D 1.1 LAND COVER CHANGE UNDER STRICT- AND FIRE-SMART REWILDING

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Executive summary

This deliverable assesses how alternative rewilding and fire-management strategies may reshape Alpine land cover over 2020-2100, using the spatially explicit REMAINS model calibrated on historical land-cover change and applied to four Italian Alpine landscapes. The analysis compares four governance scenarios, Business as Usual, Strict Rewilding with stronger suppression, Fire-Smart Rewilding with direct prevention, and Fire-Smart Rewilding with direct plus indirect prevention, through 240 simulations in total.

Across all landscapes and scenarios, the simulations show a consistent long-term increase in broadleaf forest and a decline in shrubland. Forest area expands in every case, but the magnitude of change differs strongly among landscapes, confirming that initial landscape structure matters more than scenario choice for many outcomes. Conifer and pasture responses are more variable, with conifers declining in three landscapes but increasing in the Northeastern Alps, and pasture losses ranging from negligible to substantial depending on context.

Among the tested strategies, Fire-Smart Rewilding with direct and indirect prevention (FSR_DIP) generally produces the largest net forest expansion, with gains ranging from +0.80% to +5.67% of initial forest area depending on the landscape. However, the results also show that maximizing forest cover alone is not an adequate planning target, because forest expansion can occur at the expense of non-forest classes that support biodiversity, ecological heterogeneity, and lower fuel continuity.

The main policy implication is that rewilding should be planned as a landscape-specific, fire-aware strategy rather than as uniform management withdrawal. The most effective approach combines selective forest expansion with the maintenance of strategic open or low-flammability mosaics, supported by targeted fuel breaks, composition-aware management, and adaptive spatial allocation of rewilding actions. Overall, the deliverable supports multi-criteria planning that jointly considers forest gain, forest composition, and mosaic integrity to improve both climate and biodiversity outcomes under increasing fire risk.

Keywords

Rewilding; Alpine space; land-use change; forest fire; afforestation; proforestation; Remains; forest modeling; simulation models; integrated modeling.

1. Introduction

Rewilding is increasingly proposed in Europe as a pathway to recover biodiversity, restore ecological processes, and strengthen long-term carbon storage in terrestrial ecosystems (Perino et al., 2019; Wentworth and Alison, 2016). At landscape scale, rewilding can increase structural complexity, expand natural habitats, and support the persistence of species linked to less intensive land use. Current science-policy assessments also emphasize that climate mitigation and biodiversity restoration are more effective when planned together, because the same land decisions shape both carbon outcomes and ecosystem integrity (Pörtner et al., 2023).

In mountain regions, these objectives are highly relevant. The Alps hold large carbon stocks, critical biodiversity, and dense mosaics of forests, grasslands, pastures, and human infrastructure. Over recent decades, many Alpine areas have experienced agricultural decline and partial abandonment, with expansion of shrub and forest cover in less accessible terrain (Anselmetto et al., 2024). This long-term trend has altered habitat patterns, landscape connectivity, and fuel structure. European assessments have repeatedly linked abandonment and extensification in mountain systems to major ecological and hydro-geomorphic consequences, including changes in biodiversity patterns and land stability processes (Ustaoglu and Collier, 2018).

The current challenge is that rewilding outcomes depend strongly on where and how rewilding is implemented (Hart et al., 2023). In fire-prone settings, unmanaged biomass accumulation and increasing fuel continuity can raise the probability of large, severe fire events. Under those conditions, a rewilding strategy that ignores fire context can fail to deliver expected carbon and biodiversity benefits over time, because repeated disturbances can reset stand development, shift composition, and increase landscape instability. Evidence from European fire literature supports the need to move from suppression-only approaches towards a landscape planning approach that integrates suppression, direct prevention (e.g. actively managing biomass to reduce vegetation flammability at specific infrastructures, such as fuelbreaks) and fuel-aware landscape design, e.g. mosaic of agriculture, pasture and forest management areas that mitigates fire potential in synergy with direct prevention (Held et al., 2026).

For this reason, the key policy question is no longer whether rewilding is desirable in general, but which **rewilding configuration** is effective under specific disturbance regimes (Selwyn et al., 2025). Choices about management withdrawal, suppression investments, strategic fuel management, investments in mountain agriculture, produce different long-term trajectories. These choices influence whether landscapes converge toward resilient mosaics or toward more continuous, high-load fuel structures. They also influence whether post-fire regeneration pathways maintain forest cover, shift forest types, or increase temporary non-forest states.

The introduction of fire-smart logic into rewilding planning responds directly to recent European findings. Reports and empirical studies indicate that land abandonment (Sil et al., 2019), climate pressure (Abatzoglou et al., 2025), and expanding wildland-urban interfaces (Guo et al., 2024) are increasing fire-prone conditions, while integrated landscape prevention can lower hazard and potential ire-induced emissions when implemented coherently at landscape scale. This literature supports the central premise of the present work: rewilding and fire policy should be analyzed jointly, because their interaction determines whether climate and biodiversity goals are reinforced or undermined over time (Plumanns-Pouton et al., 2025).

The Alpine context is particularly suitable for this analysis because it combines strong biophysical gradients and strong land-use legacy effects. Elevation, slope, and exposure modify growth and regeneration rates; settlement patterns and accessibility shape management intensity; historical abandonment leaves persistent signals in present-day class composition and age structure. Under these conditions, the same intervention can produce different outcomes in different landscapes. A strict rewilding target may increase long-term forest continuity in one area and amplify fire exposure in another. A fire-smart design may reduce spread potential in one topographic setting and have limited effect in another where baseline structure is already fragmented. Long-term carbon and biodiversity potential therefore emerges from repeated interactions among transition demand, spatial allocation, suppression/prevention policy, and post-fire regeneration dynamics. Spatially explicit modelling is therefore required to capture heterogeneity in both baseline and response.

In this report, the analysis focuses on Lan Use Land Cover (LULC) outcomes that are directly interpretable for planning: class trajectories, transition flows, and scenario contrasts across four large Alpine landscapes (~50 km^2). The intent is to provide a robust evidence base for designing rewilding strategies that remain effective under recurrent disturbance.

2. Methods

2.1 Study design and modelling objective

This study evaluates long-term LULC trajectories in Alpine landscapes under alternative governance strategies for rewilding and fire management. The objective is to measure how strongly policy design influences landscape composition over time when starting from the same baseline conditions.

To do this, we used **REMAINS** (a spatially explicit landscape dynamics model; Pais et al., 2023) as the core simulation engine. REMAINS represents the landscape as a raster grid and updates each cell annually according to ecological rules, management settings, and disturbance processes. In this framework, land-cover change is not imposed as a static map replacement. It emerges from the interaction among transition demand, spatial suitability, neighborhood effects, and fire-related feedbacks. This makes the model suitable for policy testing because it can represent both direct interventions (for example firebreak-based prevention) and indirect effects (for example altered succession and post-fire pathways).

The experimental design is factorial over study landscapes and governance scenarios, with annual time steps over an 80-year horizon (2020-2100). The simulation design was:

- **4 landscapes**
- **4 scenarios**
- **15 stochastic repetitions per landscape-scenario**

This results in 240 simulations in total. Replication is necessary because ignition, spread, and spatial allocation are partly stochastic; therefore scenario comparisons are based on ensemble behaviour rather than single trajectories.

The four scenarios are Business as usual (BAU), Strict rewilding and fire suppression (StR_S), Fire-smart rewilding and direct prevention (FSR_DP), and Fire-smart rewilding and direct-indirect prevention (FSR_DIP) (see par. 2.6 for details).

These scenarios differ in three controlled dimensions: (i) management/freeze layers, (ii) rewilding activation logic, and (iii) suppression/prevention settings (see Deliverable 3.1). Because these levers are changed systematically while keeping model structure and initialization consistent, observed differences among outputs can be interpreted as scenario effects.

Historical CORINE series and ancillary historical sources are used to reconstruct initial landscape states, derive observed transitions, and calibrate transition behavior before projection. The analytical scope of this deliverable is LULC-focused: fire processes (see Deliverable 3.1) are included insofar as they influence land-cover transitions and long-term composition. Output interpretation is based on class trajectories, transition flows, and variability across repetitions.

2.2 REMAINS: model description and treatment of land-cover change

REMAINS is a cell-based, annual-step simulation model for coupled landscape dynamics (Pais et al., 2023), implemented in the R programming framework. Each raster cell stores a land-cover state and age-related attributes, and the model updates these states year by year by combining policy constraints, ecological transitions, and disturbance modules. At a conceptual level, REMAINS treats land-cover change through three linked components:

1. **Demand**: how many cells must change for each transition type in a given year (from input table `lcc.demand`).
2. **Transition potential**: which eligible cells are preferred for change, based on class, topography, risk-related masks, and optional interface or fire-smart weighting.
3. **Spatial spreading**: how selected transitions are arranged in space, using neighborhood rules to produce clustered, landscape-like patterns rather than isolated random pixels.

This structure is implemented mainly in the R function `land.cover.change()`. The function first identifies eligible cells (source class + constraints), then computes transition potential, allocates the required number of cells to satisfy annual demand, and finally applies nearest-neighbour spreading to enforce spatial coherence.

Fire is coupled to LULC dynamics rather than treated as an external layer. Fire risk is calculated from class flammability and terrain controls, while ignition/spread outcomes depend on suppression and prevention settings defined by scenario. After fire, the function `postfire.rege()` updates cell states using post-fire transition logic with elevation-dependent constraints and vegetation-specific branches (broadleaf/conifer). This creates bidirectional feedback: land cover influences fire behavior, and fire reshapes future land-cover pathways.

REMAINS also includes dedicated routines for afforestation, encroachment, recovery, and interface analysis. In this project, those routines were parameterized for Alpine conditions and combined with scenario-specific policy levers. As a result, the model can represent both gradual background transitions and policy-driven shifts in landscape trajectory over long simulation horizons.

2.3 Spatial data, class harmonization, and initial conditions

LULC information was derived from CORINE Land Cover (CLC) rasters for **1990, 2000, 2006, 2012, 2018**, at **100 m × 100 m** cell size. For each study landscape, rasters were cropped and masked to a common analysis grid. The CORINE legend was reclassified using a fixed lookup table with 45 classes mapped to nine land cover classes: **urban, crop, pasture, broadleaf, conifer, shrub, sparse, barren, water**.

Summary by reclassified class

- **urban**: 11 CORINE classes (codes 1–11)
- **crop**: 10 classes (12, 13, 14, 15, 16, 17, 19, 20, 21, 22)
- **pasture**: 1 class (18)
- **broadleaf**: 1 class (23)
- **conifer**: 1 class (24)
- **mixed**: 1 class (25, split later into broadleaf/conifer)
- **sparse**: 3 classes (26, 27, 32)
- **shrub**: 2 classes (28, 29)
- **barren**: 4 classes (30, 31, 33, 34)
- **water**: 10 classes (35–44)

This 9-class legend is the one used in the final simulations and transition accounting. Class grouping was checked against satellite imagery and regional land use maps to reduce classification artifacts in Alpine contexts. Specific checks were implemented for:

- **mixed forest** split into broadleaf/conifer according to local composition rules,
- **pasture vs grassland** conflation in CLC,
- **sparse vegetation (CLC 333)**, treated as landscape-specific (barren or shrub/afforestation proxy depending on region/landscape),
- classes aggregated to water that are absent in Alpine conditions.

