D 2.2 DYNAMIC MODELS FOR REFORESTATION AND PROFORESTATION

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Executive summary

This deliverable presents how REMAINS is used to simulate, in an integrated way, the co-evolution of land-use change and wildfire dynamics, and to assess the effects of territorial rewilding policies on landscape resilience, forest fire risk, and carbon-related trajectories.

It documents a spatially explicit, annual modelling workflow where each grid cell can transition between land-use classes according to scenario rules, while class-specific flammability drives fire spread. Wildfire simulation follows four annual steps: flammability assignment, sampling of total burned area, sampling of fire events by size class, and risk-based ignition allocation. Fire then propagates according to local conditions, creating feedbacks with subsequent land transitions.

The deliverable explains why REMAINS is adopted: it bridges a methodological gap between land-use models, forest/carbon models, and fire spread models, which are often developed separately. It details inputs (baseline maps, transition rules, flammability coefficients, fire frequency distributions, risk layers), outputs (annual land-cover maps, burned-area/event maps, time series, scenario indicators), spatial and temporal scales, and the modified model workflow used in the project.

A core section describes how policies are represented parametrically, including firebreaks and targeted conversion to less flammable land uses to create a fuel mosaic and reduce spread. The document also includes a critical discussion of strengths (integration, policy relevance, transparency) and limitations (parameter sensitivity, input-data dependence, uncertainty propagation), and clarifies that results are scenario-conditioned probabilistic trajectories, not deterministic forecasts.

Keywords

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

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1. Introduction

1.1. Policy context: integrated rewilding needs science-based simulation evidence

Rewilding is increasingly proposed as a strategic response to biodiversity decline, landscape degradation, and climate change, under both a mitigation and an adaptation framework (Navarro and Pereira, 2012; Fernández et al., 2017; Perino et al., 2019). In fire-prone regions, however, rewilding interventions influence the same territorial variables that control wildfire behavior: vegetation type, continuity of fuels, edge density, and mosaic heterogeneity (Mantero et al., 2020; Bowman et al., 2009; Ruffault et al., 2020; Moreira et al., 2020; Pausas and Keeley, 2021). If these interactions are not explicitly assessed, interventions may generate unintended outcomes, including higher exposure to large fires in specific landscape configurations, and hence increased biodiversity or carbon stock losses (Mantero et al., 2020; Bowman et al., 2009; Ruffault et al., 2020; Moreira et al., 2020; Pausas and Keeley, 2021).

Mediterranean and peri-mountain landscapes in particular are experiencing an intensification of coupled socio-ecological pressures (Fayet et al., 2022; Mantero et al., 2020; Bowman et al., 2009; Ruffault et al., 2020; Moreira et al., 2020; Pausas and Keeley, 2021). Three long-term processes are especially relevant for the interplay between climate change mitigation and fire regime evolution:

- **Land-use reconfiguration**, including cropland and pasture decline in marginal areas, shrub encroachment, and forest expansion (Fayet et al., 2022; Mantero et al., 2020; Verburg and Overmars, 2009).
- **Structural fuel accumulation**, often associated with reduced active management and increased horizontal and vertical continuity of combustible biomass (Mantero et al., 2020; Moreira et al., 2020; Pausas and Keeley, 2021).
- **Climate stress and extremes**, which increase the frequency and intensity of conditions favorable to fire ignition and propagation (Bowman et al., 2009; Ruffault et al., 2020; Moreira et al., 2020; Pausas and Keeley, 2021).

These processes do not act independently. Changes in land use alter fuel mosaics and the spatial arrangement of barriers or corridors to spread (Mantero et al., 2020; Verburg and Overmars, 2009; Moreira et al., 2020). Fire events then feed back into landscape trajectories by resetting stand conditions, changing cover composition, and modifying future transition probabilities (Bowman et al., 2009; Pais et al., 2023). Policies that ignore these feedbacks can produce limited or short-lived effects, even when individual measures are technically sound. Under a planning perspective, institutions need tools that answer practical questions:

- Which type of temporal and spatial allocation of rewilding areas delivers the greatest benefits in terms of long-term carbon gain in fire-prone landscapes?
- How much can spatially targeted fire prevention reduce annual burned area and unintended carbon losses in rewilding forest landscapes?
- What trade-offs emerge between prevention-oriented landscape design, ecological trajectories, and carbon outcomes?

