age progression consistency; (3) expanding the representation of disturbance severity and recovery heterogeneity; (4) strengthening validation against observed long-term trajectories (5) testing policy-relevant counterfactuals explicitly; (6) adding uncertainty diagnostics focused on decision thresholds.

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