The initialization step converts historical land-cover information into the full year-0 state required by REMAINS. For each 100 m cell, the simulation input stores the reclassified land-cover class and an age-related state variable used by succession, rewilding, management, and post-fire dynamics modules. Age-state reconstruction integrates the CORINE sequence (1990, 2000, 2006, 2012, 2018) with historical land-use references used in the project workflow (including pre-1990 sources such as 1954 and 1936 maps). The CORINE sequence provides observed change timing over recent decades, while historical layers help separate long-established forest from more recent forest establishment. This combined reconstruction avoids treating all present-day forest as demographically equivalent and improves realism in the initial conditions.

A cell-level TSCHG variable (time since change) is then computed by identifying the most recent observed class transition along the historical sequence and measuring elapsed time from that transition to the simulation start. Where no transition is observed, persistence time accumulates. Missing observations are handled explicitly so they do not generate artificial resets. TSCHG is therefore a direct proxy of land-cover persistence and feeds age-dependent transition logic in the model.

Because this implementation uses discrete age classes, TSCHG and historical persistence are mapped to five initialization bins: 6, 12, 18, 28, and 64+ years. The 64+ class includes all cells older than the upper threshold. This discretization was adopted to maintain computational efficiency and stable calibration over large extents and long runs while preserving ecologically meaningful differences among developmental stages. For forest cells, this procedure distinguishes long-established stands from recent establishment and post-transition cohorts, which is important for subsequent fire response and transition behavior.

Before simulation, initialization rasters are checked for internal consistency: valid class codes against the project legend, non-missing state values on active land cells, plausible age-class distributions by class and landscape, and consistency with scenario masks used for management, rewilding, and prevention. The final output is one simulation-ready raster per landscape containing harmonized LULC and age-consistent state variables for every cell. This common baseline ensures that differences among scenario outcomes are attributable to scenario settings and stochastic processes rather than inconsistencies in year-0 inputs.

2.4 Transition calibration

We linked observed historical changes to simulation parameters by converting multi-temporal land-cover evidence into transition probabilities and annual transition demand that REMAINS can use directly. The starting point was the harmonized CORINE raster series (1990, 2000, 2006, 2012, 2018), already reclassified to the project legend and aligned to a common 100 m grid. For each cell, class trajectories through time were compared to identify whether change occurred, when it occurred, and between which origin and destination classes. This produced a full empirical record of observed class persistence and class-to-class turnover before scenario simulation.

Transition counts were computed by overlaying pairs of reclassified rasters and tabulating all origin-destination combinations. In operational terms, this was implemented with a function that returns, for each pair $i \rightarrow j$, the number of cells that changed from class i to class j. We built **transition matrices** for the whole Italian Alpine domain to describe broad historical patterns, and in parallel for each calibration region (Piemonte, Lombardia, Friuli) to preserve regional heterogeneity in transition behaviour. This dual scale is important because Alpine-wide matrices are informative for synthesis, while regional matrices better represent local transition regimes used for calibration and forward runs.

Raw transition counts are converted to conditional transition probabilities so that each origin class has a full probability distribution across possible destinations. For an origin class i, the probability of transition to class j is computed as

$$P_{i \rightarrow j} = \frac{N_{i \rightarrow j}}{\sum_j N_{i \rightarrow j}}$$

where $N_{i \rightarrow j}$ is the observed number of cells in that transition. The resulting probability structure captures gross dynamics rather than only net class balances, which is necessary because different transition pathways can lead to similar net changes but imply very different management relevance and fire exposure.

Observed transitions were then translated into yearly future transition demand through the input table `lcc.demand`, which specifies how many cells must undergo each transition type at each yearly step. In practical terms, `lcc.demand` can request, for example, a specific annual number of crop→broadleaf, pasture→conifer, or shrub→forest transitions, while the land-cover-change module decides where those transitions are placed according to eligibility, risk weighting, and neighborhood spreading.

Historical transition totals were then converted into an **80-year annual demand series**, combining calibrated transition probabilities with stochastic yearly allocation. Concretely, for each origin→destination transition (for example crop→broadleaf, pasture→conifer), we first estimated the total expected amount of change from the calibrated transition matrix (derived from reclassified CORINE trajectories and regional calibration). Those totals were then **scaled to each landscape size** (number of valid cells) so that transition pressure remained proportional across landscapes. After scaling, we distributed each transition total across the 80 simulation years by random sampling under a conservation constraint: yearly values can vary, but their sum over the horizon must match the calibrated cumulative target for that transition (or remain within rounding tolerance). This is the key point: variability is annual, consistency is cumulative.

The annual demand values produced by this step were written to `lcc.demand`, which tells REMAINS how many cells must transition each year for each transition type. During the simulation, however, `lcc.demand` controls only the **quantity** of change. The **realized pathway** still depends on cell eligibility (source class, slope/elevation constraints, masks), spatial spreading/clustering (nearest neighborhood expansion), fire occurrence, post-fire regeneration, and scenario levers (rewilding flags, freeze layers, suppression thresholds, direct/indirect prevention). For this reason, annual trajectories are not deterministic even when cumulative demand is fixed. This design preserves the historical long-term signal while avoiding an artificial "same change every year" pattern. It produces realistic interannual fluctuations and allows policy settings and fire dynamics to redirect when and where transitions occur, without losing coherence with the calibrated regional transition regime.

2.5 REMAINS modules and parameterization

REMAINS handles vegetation dynamics through a coupled set of modules that were parameterized for Alpine conditions before running the 80-year simulations. This parameterization ensured that landscape change emerged from coupled ecological and policy processes, while maintaining explicit numerical settings consistent with Alpine calibration and scenario design.

- The **AFFORESTATION** module simulates transitions from pasture and shrub/sparse to forest land use under explicit rate and radius constraints. For this project, afforestation was set to **0.8% yr^{-1} for broadleaf** and **1.2% yr^{-1} for conifer**, with colonization radii of **250 m (broadleaf)** and **600 m (conifer)**. Such change rates were derived from analysis of observed land use transitions from the full CLC dataset 1990-2018 at the Alpine Space scale.

- The **ENCROACHMENT** module governs progression from sparse/rocky vegetation toward shrubland through neighborhood expansion; compared with earlier settings, encroachment was reduced to an annual rate of **0.4%** (derived from CLC time series) with an effective radius of **80 m**. Shrub persistence constraints were also enforced so shrubland needed at least **9 years** residence (`rewilding.th = 9`) before becoming eligible for shrub-to-forest transition. Transitional shrub-to-forest states (`shrub-to-con`, `shrub-to-broad`) were shortened from **8 years to 4 years**, and residual transitional cells at simulation end were reset to **age class = 0**.

- The **FIRE.RISK** module estimates ignition and spread propensity by combining class-specific flammability with topographic gradients and vulnerability/damage components. Annual fire simulation uses class flammability maps, a user-defined time series of burned-area, individual fire-size distributions, ignition probability surfaces, and suppression decisions from scenario settings. See Deliverable 3.1 for a full description of fire module parameterization.

- Post-fire dynamics were handled by two linked components. **POSTFIRE REGEN** (`postfire.rege()`) applies post-fire transition probabilities with elevation constraints (see Deliverable 3.1) and class-specific branching (conifer vs broadleaf), while **FOREST RECOVER** tracks the return trajectory from transitional post-fire states. Relative to the original REMAINS parameters, developed for Mediterranean Spain, we reduced regeneration readiness to reflect slower Alpine recovery rates, including post-fire contagion probability set to **0.3**, rocky-elevation threshold set to **1500 m** (`elevation.rocky`), and conifer recovery radius reduced to **800 m**. Fire effects on stand age were also revised: most fires were considered non-stand-replacing events that reduced age of the forest by **one age class**, while stand-replacing fires in young forests (<6 years old) induced a non-forest transitional land use for 4 years (see Deliverable 3.1).

2.6 Rewilding framework and scenarios

Rewilding was operationalized as a **minimum 10% quota of eligible landscape area**, calculated across all land-cover types except **urban, water, and barren**. This quota is consistent with the targets of the EU Biodiversity Strategy, i.e., 10% of each ecosystem type under strict protection by 2030. Eligible rewilding classes include forests, pasture, sparse vegetation, and shrubland; agriculture is excluded from rewilding allocation. The simulation is based on rules that generate a conflict between rewilding allocation across the landscape and potential managed forests and pastures in each landscape. This conflict reproduces current difficulties in implementing nature restoration targets in landscapes with historical legacies related to forest and pasture management.

"Potential management areas" are the spatial mask used to reassign management when required by scenario logic. They are defined as **30% of forest area** (conifer + broadleaf) within a **150 m buffer** around forest road networks, plus **10% of pasture** and **10% of sparse** area, allocated randomly but grouped in paddock-like clusters.

The rewilding target of 10% is built through a three-step priority structure. The first component is named **Rw**, defined as cells already under indefinite aging **within protected areas** under baseline conditions. If Rw already reaches 10%, no additional allocation is required. If Rw is below target, the model activates **Rwm**, which is obtained by interrupting management inside protected areas in the predefined "potential management areas", i.e. generates a conflict with management inside protected areas. If the sum Rw + Rwm is still below target, the remaining quota is allocated as **Rwu** within non-managed zones in an expanding buffer around protected areas, using a 1 km expansion rule and successive increments until the 10% target is met. In this case rewilding is allocated outside protected areas leveraging on latent reserves, currently not under protection but that provide services like carbon storage and biodiversity (Spadoni et al. 2025).

In this implementation, management status controls age dynamics. **Management** corresponds to interruption of regular unit aging progression. **No management** corresponds to regular unit aging progression (one year of age increase for each simulation year). These definitions are used consistently in rewilding-related reallocations. Four scenarios were run:

Scenario 1: Business As Usual (BAU).

BAU applies no dedicated rewilding policy, including inside protected areas. Fire-smart rewilding is not activated. Fire suppression remains at historical baseline level. Management is assigned as follows: forests have active management on 30% of area (within the 150 m road buffer mask), with the remaining 70% under no management; pasture and sparse have 10% managed and 90% unmanaged; agriculture follows full aging/abandonment trajectory. BAU provides the counterfactual for all policy scenarios and is used to anchor suppression thresholds.

Scenario 2: Strict Rewilding + Fire-control policy (StR_S).

This scenario enforces the 10% rewilding quota (**additional to any spontaneous rewilding occurring in BAU**) through the Rw → Rwm → Rwu hierarchy. Allocation starts in protected areas and expands outward only if needed. Compared with BAU, fire suppression is increased to protect rewilding areas (operationally, +30% relative to BAU suppression level), while fire-smart prevention modules remain off. Forest and pasture management is reduced inside protected areas and, if needed, in adjacent buffers, to increase proforestation share. If protected areas already contain at least 10% indefinite-aging area (Rw), no additional rewilding is imposed. If not, the model removes management first from potential managed cells inside protected areas (Rwm), then from eligible non-managed reserves in the 1 km expansion zone (Rwu). This scenario tests strict quota-based rewilding with stronger suppression and includes the possibility of a fire-fighting trap linked to older age structure and higher flammability.

Scenario 3: Fire-smart Rewilding + Direct Prevention (FSR_DP).