In practice, institutions must evaluate where **passive recovery** is beneficial, where **active management** remains necessary, and how mixed strategies perform through time under uncertainty. Conventional single-domain assessments are insufficient for these questions because they treat key drivers as exogenous or static. In operational terms, planners need scenario-based, spatially explicit simulations that can connect annual disturbance dynamics with long-term territorial transformation (Verburg and Overmars, 2009; van Asselen and Verburg, 2013; Pais et al., 2023). This is the decision space addressed in this deliverable. Integrated and fire-smart rewilding policies require decision frameworks that combine ecological ambition with risk governance and operational feasibility. This requires models that link land-use transitions, disturbance dynamics, and management actions in the same analytical space (Pais et al., 2023; Moreira et al., 2020).

Science-based simulation data are essential in this context. They allow policymakers to move from generic principles to quantified if-then evaluations: if a given rewilding pathway is implemented in a specific landscape, what changes in fire spread potential, landscape configuration, and ecosystem trajectories should be expected over 10, 20, or 30 years? The value of modelling is therefore comparative and strategic (Verburg and Overmars, 2009; van Asselen and Verburg, 2013; Pais et al., 2023). It supports the design of adaptive rewilding portfolios that are spatially targeted, transparent in assumptions, and testable against multiple objectives.

Within this deliverable, the simulator **REMAINS** is used precisely for this policy need: to provide an integrated simulation environment where rewilding-oriented transitions, fire processes, and prevention measures can be assessed together, year by year, under coherent scenario settings (Pais et al., 2023).

1.2. State of the art and integration gap

Carbon sink trajectories depend on composition, age structure, disturbance frequency, and management intensity (Schelhaas et al., 2007; Kurz et al., 2009; Landsberg and Waring, 1997; Forrester and Tang, 2016; Collalti et al., 2016; Seidl et al., 2012). In integrated analyses, the main technical difficulty is not any single module, but the **consistency of coupling** among modules: class definitions, transition logic, disturbance handling, recovery assumptions, and temporal synchronization. Without consistent coupling, uncertainty can be underestimated, and policy comparisons can become difficult to interpret (Pais et al., 2023).

1.2.1 Land-use and land-cover change modelling

Land-use and land-cover change (LULCC) modelling has progressed from relatively simple extrapolative tools to a diverse family of frameworks designed to represent how human decisions, biophysical constraints, and policy choices shape landscapes over time (Verburg and Overmars, 2009; van Asselen and Verburg, 2013). Current approaches can be grouped into four broad classes that are often combined in hybrid architectures. **Demand-allocation models** estimate how much change is required at regional scale and then distribute that demand spatially according to suitability, accessibility, and constraints. **Suitability-based models** emphasize the spatial likelihood of each land system, typically using environmental and infrastructural predictors. **Statistical models** infer transition probabilities from historical trajectories, and are often used for calibration, baseline scenarios, or uncertainty analysis. **Agent-oriented models** represent heterogeneous actors, decision rules, and behavioral responses, helping explore how local choices scale up into emergent landscape patterns.

Within this landscape, frameworks such as CLUmondo and related systems have become influential because they connect macro-level demand trajectories with spatially explicit competition among land systems (Verburg and Overmars, 2009; van Asselen and Verburg, 2013). They are particularly useful when policy questions involve multiple land functions and contested land claims, for example food production, forest expansion, conservation, and urban pressure. In these frameworks, scenario design is usually explicit and auditable: assumptions on demand growth, policy restrictions, and conversion priorities are translated into reproducible runs. This supports comparative assessments across policy alternatives and makes model outputs easier to interpret in planning contexts.

A key strength of mature LULCC modelling is the ability to allocate requested change geographically rather than reporting only aggregate totals (Verburg and Overmars, 2009; van Asselen and Verburg, 2013). This matters because the same net change can produce very different outcomes depending on where transitions occur. Modern tools can represent legal or physical constraints, conversion resistance, neighborhood effects, and suitability gradients, producing more realistic transition patterns. They also allow users to test counterfactuals, such as stricter protection rules, altered demand pathways, or targeted incentives, under consistent assumptions. In decision support, this combination of spatial explicitness and scenario transparency is one of the major reasons LULCC models are now central to strategic territorial planning.