This scenario combines the +10% rewilding target with direct fire prevention. Rewilding is allowed outside protected areas in lower-risk locations and is protected by firebreak networks. Forest management remains aligned with BAU shares (30% forest management baseline), and suppression is 20% higher than BAU level. Rewilding allocation follows the same Rw/Rwm/Rwu logic but excludes high-flammability pixels from additional allocation steps, based on dedicated strategic masks. A fixed exclusion layer is applied outside protected areas (5% of territory selected as non-rewilding for strategic protection). In simulation behavior, firebreak cells are treated as direct prevention elements in spread/suppression logic.

Scenario 4: Fire-smart Rewilding + Direct + Indirect Prevention (FSR_DIP).

This scenario includes all direct-prevention features of FSR_DP and adds indirect prevention through preconfigured fuel/land-cover reorganization around firebreak systems. Rewilding is targeted in lower-risk zones, including areas outside protected areas. A mosaic-agriculture prevention concept is added in synergy with firebreaks. Forest management capacity is increased relative to BAU, setting **area managed to 40%** in eligible management zones (implemented through alternate management-layer selection in launcher configuration). Suppression is 20% higher than BAU level. Operational notes include firebreak handling with age reset and very low flammability behavior in those corridors; this supports their role as high-effect control lines during spread.

Across scenarios, differences in outcomes are produced by explicit changes in rewilding allocation rules, management masks, suppression thresholds, and prevention switches. This setup allows direct attribution of land-cover trajectories to policy design choices rather than to changes in baseline data or model structure.

For each run, **annual outputs** include land-cover maps, age updates, and transition logs. Analysis focused on:

- class areas over time,
- gross and net transition flows,
- scenario contrasts within each landscape,
- ensemble variability across 15 repetitions (central tendency and dispersion).

These metrics are reported consistently across all landscapes and scenarios to support direct comparison and policy interpretation.

3. Study Areas

The analysis was developed in four Alpine landscapes (Figure 1) in three Italian alpine eco-regions, processed on a **30 m grid** (900 m² per cell), all using the same common 9-class legend: **barren, broadleaf, conifer, crop, pasture, shrub, sparse, urban, water**. The four units are very similar in total size (about 42000 to 45000 hectares), which is important because it reduces scale bias in cross-landscape scenario comparison, fire size modeling, and land use transition calibration. Differences in outcomes are therefore more likely to reflect ecological structure and process interactions than simple area effects.

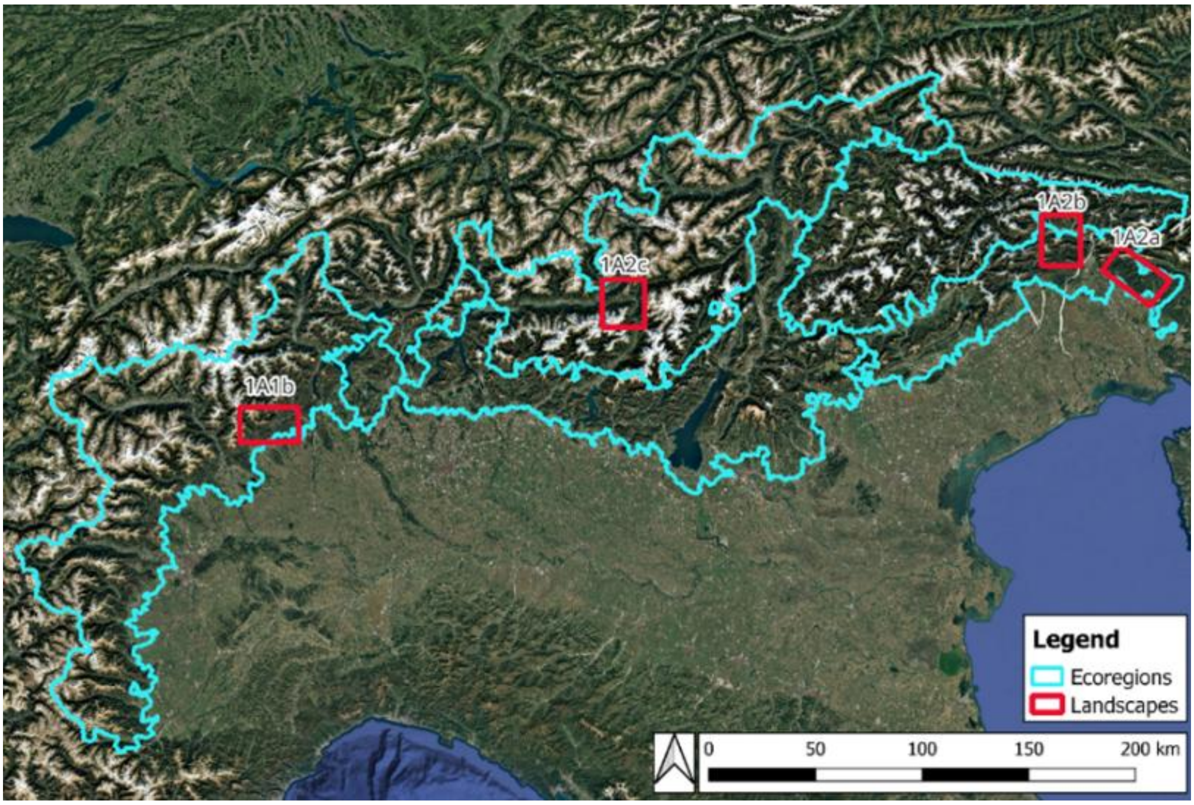

Figure 1 – Study landscape location in Alpine eco-regions: 1A1b = Northwestern Alps, 1A2a = Pre-Alps, 1A2b = Dolomiti and Carnia, and 1A2c = Northeastern Alps.

These landscapes represent four distinct Alpine ecoregions: **1A1b Northwestern Alps**, **1A2a Pre-Alps**, **1A2b Dolomiti and Carnia**, and **1A2c Northeastern Alps**, following ISTAT classification[1]. These are spatial units defined by relatively homogeneous combinations of climate, geomorphology, potential vegetation, and ecological dynamics, and are used to compare landscapes within a consistent biophysical context. The four selected subsections belong to the Alpine Province (Temperate Division), whose climate is described in the reference framework as cold-temperate mountain climate with strong topographic control: mean annual temperature generally ranging from about 0 to 10 °C along elevation gradients, abundant precipitation with a continental seasonal regime (minimum in winter, maximum in summer), and marked local variability linked to slope exposure and valley orientation. Across the province, thermal continentality tends to be weaker in northern and highest sectors, intermediate in the western sector, and stronger in central-eastern prealpine valleys. Within this common Alpine signal, subsection-level differences are relevant for interpretation. **1A1b Northwestern Alps** belongs to the Western Alps section, where semi-continental conditions are frequent, while more oceanic traits occur at high elevations; it represents a high-relief western Alpine mosaic with broad elevation range and mixed mountain forest systems. **1A2a Pre-Alps** belongs to the Central and Eastern Alps section and occupies lower to mid-elevation prealpine belts; here large morainic lakes mitigate local thermal extremes, and potential vegetation is dominated by temperate deciduous forests, consistent with the strong broadleaf signal observed in baseline composition. **1A2b Dolomiti and Carnia** is characterized by pronounced relief energy and extensive carbonate massifs with many peaks above 3000 m, with a stronger mountain-climate imprint and widespread potential for conifer forests, dwarf

[1] https://www.istat.it/it/archivio/224780

shrublands, and high-elevation grasslands. **1A2c Northeastern Alps** extends over the inner northeastern chain, with high relief energy and a prevalence of metamorphic substrates; climatically and ecologically it expresses strong inner-Alpine traits and supports extensive acidophilous conifer and subalpine/open high-elevation communities. This classification strengthens interpretation because it links scenario outcomes to ecologically meaningful regional contexts, not only to administrative or geometric units.

Two major gradients shape the expected behavior of the simulations: a **topographic gradient** and a gradient linked to **protected-area availability** (Table 1). The topographic signal is clear. Landscape 1A2c occupies the highest mountain domain (mean elevation 1457 m, maximum 2806 m), while 1A2b and 1A2c are the steepest systems (mean slope about 27.7°), and 1A2b has the strongest upper-tail slope regime (P90 = 44.96°). By contrast, 1A2a is the lowest and topographically less extreme among the four. These differences are directly relevant to land-use change trajectories, as slope and elevation constrain where transitions are feasible, where management actions can be practically implemented, and where fire spread can persist through connected fuels. In practical terms, the same transition demand and the same policy settings can produce different realized pathways simply because steep high-relief landscapes have fewer accessible and more spatially constrained options for intervention. The second gradient concerns the amount of protected land available at baseline. Landscapes 1A1b and 1A2c have much higher protected-area shares (20.36% and 19.01%) than 1A2a and 1A2b (10.83% and 9.91%) (Table 1). This has immediate consequences for rewilding implementation under the project rules. Since the 10% rewilding target is first allocated in protected areas (Rw), landscapes with larger protected stocks can satisfy a larger fraction of the target before the model activates additional allocation steps in potential managed cells (Rwm) and external buffers (Rwu). Landscapes with lower protected coverage are expected to reach these secondary allocation phases earlier, with stronger interaction between rewilding, management reassignment, and fire-risk constraints.

The four landscapes start from clearly distinct ecological mosaics (Table 2), and this is a key condition for interpreting deliverable outcomes because REMAINS applies class-dependent transition logic, class-specific flammability, and post-fire regeneration pathways. In **1A2a (Pre-Alps)**, the baseline is dominated by broadleaf forest (**81.32%**) with a very small conifer component (**2.00%**), describing a mainly deciduous matrix where baseline fire behavior is expected to be less driven by conifer continuity and more by local interfaces and management placement. **1A2b (Dolomiti and Carnia)** shows a mixed woody system (**69.23% broadleaf**, **14.48% conifer**) with the highest barren fraction (**1.53%**), a configuration that combines substantial forest continuity with mountain open patches and may therefore express strong disturbance-feedback behavior when fire and land-cover transitions interact. **1A2c (Northeastern Alps)** is the most compositionally balanced between broadleaf and conifer (**35.25%** vs **35.72%**) and has the largest sparse share (**5.80%**), indicating a heterogeneous high-elevation mosaic with frequent boundaries among forest, sparse, shrub, and pasture domains. **1A1b (Northwestern Alps)** retains high broadleaf cover (**65.01%**) but also relevant shrub and pasture components and the highest urban share (**8.21%**), pointing to a more anthropogenic and interface-rich system. These contrasts are directly relevant for scenario results. First, differences in broadleaf-conifer balance alter ignition potential, spread behavior, and the probability of post-fire type shifts. Second, differences in shrub, sparse, and pasture pools modify how much ecological space is available for rewilding allocation, encroachment, and afforestation-like dynamics under policy constraints. Third, differences in urban presence and interface density change where prevention and suppression actions can have the greatest leverage on realized trajectories.

A **structural reading** of each landscape is essential for interpreting subsequent scenario outcomes (Table 3). Landscape 1A2b combines the largest **mean forest patch size** (62 ha) with the lowest **number of forest patches** (608), indicating high woody continuity. In a steep topographic context, this configuration can support longer and more spatially coherent fire spread pathways when flammable classes remain connected, and can therefore amplify the effect of differences in suppression rules and prevention design. Landscape 1A2c shows the opposite configuration: the highest **edge density** (130.95 m/ha), the highest patch count (1,787), and the smallest mean forest patch size (19.76 ha). This is a highly fragmented mosaic where interface processes are expected to dominate, including localized transitions, stronger boundary effects, and greater sensitivity to where firebreaks and rewilding allocations are spatially placed. Landscape 1A2a has the lowest edge density (63.79 m/ha), suggesting smoother internal configuration and weaker boundary complexity at baseline, while 1A1b occupies an intermediate-to-high position for both edge density and patch size, with a mixed urban-forest-open pattern that can activate both continuity-driven and interface-driven dynamics depending on scenario settings.

In summary, these data describe four different **archetipal Alpine mosaics** (Figure 2):

- Landscape 1A1b (Northwestern Alps, Piemonte) is a mixed montane mosaic with relatively high protected-area availability and the highest urban share among the four, making it particularly relevant for evaluating how rewilding interacts with human-facing interfaces and with protected-area-first allocation rules.
- Landscape 1A2a (Pre-Alps, Friuli Venezia Giulia) is a low-to-mid elevation broadleaf-dominated system with smoother boundaries and limited conifer presence, so baseline fire behavior is expected to be less controlled by conifer continuity and more by local configuration and management positioning.
- Landscape 1A2b (Dolomiti and Carnia, Friuli Venezia Giulia) combines steep terrain, large connected woody patches, and mixed forest composition, making it a key test case for continuity-mediated disturbance feedbacks and for differences between strict rewilding and fire-smart prevention settings.
- Landscape 1A2c (Northeastern Alps, Lombardia) is high-elevation, compositionally mixed, and structurally fragmented, so outcomes are expected to be highly responsive to spatial targeting of direct and indirect prevention and to transition weighting at class interfaces.

These contrasts act as mechanistic drivers of divergence. The same formal policy lever — including a 10% rewilding target, identical suppression thresholds, or the same direct/indirect prevention switch — are applied to landscapes with different relief constraints, different protected-area starting stocks, land-cover composition, and different fragmentation geometry. Because REMAINS allocates transitions through class-specific probabilities and spatial neighborhood rules, while explicitly coupling land-cover dynamics with fire processes, realized trajectories necessarily depend on initial landscape structure. Differences across landscapes should therefore be interpreted as expected structural filtering of policy actions. This four-landscape design is particularly informative for land-use-change assessment: it enables separation of policy effect from landscape-context effects and supports more defensible interpretation of scenario performance in Alpine planning conditions.

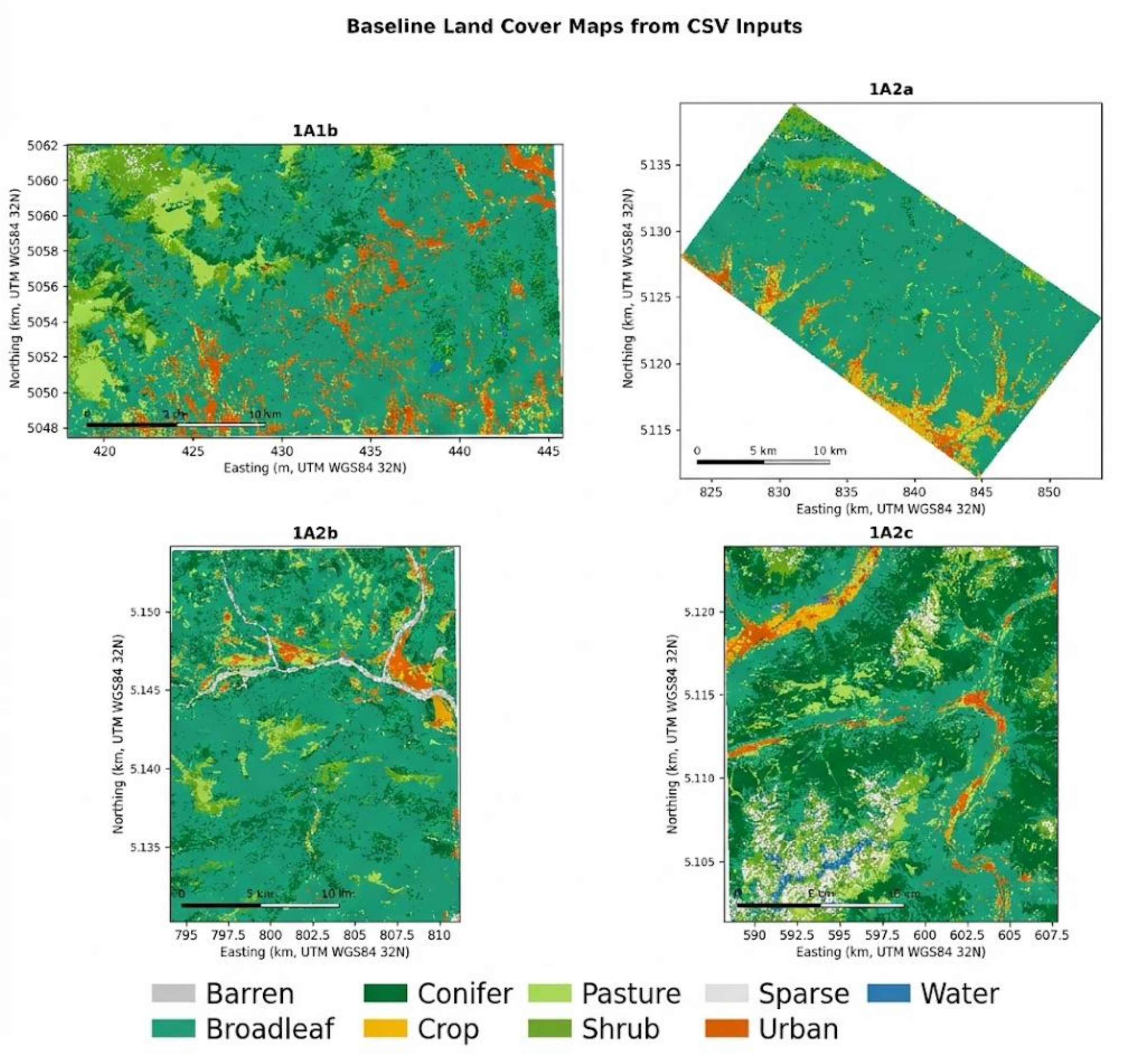

Figure 2 – Land cover classes in the four study landscapes. 1A1b = Northwestern Alps, 1A2a = Pre-Alps, 1A2b = Dolomiti and Carnia, and 1A2c = Northeastern Alps

Table 1. Core geographic and topographic descriptors at baseline

ID	Ecoregion subsection	Administrative region	Cells (n)	Area (ha)	Protected area (%)	Elevation min / mean / max (m)	Mean slope (°)	P90 slope (°)
1A1b	NW Alps	Piemonte	501,599	45,144	20.36	163 / 827 / 2547	22.26	36.89
1A2a	Pre-Alps	Friuli Venezia Giulia	465,060	41,855	10.83	92 / 529 / 1864	23.12	38.07
1A2b	Dolomiti - Carnia	Friuli Venezia Giulia	482,425	43,418	9.91	119 / 772 / 1906	27.77	44.96
1A2c	NE Alps	Lombardia	496,017	44,642	19.01	269 / 1457 / 2806	27.72	40.71

Table 2. Baseline land-use/land-cover composition (% of landscape area)

Class (%)	1A1b	1A2a	1A2b	1A2c
Broadleaf	65.01	81.32	69.23	35.25
Conifer	8.77	2.00	14.48	35.72
Pasture	8.65	5.59	6.92	8.45
Shrub	7.41	3.01	3.11	8.12
Urban	8.21	3.93	2.67	2.82
Crop	0.86	3.59	0.74	1.93
Sparse	0.30	0.02	0.92	5.80
Barren	0.36	0.27	1.53	0.30
Water	0.43	0.28	0.40	1.62

+Table 3. Initial spatial structure indicators

Landscape	Edge density (m/ha)	Forest patch count (n)	Mean forest patch size (ha)
1A1b	105.71	825	44.43
1A2a	63.79	1,168	30.94
1A2b	103.90	608	62.00
1A2c	130.95	1,787	19.76

(Forest = broadleaf + conifer + shrub, 4-neighbor connectivity)

4. Historical land use transitions

This section reports observed transitions from the empirical transition-probability matrices (1990–2018), using both original CLC information and the reclassified legend used in this deliverable. For the historical analysis, **the mixed forest class was retained as an observed class**. Mixed forest was reallocated only later during model-initialization of scenario landscapes. Persistence transitions (class unchanged) were excluded from ranking analyses of dominant flows.

The Alpine-wide signal is clear and internally coherent (Figure 3, Figure 4). Based on the transition matrix, the dominant pathways occur within existing forest classes, specifically **mixed forest → conifer** (P = 0.2529), which is the largest transition in absolute terms (133,613 pixels), followed by **mixed forest → broadleaf** (P = 0.1326; 70,025 pixels). These high-probability and high-magnitude pathways however could also reflect changes in the classification algorithm or accuracy in different Corine assessment, and must be interpreted with cation. A second crucial group of transitions highlights the active colonization of high-altitude or marginal environments: the massive shift from **barren → sparse vegetation** (P = 0.1148; 56,298 pixels) indicates strong primary succession, potentially driven by the upward shift of vegetation lines in response to climate warming. Finally, a distinct signal of secondary succession is evident at the agro-pastoral interface, marked by rapid naturalization. We observe substantial shifts from open and semi-open systems toward denser vegetation, notably **shrub → broadleaf** (P = 0.1614; 25,695 pixels) and **pasture → broadleaf** (P = 0.1279; 5,690 pixels). Interpreted ecologically, this pattern is highly consistent with a widespread process of land abandonment in mountain territories: low-intensity uses (such as pastures and shrublands) are no longer maintained and spontaneously transition toward mature forest states. This broad interpretation is consistent with European and Alpine evidence on **mountain land abandonment and post-abandonment vegetation dynamics** (MacDonald et al., 2000; Tasser and tappeiner, 2002; Prévosto et al., 2011). Conversely, within human-dominated landscapes, agricultural areas are subject to significant **land consumption**, with the primary transition from crop to urban land (P = 0.0702; 31,191 pixels) underscoring the ongoing pressure of infrastructural development and urban sprawl in valley bottoms.

The detailed CORINE matrix helps to clarify the processes underlying these aggregate flows. At this level of disaggregation, very high conditional probabilities may arise for small source classes, so interpretations should always be validated against the corresponding counts. Still, the detailed classes confirm that transitions among forest classes (311, 312, 313), as well as exchanges between open and semi-natural categories, are central to the Alpine trajectory. his interpretation is supported by the CORINE class definitions: class 313 (“mixed forest”) is explicitly defined as an intermediate composition class (25–75% broadleaf/conifer), making directional transitions from 313 to 311 or 312 both ecologically and cartographically plausible over multi-year inventories.