At the same time, an important limitation remains in many implementations: **wildfire is often treated as exogenous**. In practical terms, fire may be introduced as a static hazard layer, a periodic disturbance mask, or a post-processing correction on top of land allocation outputs. This representation can be sufficient for some screening exercises, but it becomes limiting in fire-prone regions where disturbance is an annual driver of land trajectories. When fire is external to the transition engine, models may miss feedbacks in which landscape composition influences spread potential, fire alters future transition opportunities, and management responses modify both processes in subsequent years (Finney, 1998; Finney, 2006; Pais et al., 2023).

This integration gap is not a minor technical detail. It affects policy interpretation. If disturbance is external, scenario comparisons may underestimate path dependency and overestimate the stability of long-term targets. A landscape designed to optimize biodiversity or restoration in static terms may perform differently once annual ignition, spread, and post-fire transitions are represented dynamically (Finney, 1998; Finney, 2006; Pais et al., 2023). For this reason, the next frontier for LULCC scenario analysis is tighter coupling between land-system change and endogenous disturbance processes, especially wildfire, so that policy evaluation reflects the co-evolution of land use, fuel structure, and risk over time (Pais et al., 2023; Moreira et al., 2020; Pausas and Keeley, 2021).

1.2.2 Wildfire spread modelling

Wildfire spread modeling is central to any framework that aims to evaluate rewilding or land-use policies in fire-prone landscapes, because changes in vegetation cover and management affect not only the amount of **flammable biomass**, but also its spatial continuity, and therefore the capacity of fires to propagate across the landscape. Contemporary fire regimes in Mediterranean and mountain regions are increasingly shaped by the interaction of **warming climate, drought, fuel accumulation, land abandonment, and changing suppression effectiveness**, which makes static hazard representations insufficient for scenario analysis

(Moreira et al., 2020; Pausas and Keeley, 2021; Ruffault et al., 2020). For this reason, wildfire spread should be treated as an **endogenous landscape process** rather than as an external disturbance imposed after land-cover change has already been simulated.

At the model-design level, existing wildfire spread tools provide complementary strengths. FARSITE was developed to simulate two-dimensional fire growth from known ignition points by integrating established surface and crown fire behavior models in a spatially explicit environment, and remains a benchmark for event-scale fire growth simulation (Finney, 1998). FlamMap extended this logic to landscape-wide estimation of potential fire behavior under constant environmental conditions and introduced minimum travel time approaches that are especially useful for fuel treatment assessment and comparative planning (Finney, 2006). These systems are powerful for operational or treatment-oriented applications, but they are not primarily designed to simulate long time series in which land-use transitions, vegetation change, ignitions, spread, suppression, and post-fire recovery are all updated within the same annual loop.

The REMAINS framework addresses this integration problem by coupling fire spread with vegetation and land-use dynamics in a spatially explicit, process-based structure implemented in R (Pais et al., 2023). In this perspective, wildfire spread is modeled as a recurrent process whose probability and extent depend on the current configuration of land-cover classes and management options. This makes the framework especially suitable for policy experiments in which rewilding, fuelbreak deployment, mosaic restoration, prescribed burning, or suppression strategies alter both the probability of ignition and the pathways available for fire propagation through time (Pais et al., 2023; Moreira et al., 2020).

In the modified REMAINS implementation used here, wildfire spread is represented annually through a sequence that links fire-regime assumptions to spatial propagation (see Deliverable 3.1). First, each land-use or land-cover class is assigned an effective flammability value, so the landscape is translated into a combustibility surface. Second, total annual burned area and the number of fires by size class are sampled from user-defined distributions calibrated on observed fire activity and scenario assumptions. Third, a fire-risk layer is updated from land configuration and contextual modifiers, and is used to allocate ignitions probabilistically. Fourth, spread proceeds from ignited cells through neighborhood interactions, with propagation conditioned by local flammability, spatial connectivity, topographic controls, and suppression-related modifiers. In this way, the model links changes in landscape structure directly to changes in fire spread potential and realized burn patterns within the same simulation year.