Regional trajectories differ substantially, both in dominant pathways and in transition mass, which is critical for interpreting scenario divergence in later chapters. **Piemonte** shows strong **open-land dynamism alongside major forest transitions**. The top probability transition is indeed barren → sparse (P=0.2540), but it is closely followed by the forest pathway mixed → conifer (P=0.2473). In terms of absolute pixel counts, the largest flow by far is mixed → conifer (57,588 pixels), followed by mixed → broadleaf (30,188 pixels) and a strong urbanization signal from crop → urban (27,492 pixels). The most plausible interpretation is a landscape characterized by highly active vegetation succession, patch-level transitions from sparsely vegetated states toward denser coverage, and significant artificialization of agricultural areas.

Lombardia has a concentrated and directional forest-composition signal, heavily dominated by transitions toward conifers rather than broadleaf. Mixed → conifer is dominant both in absolute magnitude (37,979 pixels) and in probability (P=0.2531). This is followed by mixed → broadleaf (22,664 pixels; P=0.1511) and shrub → broadleaf (16,184 pixels; P=0.1807). This is a strong indicator of systematic compositional transition or reclassification within mixed stands.

Friuli Venezia Giulia has lower overall transition mass, but a highly directional structure. While **agro-pastoral transition** probabilities are extremely high—such as pasture → broadleaf (P=0.2921) and pasture → shrub (P=0.2773)—the total area of active pasture is very small. In absolute counts, the largest transition is overwhelmingly mixed → conifer (38,046 pixels; P=0.2815). This means that the largest territorial reallocation is driven almost entirely by changes in forest composition. Friuli therefore emerges as a regime dominated by structural forest changes, likely because **most transitions from open land to forest occurred prior to 1990**, beginning in the post–Second World War period, with subsequent dynamics dominated more by internal forest reclassification than by primary afforestation.

The regional contrasts above are consistent with established literature on Alpine land-use trajectories. A common long-term Alpine pattern is abandonment of marginal agricultural/pastoral land followed by shrub encroachment and forest expansion, but this process is spatially uneven and filtered by local accessibility, management continuity, and topography (Anselmetto et al., 2024). Our results match this framework well:

- Piemonte aligns with stronger semi-open/successional turnover.
- Lombardia aligns with strong forest compositional consolidation.
- Friuli aligns with mixed mountain dynamics where agricultural and forest transitions co-occur.

Figure 3 – Land use transitions 1990-2018 in the Alpine space and in the study regions (excluding persistence)

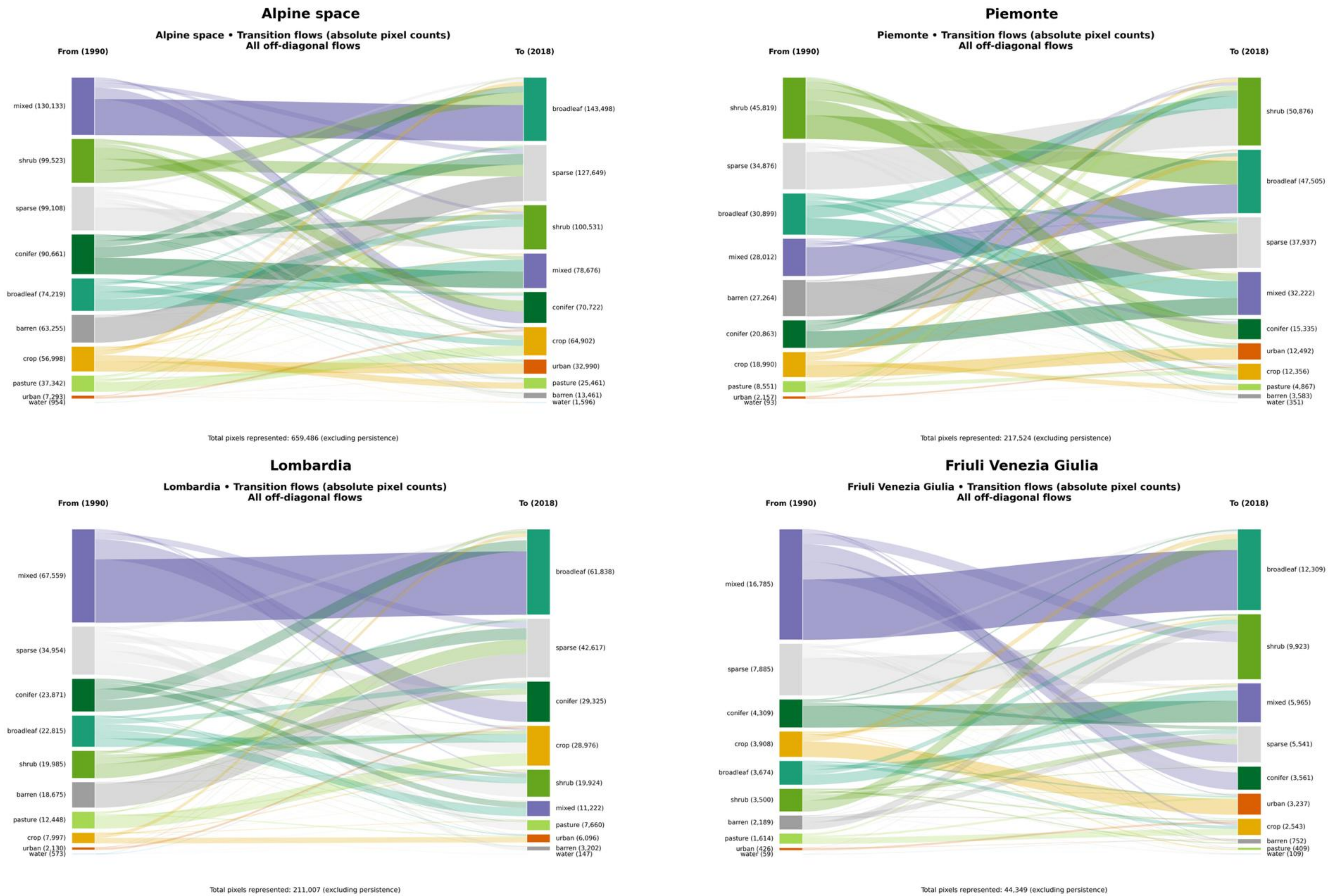

Figure 4 – Land use transitions 1990-2018 in the Alpine space and in the study regions (including persistence).

5. Forecasted land use transitions

The simulation ensemble includes four landscapes (1A1b, 1A2a, 1A2b, 1A2c), four governance scenarios (BAU, StR_S, FSR_DP, FSR_DIP), and 15 stochastic runs per landscape-scenario combination. Results are interpreted with two complementary metrics:

- **Net simulated transition** within each scenario: $\Delta = \text{area}_{80} - \text{area}_{0}$
- **Endpoint divergence from BAU**: area $_{80,scenario}$ $-$ area $_{80,BAU}$

Using the run-aggregated outputs, the most consistent signal is a persistent shift toward forest classes, characterized by **broadleaf expansion** and **shrub contraction** (Figure 5**.** Broadleaf expansion emerges as the most stable, integrative indicator of transition pressure across the full experimental design. Shrub contraction represents the complementary aspect of the same process. Together, these patterns indicate that much of the long-run dynamics is concentrated at the shrub-forest interface, with repeated recruitment and transition into forest states over the 80-year horizon. Variations in magnitude among scenarios primarily reflect how fire prevention, suppression strategies, and management interventions redistribute opportunities for land use transitions across space and time.

The **conifer trajectory** provides more a diagnostic view of landscape-specific behavior. This land use declines in three landscapes (1A1b, 1A2a, 1A2b), but increases in 1A2c. This contrast suggests that conifer is the class most sensitive to the interaction between local configuration and scenario conditions, likely because it is influenced by multiple processes: disturbance exposure, recovery pathways, and competition with broadleaf species during succession. In other words, conifer does not follow a single regional patterns; instead, its dynamics reflect local transition geometry shaped by governance strategy.

Pasture generally acts as a secondary donor class in most simulations, exhibiting stable-to-negative changes, with the strongest contraction observed in 1A2c. This is important for interpretation because it demonstrates that forest expansion is not driven solely by shrub dynamics. In certain landscapes, particularly 1A2c, a substantial proportion of forest gains is linked to reductions in pasture, indicating more pronounced restructuring of landscape mosaic and potentially larger consequences for open-habitat functions and the continuity of agro-pastoral systems.

Taken together, the responses of these four classes define the core simulated regime:

1. broadleaf is the most consistent net winner,
2. shrub is the most consistent net loser,
3. conifer is the principal landscape-contingent class,
4. pasture shows variable decline, which can become substantial in specific contexts.

Overall, this indicates that the model drives a directional transformation of the landscape mosaic consistent with successional processes and long-term compositional reorganization, while still retaining scenario-level modulation and stochastic spread around the mean.

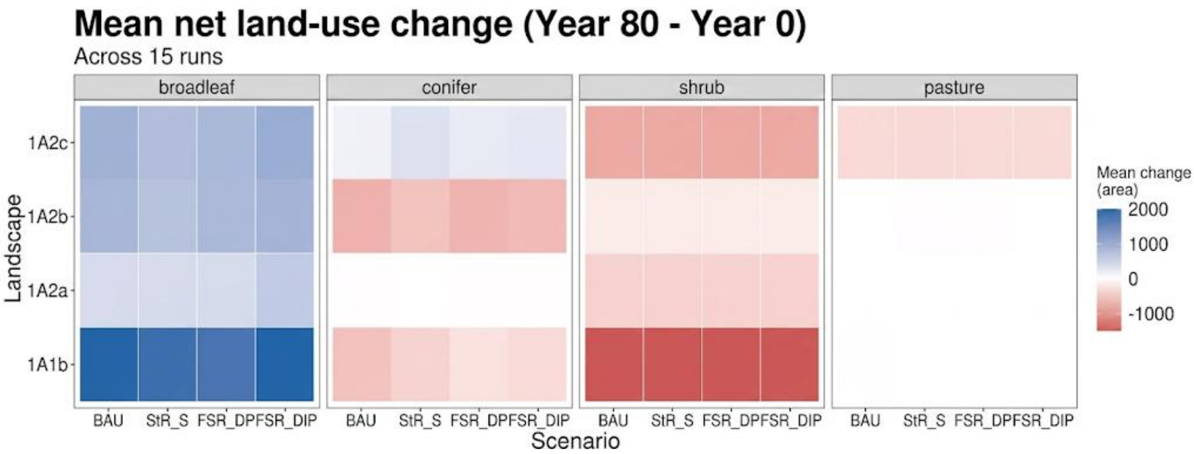

Figure 5 - Heatmap of mean net change (year 80-year 0) for key land cover classes (broadleaf, conifer, shrub, pasture) across landscapes and scenarios.

By design, the simulated trajectories align with the **historical transition** patterns reconstructed for 1990-2018. According to the historical analysis, the Alpine domain exhibited pronounced compositional shifts, particularly among mixed and broadleaf classes, active exchanges among at shrub-sparse-pasture interfaces, and region-specific heterogeneity in pathway dominance. The 80-year simulations preserve this underlying logic, projecting these historical directional tendencies under different governance constraints and fire-prevention strategies:

- in landscapes where historical pathways already favored woody expansion, scenarios primarily affect the pace and composition of change;
- in areas with stronger historical agro-pastoral interface dynamics, scenario divergence is more pronounced in the reallocation among pasture, shrub, and forest;
- where historical compositional shifts were concentrated, scenario effects are manifest more in conifer-vs-broadleaf partitioning than in overall forest increase.

Landscape identity emerges as a primary driver of these outcomes. Even under identical governance scenario, the four landscapes retain distinct transition signatures:

1A1b (Northwestern Alps) exhibits one of the strongest conversion intensities toward broadleaf cover. It functions as a high-momentum successional landscape, with shrub and conifer serving as the primary donor pools for broadleaf expansion. Scenario interventions can redistribute transition pathways, but they do not reverse the dominant successional trend.

- **BAU mean net change**: broadleaf **+2100 ha**, shrub **-1572 ha**, conifer **-538 ha**, pasture **+10 ha**. The same sign pattern is retained in all scenarios.
- Broadleaf gains remain very high in FSR_DIP and BAU; FSR_DP is comparatively lower.
- Conifer losses are systematic, although prevention-focused scenarios reduce the magnitude relative to BAU.

1A2a (Pre-Alps) is the most conservative landscape in terms of absolute change, exhibiting lower transition elasticity. Scenario effects are present but relatively small and spatially localized, indicating stronger structural constraints imposed by initial class configuration and local neighborhood opportunities.

- **BAU mean net change**: broadleaf **+420 ha**, shrub **-402 ha**, conifer **-16 ha**, pasture **-1 ha**.
- Shrub decline is stable around -400 ha across all scenarios.
- Conifer remains near-neutral to weakly negative.
- FSR_DIP is the only scenario showing a marked broadleaf amplification (**+658 ha**).

1A2b (Dolomiti and Carnia) exhibits strong broadleaf gains alongside substantial conifer decline, reflecting a pronounced trade-off between broadleaf accretion and conifer contraction. This landscape is particularly sensitive to governance objectives that target compositional balance, rather than total forest area alone.

- **BAU mean net change**: broadleaf **+890 ha**, shrub **-175 ha**, conifer **-704 ha**, pasture **-10 ha**.
- FSR_DIP provides the largest broadleaf gain (**+935 ha**).
- StR_S lowers broadleaf gain (**+720 ha**) but also reduces conifer loss (**-534 ha**) compared with BAU.
- Shrub contraction exists but is smaller than in 1A1b and 1A2c.

1A2c (Northeastern Alps) is structurally distinct and policy-relevant. Unlike the other landscapes, it supports simultaneous growth of broadleaf and conifer, with pasture serving as the primary donor class. This pattern reflects a different initial configuration and transition network, where both forest components can expand under fire-prevention and rewilding logic.

- **BAU mean net change**: broadleaf **+969 ha**, shrub **-789 ha**, conifer **+157 ha**, pasture **-337 ha**.
- FSR_DIP further increases both broadleaf and conifer (**+1041 ha and +264 ha**, respectively).
- StR_S generates the largest conifer increase (**+355 ha**) but also stronger pasture decline (**-369 ha**).
- Shrub decreases consistently across scenarios (~ -788 to -790).

Scenario effects (Figure 6) are evident but context-dependent, and should be interpreted as modulations of landscape-specific pathways rather than uniform responses. Differences among scenarios are meaningful, yet they are often smaller than the structural differences between landscapes. Governance plays a role, but primarily through the lens of initial landscape configuration and the spatial geometry of class neighborhoods.

BAU serves as the counterfactual, reflecting historical fire suppression and baseline management allocations. Across all landscapes, BAU already generates directional transitions toward broadleaf expansion and shrub decline. This indicates that strong long-term dynamics are inherent to baseline transition regimes, rather than being driven solely by intervention scenarios.

StR_S (Strict rewilding + strengthened suppression) often reduces outcome variability and can help maintaining conifers where they would otherwise decline, particularly in 1A1b and 1A2b. In 1A2c, it can strongly promote conifer expansion. This pattern reflects the interaction between increased suppression strength and rewilding allocation, which dampens disturbance-driven compositional turnover while supporting forest continuity in selected contexts.

FSR_DP (Fire-smart rewilding + direct prevention) can reduce broadleaf gains relative to BAU or FSR_DIP in certain landscapes. The firebreak and freeze logic likely modify local transition opportunities and age progression, limiting part of the otherwise broadleaf-favorable trajectory. Its effects are not uniformly stronger or weaker than other scenarios; rather, they are selective, depending on where prevention infrastructure intersects high-transition cells.

FSR_DIP (Fire-smart + direct + indirect prevention) most often produces the largest broadleaf gains and strongest departures from BAU at the simulation endpoint. This outcome reflects the combined effect of direct suppression and pre-simulation indirect reconfiguration around prevention structures. In landscapes with favorable topology and class adjacency, this compound strategy amplifies trajectory shifts more effectively than direct prevention alone.

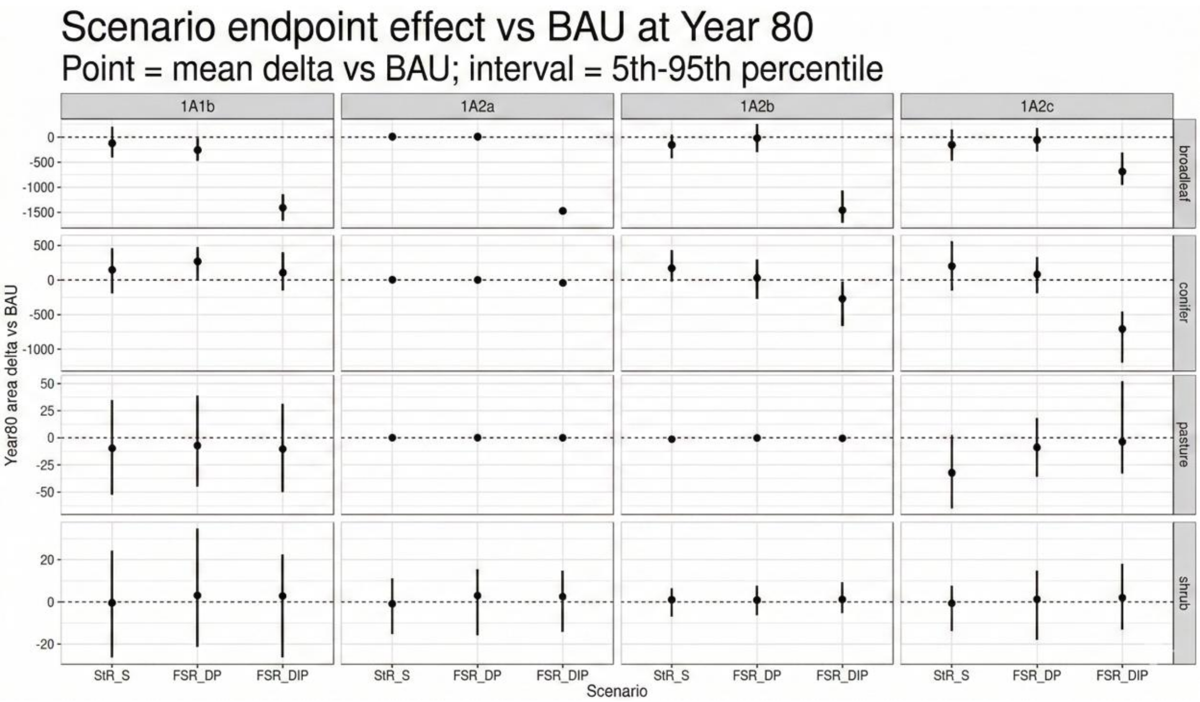

Figure 6 – Scenario endpoint deltas vs BAU at year 80 (mean with q05-q95). BAU = business as usual; StR_S = Strict rewilding + strengthened suppression; FSR_DP = Fire-smart rewilding + direct prevention; FSR_DIP = Fire-smart + direct + indirect prevention.

To evaluate the relevance of these results for rewilding policy, we derived a synthetic indicator of forest response from the simulation summaries: **net forest change over 80 years**, where forest is defined as the sum of broadleaf and conifer classes. For each landscape and scenario, net forest expansion was calculated as $(F_{80} - F_0)/F_0 \times 100$, using ensemble means across 15 runs. We also quantified the change in forest share of total landscape area in percentage points. These metrics allow for direct comparison of rewilding performance across landscapes and governance designs.

The results indicate positive net forest expansion **across** all landscape-scenario combinations, though the magnitude varies considerably (Table 4). In 1A1b (Northwestern Alps), net forest expansion is +4.69% (BAU), +4.72% (StR_S), +4.70% (FSR_DP), and +5.67% (FSR_DIP), corresponding to forest-share gains between +3.46 and +3.99 percentage points. In 1A2a (Pre-Alps), expansion is smaller: +1.16% (BAU), +1.16% (StR_S), +1.15% (FSR_DP), and +1.93% (FSR_DIP), with forest-share gains from +0.96 to +1.52 points. In 1A2b (Dolomiti and Carnia), expansion is limited: +0.51% under BAU/StR_S/FSR_DP and +0.80% under FSR_DIP, with share gains from +0.43 to +0.64 points. In 1A2c (Northeastern Alps), expansion is again substantial: +3.55% (BAU), +3.66% (StR_S), +3.58% (FSR_DP), and +4.34% (FSR_DIP), with share gains from +2.52 to +2.92 points. Across all landscapes, FSR_DIP (Fire-smart + direct + indirect prevention) **consistently produces the largest forest expansion**, while BAU, StR_S, and FSR_DP often yield similar total forest gains, particularly in landscapes with lower transition elasticity.

Table 4 - Net forest expansion by landscape and scenario (Year 0 → 80). 1A1b = Northwestern Alps, 1A2a = Pre-Alps, 1A2b = Dolomiti and Carnia, and 1A2c = Northeastern Alps. BAU = business as usual; StR_S = Strict rewilding + strengthened suppression; FSR_DP = Fire-smart rewilding + direct prevention; FSR_DIP = Fire-smart + direct + indirect prevention.

Landscape	Scenario	Net forest change (area units)	Net forest expansion (% of initial forest)	Forest share change (%)
1A1b	BAU	+1561.9	**+4.69%**	+3.46
1A1b	StR_S	+1572.3	**+4.72%**	+3.48
1A1b	FSR_DP	+1566.3	**+4.70%**	+3.47
1A1b	FSR_DIP	+1800.6	**+5.67%**	+3.99
1A2a	BAU	+403.4	**+1.16%**	+0.96
1A2a	StR_S	+404.4	**+1.16%**	+0.97
1A2a	FSR_DP	+400.3	**+1.15%**	+0.96
1A2a	FSR_DIP	+637.8	**+1.93%**	+1.52
1A2b	BAU	+185.3	**+0.51%**	+0.43
1A2b	StR_S	+185.6	**+0.51%**	+0.43
1A2b	FSR_DP	+184.5	**+0.51%**	+0.43
1A2b	FSR_DIP	+275.9	**+0.80%**	+0.64
1A2c	BAU	+1125.9	**+3.55%**	+2.52
1A2c	StR_S	+1158.7	**+3.66%**	+2.60
1A2c	FSR_DP	+1133.7	**+3.58%**	+2.54
1A2c	FSR_DIP	+1305.3	**+4.34%**	+2.92

6. Discussions

6.1 Main findings

The simulations identify a robust cross-scenario signal over the next 80 years: **broadleaf area increases and shrub area decreases in all landscapes**. This directional trend holds under BAU, StR_S, FSR_DP, and FSR_DIP, and remains evident when accounting for uncertainty across 15 stochastic runs per landscape-scenario combination. It represents the most reliable outcome of the experiment, indicating that long-term dynamics in the calibrated system favor progressive woody reorganization, with shrub domains functioning as recurrent donor states.