This neighborhood-based representation is consistent with the broader literature on **cellular automata and raster wildfire models**, where fire propagation emerges from local transition rules applied repeatedly across adjacent cells (Alexandridis et al., 2008; Freire and DaCamara, 2019). This modeling family is therefore well aligned with scenario-based analyses of territorial reconfiguration, where the geometry and composition of the fuel mosaic matter as much as the characteristics of any individual ignition.

A key implication for this deliverable is that wildfire spread modeling should be interpreted **comparatively rather than deterministically**. The aim is not to predict the exact perimeter of future fires, but to estimate how different policy pathways modify the distribution of fire opportunities across the landscape. Under this interpretation, spread modeling becomes a tool for testing whether rewilding trajectories increase fuel continuity, whether agricultural or low-flammability mosaics constrain large-event propagation, and whether direct prevention measures improve containment under worsening climatic pressure.

1.2.3 Forest dynamics and carbon modelling

Forest dynamics models span a continuum from empirical/accounting approaches to process-based simulators. **Empirical and bookkeeping-oriented models**, for example **EFISCEN** (Schelhaas et al., 2007) or the **Carbon Budget Model** of the Canadian Forest Service (Kurz et al., 2009), are effective for stock-change accounting and scenario comparison under well-defined management assumptions, but are less detailed in climate sensitivity and disturbance integration. Their main advantage is operational robustness. They are transparent, relatively parsimonious in data requirements, and suitable for comparing management pathways under clearly defined assumptions. This makes them particularly effective for policy-facing assessments that require consistency, replicability, and compatibility with reporting systems. However, these models typically represent ecological processes through aggregated relationships and transition rules, so they may be less sensitive to physiological responses under novel climate conditions. Disturbance can be included, but often through externally prescribed regimes or simplified disturbance modules rather than fully endogenous, climate-responsive disturbance dynamics.

Process-based models, including examples such as **3PG**/3PGmix (Landsberg and Waring, 1997; Forrester and Tang, 2016), **3D-CMCC-FEM** (Collalti et al., 2016), or **iLand** (Seidl et al., 2012) provide richer mechanistic representation of growth, mortality, physiology, competition, and **climate sensitivity**; but are often less complete in terms of standardized treatment libraries for silvicultural operations across heterogeneous systems. They explicitly simulate key mechanisms behind productivity and stand development, including carbon assimilation, respiration, allocation, water balance, competition, mortality, regeneration constraints, and responses to climate variability. This level of detail is critical when the objective is to understand climate sensitivity, tipping behavior, adaptation options, and long-term ecological trajectories under changing environmental conditions. These models are therefore indispensable for advanced analyses of resilience and carbon dynamics. Their challenge is different: the stronger ecological realism often comes with greater calibration complexity, heavier input requirements, and, in some applications, less complete or less standardized treatment libraries for silvicultural operations across heterogeneous management systems.

All these models are essential for forest productivity and carbon assessments, but they are not always designed to natively simulate broad multi-class land-use transitions with annual spatial fire spread at landscape scale. The trade-off is clear: models that are strong for transparent accounting and scenario consistency are often less detailed in ecological mechanisms, while models with rich biophysical realism can be harder to align with management reporting and large-scale planning constraints. Coupling is possible, but often requires significant harmonization of state variables, temporal resolution, and spatial units (Pais et al., 2023).

The integration challenge emerges when one needs to evaluate policies that simultaneously affect **forest condition**, **land-use transitions**, **disturbance regimes**, and **carbon outcomes**. Most forest dynamics models, regardless of family, are not natively designed to represent broad multi-class land-use change together with annual, spatially explicit wildfire spread across a mixed landscape mosaic. They usually operate within a forest-domain ontology, while landscape models include non-forest classes, cross-sector transitions, and land-system competition. Coupling these domains is feasible and increasingly necessary, but methodologically demanding. It requires harmonization at multiple levels:

- **State variables**, because “age,” “biomass,” “stock,” and “disturbance status” may have different meanings across models.
- **Temporal resolution**, because annual fire dynamics and episodic disturbance events must be synchronized with growth and transition time steps.
- **Spatial units,** because stand-, cell-, and polygon-based systems use different geometries and scaling assumptions.
- **Class definitions and transition logic**, because forest types in growth models do not always align with land-cover classes used in LULCC and risk mapping.