A second robust result is that **landscape identity matters more than scenario identity** for several land cover classes. The same governance strategy does not produce equivalent magnitude or class balance across the four landscapes. Conifer trends, in particular, are heterogeneous: conifer declines in three landscapes but increases in 1A2c (Northeastern Alps). Pasture responses also vary markedly, from near-neutral in some contexts to substantial declines in others. These patterns confirm that **the initial landscape structure strongly constrains** and channels scenario effects. Rewilding-oriented strategies increase forest extent in all tested contexts, their effectiveness is landscape-dependent: the same policy can yield high large gains in one landscape and only marginal gains in another. Initial landscape state limits transition opportunities through class adjacency, topographic filters, and fire exposure. Practically, this implies that **expected forest expansion cannot be assumed as a uniform target** across territories without accounting for local structure.

Scenario dependence primarily manifests in **magnitude of change, compositional partitioning, and the width of uncertainty**. FSR_DIP often amplifies broadleaf gains and produces stronger endpoint departures from BAU, while StR_S tends to moderate variability and, in some landscapes, retain more conifer relative to BAU. FSR_DP shows selective effects that depend on how firebreak and freeze logic intersects active transition zones. These differences are meaningful, but they should be interpreted as modulation of landscape-specific trajectories, rather than as universal reversals of trend.

Two additional findings are central for interpretation. First, contrasts at the simulation endpoint vs BAU at year 80 and net transitions from year 0 to 80 are complementary but not always equivalent. Second, uncertainty is non-negligible for the classes experiencing the largest transitions, indicating that policy conclusions should be based on effect sizes relative to uncertainty intervals, rather than on mean values alone.

6.2 Mechanistic interpretation

The observed trajectories are coherent with the model structure where annual land-use change is jointly shaped by transition propensity (**k**), annual transition demand (`lcc.demand`), spatial allocation/spreading logic, and disturbance feedbacks from fire occurrence and post-fire regeneration.

At a mechanistic level, **k** controls the relative tendency for source-to-target transitions, but realized change is constrained by demand quotas and cell eligibility filters. This means high propensity alone does not guarantee large realized conversion in a given year; conversions occur when propensity, demand, and spatially eligible cells align. Over long horizons, repeated annual allocation generates directional class rebalancing, especially where adjacency and topographic constraints repeatedly expose similar transition pathways.

The simulated outcomes are broadly aligned with documented Alpine land-use trajectories over recent decades: decline or reconfiguration of traditional open systems, progressive woody encroachment in many mountain contexts, and increasing importance of disturbance-mediated dynamics under climate pressure (Anselmetto et al., 2024). The robust broadleaf increase and shrub decline are coherent with this direction, while inter-regional heterogeneity in conifer and pasture response reflects known differences in land-use history, elevation gradients, management legacies, and disturbance regimes.

Fire dynamics interact with this system in two ways. First, fire risk and suppression alter which cells burn and the timing of fires, thereby modifying age structures and class trajectories (see Deliverable 3.1). Second, post-fire regeneration and recovery routines alter return pathways and transition timing, potentially shifting composition under repeated events. This helps explain trade-offs between rewilding progression and flammability context. **Rewilding can enhance long-term woody continuity, but in fire-prone landscapes, this continuity may increase exposure unless prevention and suppression strategies effectively mitigate fuel connectivity** (Plumanns-Pouton et al., 2025). The "fire-fighting trap" logic is particularly relevant: stronger suppression can reduce burned area in the short to medium term while allowing fuel accumulation and age progression that alter future risk structure (Regos, 2025). Scenario differences align with this mechanism. StR_S modifies suppression behavior without implementing a full fire-smart spatial redesign. FSR_DP adds direct prevention via firebreak logic during fire spread. FSR_DIP incorporates indirect, pre-simulation landscape reconfiguration around prevention structures. This compound strategy can alter early transition pathways and produce stronger divergence in long-term endpoints.

Fuel-management mechanisms influence transitions most strongly where three conditions co-occur: high interface density, active transition demand in adjacent classes, and recurrent fire opportunity. In such contexts, prevention layers do more than reduce fire spread;. they re-route long-term class exchanges by altering where transitions can accumulate and how quickly post-disturbance states reconnect to forest classes.

The model does not support a single deterministic "forest increase" storyline. Instead, it demonstrates that **policy design and fire-prevention architecture** can generate materially different balances among broadleaf, conifer, shrub, and pasture, even under the same historical transition calibration. This level of detail is critical for decisions where biodiversity, carbon storage, and fire-risk objectives may conflict. The added value of REMAINS-based coupled simulation lies in its ability to jointly represent land-use transitions and fire feedbacks under stochastic replication. Many assessments treat land-use change and fire as separate analytical blocks, but here they are dynamically coupled, allowing detection of pathway-dependent outcomes that static scenario arithmetic would miss. This is particularly relevant in Alpine systems, where ignition patterns, suppression capacity, topography, and fuel continuity co-determine future landscape structure.

6.3 Methodological strengths and caveats

A key strength of this study is the ensemble design: 15 runs per landscape-scenario combination enable interval-based interpretation and reduce reliance on single-run artifacts. A second strength is process coupling between land cover transitions, fire dynamics, and recovery, which supports more realistic pathway analysis than uncoupled projections. A third strength is calibration against historical land-cover transitions, anchoring forward scenarios in observed regional behavior.

Main caveats stem from input and structural assumptions. The historical calibration windows may not fully represent future socio-economic discontinuities, climate extremes, or policy shifts. Reclassification and aggregation, while necessary, reduce thematic detail and may merge ecologically distinct subclasses into broader categories. Parameterization of transition propensity and recovery routines inevitably contains uncertainty, especially when assumptions are transferred across heterogeneous landscapes. Scenario-specific initialization or pre-processing choices can also influence endpoint contrasts, which is why both endpoint and net-transition metrics must be interpreted jointly.

Finally, model structure imposes abstractions. Real-world implementation frictions, institutional delays, and behavioral responses are not fully represented in cellular dynamics. This does not invalidate the results, but it defines their scope: they are comparative policy experiments under explicit assumptions, not deterministic forecasts.

7. Policy Relevance and Operational Implications

7.1 What the results imply for planning

The simulations show that **forest gains** can occur alongside substantial **reductions in non-forest classes**, especially shrub and, in specific cases, pasture. This is relevant because open and semi-open land covers contribute to ecological heterogeneity, habitat diversity, and interruption of fuel continuity. A strategy focused only on total forest increase may therefore underperform against multi-objective goals, including fire resilience and biodiversity at landscape scale. Within this framework, the key question is not whether forest should expand, but where, how quickly, and with what compositional and spatial outcomes.

The results support a functional compromise: selective forest expansion combined with intentional mosaic maintenance. Expansion is desirable where it strengthens ecological continuity and long-term recovery under acceptable flammability conditions. Mosaic retention is desirable where open or lower-flammability patches reduce contagion pathways, preserve priority habitats, or prevent excessive homogenization of fuels. Fire-smart rewilding mechanisms, particularly when paired with direct and indirect prevention, are most valuable because they enable this spatial differentiation, rather than enforcing uniform expansion.

Operationally, this implies defining rewilding targets with at least three concurrent metrics: (i) **net forest gain**, (ii) **forest-class composition balance** (broadleaf/conifer), and (iii) **mosaic integrity** in strategic interfaces and high-leverage fire corridors. Scenario comparisons indicate that **FSR_DIP (Fire-smart + direct + indirect prevention) offers the strongest lever for steering long-term structure**, but its implementation should remain spatially targeted to avoid replacing all non-forest dynamics with a single expansion logic. A landscape with more forest is not automatically more resilient; resilience depends on configuration, composition, and **interactions with disturbances**.

The clearest planning implication is that **strategy must be landscape-specific**. A single policy package applied uniformly across Alpine territories will not produce balanced outcomes. Even when direction of change is consistent, the magnitude and composition of transitions differ substantially depending on initial landscape state. For achieving balanced outcomes, scenario logics that integrate prevention with rewilding are generally more effective than rewilding-only approaches. FSR_DIP frequently delivers stronger compositional steering, while StR_S can reduce variability and stabilize some class outcomes. Planning should therefore compare strategies against explicit objectives: target class mix, acceptable pasture decline, conifer retention where needed, and fire-risk constraints.

Spatial targeting principles emerging from the simulations include:

- prioritize interventions in areas of high interface density with active transitions,

- apply prevention and rewilding allocations jointly, rather than sequentially,
- identify zones where woody expansion supports objectives and zones where open-habitat persistence is critical,
- calibrate management intensity to local fuel continuity and suppression feasibility.

7.2 Fire-smart rewilding levers

Fuel breaks and lower-flammability mosaics are effective when integrated into a broader landscape-transition framework, rather than treated as isolated infrastructure. Direct prevention influences ignition and spread dynamics in real time, while indirect prevention can reshape the initial configuration, affecting cumulative trajectories over decades.

The simulations show that interventions are most impactful where fire feedback and transition demand coincide. In these locations, prevention not only modifies burn patterns but also alters long-term class-to-class exchange. Conversely, in areas with weak transition pressure or limited class eligibility, the same interventions yield smaller long-term differences.

Operationally, the results support a layered approach:

1. strategic placement of fuel breaks in high-leverage interfaces,
2. composition-aware management in surrounding buffers,
3. adaptive rewilding allocation that excludes the highest-flammability pixels when required,
4. periodic recalibration as landscape composition evolves.

8. Conclusions

Historical evidence and scenario simulations converge on a consistent message: Alpine landscapes in the study domain are undergoing directional reorganization, and future trajectories continue this trend under all governance settings tested. Broadleaf expansion and shrub decline emerge as robust outcomes, whereas conifer and pasture responses vary depending on landscape context and intervention logic. This confirms that scenario design can modulate trajectories, but does not override the structural influence of initial landscape configuration.

From a rewilding perspective, all scenarios generate positive net forest expansion over 80 years, with gains ranging from +0.51% to +5.67% of initial forest area depending on landscape and scenario. FSR_DIP consistently produces the largest expansion. However, the results also highlight that maximizing forest area alone is an incomplete policy objective: expansion can be coincide with contraction of non-forest classes that are functionally important for biodiversity and fire regulation. Therefore, the preferred approach is spatially explicit rewilding that balances forest recovery with mosaic persistence where needed.

Two key conclusions emerge for policy and management. First, **interventions must be landscape-specific**: identical policy packages yield different outcomes across territories. Second, **fire-smart design influences long-term land-use pathways**, not just annual fire metrics, and should be integrated from the outset of planning. Overall, this deliverable supports adaptive, fire-aware rewilding strategies that optimize forest area, composition, and spatial configuration simultaneously. Operationally, this requires setting explicit multi-criteria targets, monitoring trajectory deviations, and updating intervention placement as landscape structure and disturbance regimes evolve.

The framework is transferable to other Alpine territories when three conditions are met: compatible land-cover data, credible transition calibration, and scenario definitions translated into local governance instruments. The coupled REMAINS setup is especially valuable where fire-landscape feedback is a primary management concern. Context-specific factors — such as parameter values, class semantics in reclassification, local transition eligibility, and implementation constraints — must still be adapted. Other territories can adopt the workflow and scenario logic, but should recalibrate propensity, demand structure, and prevention thresholds to local history and landscape configuration.

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Annex A. Detailed class legend and crosswalk

This annex documents the operational crosswalk used to map CORINE Land Cover (CLC) classes into the REMAINS land-cover taxonomy adopted in this deliverable.

A.1 REMAINS class legend used in this deliverable

REMAINS class	Code	Operational meaning in this study
urban	1	Artificial and built-up surfaces, infrastructure, extractive/construction urbanized uses, and urban green/recreation classes merged as anthropogenic domain.
crop	2	Agricultural cultivation domain (arable, permanent crops, complex cultivation patterns, agro-forestry units).
pasture	3	Grassland and pasture systems, including natural grasslands and transitional herbaceous covers used as open vegetated matrix.
broadleaf	4	Broadleaved forest domain (including mixed forest share assigned to broadleaf after split rule in initialized landscapes).
conifer	5	Conifer forest domain (including mixed forest share assigned to conifer after split rule in initialized landscapes).
shrub	6	Shrub/herbaceous transitional vegetation and moor-heath/sclerophyllous units; includes portions interpreted as shrub encroachment in Alpine context.
sparse	7	Sparsely vegetated domain (kept distinct from barren for process representation).
barren	8	Bare or near-bare natural surfaces (rocks, burnt areas, snow/ice) with very limited vegetation function in LUC dynamics.
water	9	Inland/coastal/marine water and wetland-water classes aggregated in non-burnable/non-convertible aquatic domain for this application.

A.2 Full CLC to REMAINS

CORINE class label	REMAINS class	code
Continuous urban fabric	urban	1
Discontinuous urban fabric	urban	1
Industrial or commercial units	urban	1
Road and rail networks and associated land	urban	1
Port areas	urban	1
Airports	urban	1
Mineral extraction sites	urban	1
Dump sites	urban	1
Construction sites	urban	1
Green urban areas	urban	1
Sport and leisure facilities	urban	1
Non-irrigated arable land	crop	2
Permanently irrigated land	crop	2
Rice fields	crop	2
Vineyards	crop	2
Fruit trees and berry plantations	crop	2
Olive groves	crop	2

Pastures	pasture	3
Annual crops associated with permanent crops	crop	2
Complex cultivation patterns	crop	2
Land occupied by agriculture, with areas of natural vegetation	crop	2
Agro-forestry areas	crop	2
Broad-leaved forest	broadleaf	4
Coniferous forest	conifer	5
Mixed forest	Mixed (temporary)	—*
Natural grasslands	pasture	3
Moors and heathland	shrub	6
Sclerophyllous vegetation	shrub	6
Transitional woodland-shrub	shrub	6
Beaches, dunes, sands	barren	8
Bare rocks	barren	8
Sparsely vegetated areas	sparse	7
Burnt areas	barren	8
Glaciers and perpetual snow	barren	8
Inland marshes	water	9
Peat bogs	water	9
Salt marshes	water	9
Salines	water	9
Intertidal flats	water	9
Water courses	water	9
Water bodies	water	9
Coastal lagoons	water	9
Estuaries	water	9
Sea and ocean	water	9

* `mixed forest` is retained in intermediate CLC summaries, then split into broadleaf/conifer in landscape initialization according to the project rule set.

A.3 Special handling rules used in this deliverable

1. **Mixed forest handling:** Mixed forest is preserved in historical CLC accounting, then reallocated during model landscape initialization to broadleaf and conifer using the landscape-specific split logic.
2. **Sparse vs barren separation:** `Sparsely vegetated areas` are maintained as **sparse** (separate from barren), while bare rocks, burnt areas, snow/ice are mapped to **barren**. This distinction is required because sparse participates in ecological transitions differently from barren in REMAINS.
3. **Shrub domain composition:** Shrub aggregates moors/heath, sclerophyllous, and transitional woodland-shrub classes. In Alpine interpretation, parts of this domain can represent encroachment/afforestation fronts; this is handled through process modules (afforestation, encroachment, succession thresholds), not by reclassification alone.
4. **Water/wetland aggregation:** Wetland-related classes were aggregated into **water** in this implementation to keep a consistent non-terrestrial/non-convertible domain for simulation accounting.
5. **Urban domain scope:** Urban includes all artificial/built-up and associated infrastructure classes, including green urban and sport/leisure surfaces, to maintain a single anthropogenic class in LUC transitions.
6. **NODATA treatment:** NODATA is removed before transition-matrix computation and is not part of REMAINS demand or transition probabilities.

Annex B. Scenario parameter tables

This annex provides a structured, report-ready template and consolidated settings based on the information used in the deliverable.

B.1 Scenario definitions used in simulations (80-year horizon, 15 runs per scenario)

Scenario	Core governance logic	Rewilding logic	Fire suppression logic	Direct prevention	Indirect prevention
BAU	Baseline management and historical suppression	No additional rewilding policy push beyond baseline structure	Historical suppression settings	No	No
StR_S	Strict rewilding + strengthened suppression	Rewilding target 10% via Rw → Rwm → Rwu hierarchy	Fuel suppression increased vs BAU (+0.1 on suppression intensity rule set)	No	No
FSR_DP	Fire-smart rewilding + direct prevention	Rewilding with fire-smart spatial filters	BAU suppression baseline + firebreak-based direct suppression behavior	Yes (firebreaks active)	No
FSR_DIP	Fire-smart rewilding + direct + indirect prevention	Same fire-smart rewilding framework	BAU suppression baseline + firebreak behavior	Yes	Yes (pre-run conversion around firebreak network)

B.2 Rewilding allocation and management masks

Item	Operational rule
Eligible domain for 10% rewilding target	All LCT except urban, water, barren
Priority 1 (Rw)	Areas already in indefinite aging inside protected areas
Priority 2 (Rwm)	Stop management in potential managed areas inside protected areas
Priority 3 (Rwu)	If needed, expand to non-managed zones within 1 km buffer around protected areas
Potential managed areas	30% forests in 150 m buffer from forest roads + 10% pasture + 10% sparse (grouped paddock distribution)

B.3 Fire and prevention parameters (scenario settings)

From your scenario notes and launcher logic:

Parameter	BAU	StR_S	FSR_DP	FSR_DIP
fuel.th	0.05	0.08	0.05	0.05
mosaic.th	4.00	4.00	4.00	4.00
direct_prev (firebreak active in spread/suppression)	FALSE	FALSE	TRUE	TRUE
indirect_prev (pre-run conversion around firebreaks)	FALSE	FALSE	FALSE	TRUE
ignition on firebreak cells	n.a.	n.a.	disabled	disabled
suppression priority by firebreak	no	no	yes	yes
management mask variant	baseline	strict rewilding mask	fire-smart direct mask	fire-smart direct+indirect mask (forest_20 noted)

B.4 Process-parameter adaptations from original REMAINS used in this project

Process	Project adaptation
Afforestation rates (context adaptation)	conifer ~1.2%, broadleaf ~0.8% (from warmer-climate defaults)
Afforestation radius	conifer 600 m; broadleaf 250 m
Encroachment (sparse → shrub)	rate reduced to 0.4; radius 80 m
Post-fire contagion/recovery propensity	reduced from 0.4 to 0.3
Elevation threshold for rocky constraints	raised to 1500 m
Conifer recovery radius	reduced from 1000 m to 800 m
Shrub-to-forest transitional duration	reduced to 4 years (from prior 8-year setting)
Non-stand-replacing fire age effect	age reduced by 1 timestep (instead of larger decrement)

Annex C. Full transition matrices

C.1 Observed transitions, Alpine space (1990 → 2018, pixel counts)[2]

from \ to	barren	broadleaf	conifer	crop	mixed	pasture	shrub	sparse	urban	water
barren	427135	846	953	581	209	133	3735	56298	219	281
broadleaf	827	924202	5858	14113	26486	1213	16610	6191	2816	105
conifer	199	14148	876629	1345	37254	835	11607	24432	797	44
crop	875	2870	211	398047	93	1117	5978	3616	31191	525
mixed	73	70025	133613	1717	313501	524	5661	2314	725	51
pasture	142	5690	665	2551	730	30235	2418	1726	270	74
shrub	1114	25695	2784	5304	2908	544	110146	10165	430	125
sparse	3556	7254	1307	2354	1428	440	9000	158357	497	440
urban	289	72	16	8516	5	20	66	62	77052	45
water	379	68	6	380	2	9	19	172	106	31987

C.2 Observed transitions, Piemonte (1990 → 2018, pixel counts)

from \ to	barren	broadleaf	conifer	crop	mixed	pasture	shrub	sparse	urban	water
barren	72463	106	67	231	31	49	1130	25328	85	237
broadleaf	483	304121	645	4055	12464	366	9064	1990	1807	25
conifer	6	2458	82125	104	12620	37	4170	1421	44	3
crop	678	1324	53	201794	64	824	3949	1973	27492	388
mixed	13	30188	57588	605	139660	200	3221	923	444	37
pasture	86	2646	217	549	247	17895	1324	916	130	40
shrub	327	7309	545	1446	1061	215	39687	2174	285	70
sparse	2081	3349	399	701	545	269	4474	122017	330	261
urban	140	53	11	3100	2	8	42	41	52205	30
water	253	22	1	96	0	1	5	17	43	12535

[2] observed matrices still include the **`mixed`** class, consistent with your historical analysis workflow before mixed-forest reassignment in initialized REMAINS landscapes.

C.3 Observed transitions, Lombardia (1990 → 2018, pixel counts)

from \ to	barren	broadleaf	conifer	crop	mixed	pasture	shrub	sparse	urban	water
barren	91770	207	715	64	7	6	503	17090	74	9
broadleaf	23	217505	3674	6055	6049	510	4382	1593	525	4
conifer	88	7999	120868	296	4233	137	2609	8312	191	6
crop	173	1225	148	151972	24	291	1581	1312	2158	54
mixed	42	22664	37979	1037	85468	177	1696	804	151	8
pasture	56	2827	368	1959	426	12340	794	744	83	17
shrub	710	16184	1973	2902	1214	203	59552	6685	114	36
sparse	1468	3378	901	1312	830	168	3012	30811	129	97
urban	96	17	5	4138	2	6	21	20	19620	13
water	37	20	3	106	1	0	0	30	20	11688

C.4 Observed transitions, Friuli Venezia Giulia (1990 → 2018, pixel counts)

from \ to	barren	broadleaf	conifer	crop	mixed	pasture	shrub	sparse	urban	water
barren	12813	63	4	100	44	0	1102	807	34	35
broadleaf	37	106206	4	496	1548	0	734	605	213	37
conifer	47	206	29037	24	3277	5	241	486	15	8
crop	24	321	10	44281	5	2	448	331	1541	83
mixed	18	7173	38046	75	88373	3	744	587	130	6
pasture	0	217	80	43	57	0	206	66	57	17
shrub	77	2202	266	956	633	2	10907	1306	31	19
sparse	7	527	7	341	53	3	1514	4685	38	82
urban	53	2	0	1278	1	0	3	1	5227	2
water	89	26	2	178	1	0	14	125	43	7764