Without careful harmonization, coupling can introduce structural inconsistencies that are larger than parametric uncertainty. For this reason, integrated applications should prioritize transparent variable mapping, explicit assumptions on scale conversion, and scenario protocols that keep cross-model interactions auditable. This is the core methodological motivation for frameworks that aim to bridge forest dynamics, disturbance simulation, and land-use change within a unified scenario engine (Figure 1).

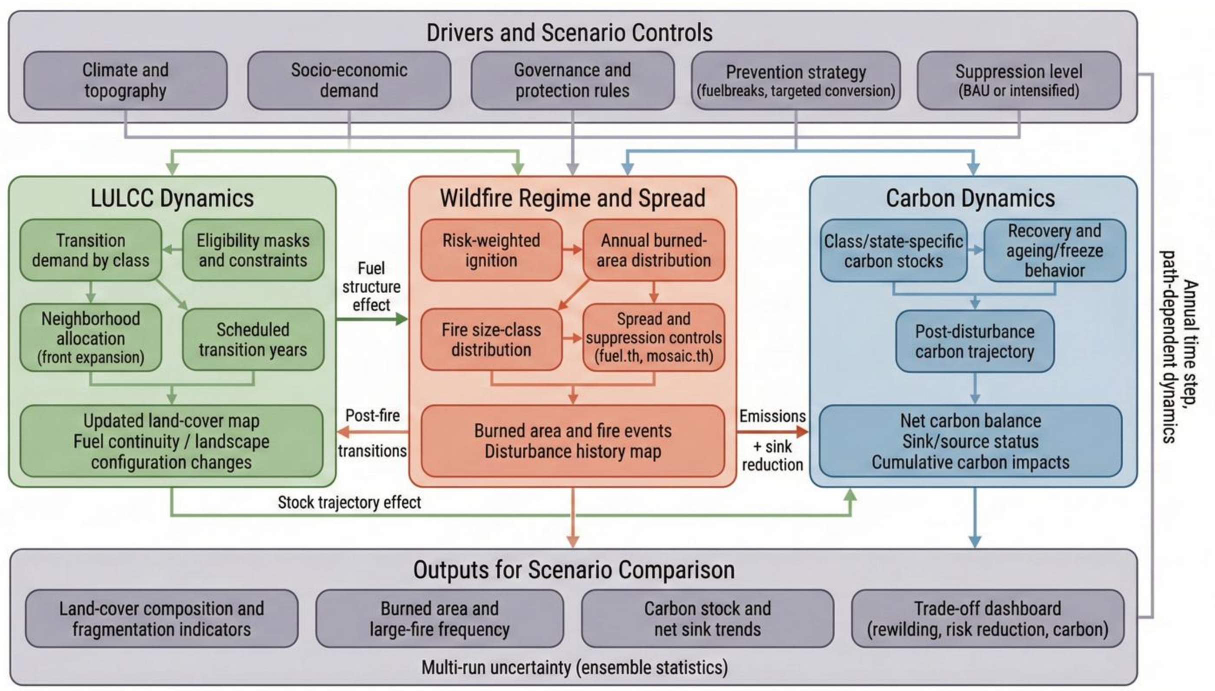

Figure 1. Conceptual integration of LULCC, wildfire, and carbon dynamics.

1.3. Rationale for REMAINS and aim of the deliverable

A model supporting policy design needs to represent, within one framework: transitions among land-use classes, annual ignition and fire spread dynamics, management interventions that modify both transitions and flammability, and resulting implications for fire risk, carbon sink and landscape trajectories over time, including feedback loops on future landscape flammability. This requirement defines the methodological niche addressed by REMAINS in the project. REMAINS is adopted because it supports integrated, spatially explicit simulation of annual landscape evolution and wildfire dynamics under alternative policy scenarios (Pais et al., 2023). In the project configuration, the model enables six capabilities that are central for decision support:

1. **Spatially explicit, cell-level annual transitions** among land-use/cover classes, driven by scenario-specific rules and land use change demands, which can be parameterized from observed transitions.
2. **Annual wildfire simulation** through class-based flammability, target burned-area distributions, fire-size-class event distributions, and risk-based ignition probability.
3. **Endogenous feedbacks** between disturbance and subsequent landscape transitions.
4. **Flexibility for policy parameterization**, including interventions that alter transition pathways and/or effective flammability.
5. **Cell-based tracking of time since land cover change**, which in the absence of a full forest dynamic module might still allow to link to external age-based forest development and carbon stock equations.
6. **Stochastic assessment** of disturbance location and area, allowing to build credible intervals for expected future fire risk and landscape configuration, based on running multiple model iterations.

The deliverable documents a modified implementation of REMAINS developed for the REWILDFIRE project goals. The methodological core includes:

- explicit handling of management policies such as fuelbreaks and conversion-based fuel mosaic design,
- workflow choices for annual sequencing of transitions and fire processes,
- scenario logic for intervention intensity and spatial targeting,
- harmonized outputs for cross-scenario comparison.

The deliverable has three operational objectives: (1) **Documentation**: provide transparent description of model structure, assumptions, and parameterization in the project context. (2) **Reproducibility**: define inputs, processing steps, and outputs so that scenario experiments can be replicated and audited. (3) **Interpretation**: clarify strengths, limitations, and uncertainty boundaries for correct use of results in planning and policy dialogue.

This document covers model workflow and annual simulation logic, data requirements and spatial-temporal scales, policy scenario implementation, output indicators and interpretation framework. It does not claim deterministic prediction of future fire events. Results are interpreted as probabilistic trajectories conditional on model assumptions and scenario definitions.

2. Model structure and processes

This chapter describes the structural design of the modified REMAINS implementation used in the project. The objective is to clarify how the model represents space, time, and state variables before introducing process modules (land-use transitions, wildfire, post-fire dynamics, and policy interventions) in subsequent chapters.

The updated REMAINS architecture is built as a **cell-based, annual, scenario-driven simulation framework**. Each simulation year updates the state of every grid cell according to transition rules, disturbance dynamics, and management constraints. This design allows consistent comparison across scenarios while preserving spatial detail and temporal feedbacks.

2.1 Spatial and temporal units

The fundamental simulation unit is the **grid cell**, with resolution defined during scenario setup. All model processes are mapped to this common geometry, including:

- land-use/land-cover (LULC) class assignment;
- time since last land cover change;
- flammability attribution;
- ignition probability and fire spread interactions;
- policy treatments (for example, fuelbreak/firebreak membership);
- yearly updates of state variables.

The simulation runs at a **one-year time step**. Within each year, REMAINS executes model components in a defined sequence (detailed in workflow chapters), updating cell states after each process block. Operationally, model results in the Rewildfire settings are aggregated every five years.

The model is run over a **multi-year horizon**, typically long enough to capture cumulative effects of repeated fire disturbance, delayed effects of land-use transitions, persistence or decay of treatment effectiveness, and pathway-dependent divergence among scenarios. Because the model is stochastic in key components, multi-year horizons are usually paired with repeated runs to characterize trajectory uncertainty. In the Rewildfire framework, **80 year long** simulations were run with **15 iterations** for every site and scenario combination.

2.2 Cell state representation

Each grid cell is defined by a set of **state variables** that together describe its current ecological/landscape condition and its eligibility for future change. The modified REMAINS implementation uses a compact but expressive state structure, designed to support annual updates and cross-module consistency.

Every cell has a current LULC class, which determines what transitions are allowed, how flammable the cell is, how it interacts with neighboring cells in fire spread dynamics, and how policy interventions apply. It also allows for external coupling with carbon stock allometric equations. This is the primary categorical state variable and the main output of landscape evolution. In the Rewildfire configuration, allowed classes are:

- crop
- pasture
- shrub
- broadleaf
- conifer
- urban
- water
- other

Cells also store an **age-like variable** (or equivalent successional/management proxy) used to represent stand development stage, recovery status, or management recency. Depending on scenario settings, this variable can increment annually (ageing of unmanaged forests – "proforestation"), reset or be reduced after specific transitions or disturbances, or be "frozen" for managed classes/features (for example for regularly managed forests, to represent the absence of change in landscape-scale forest age structure, and under specific firebreak settings). This variable is central for linking disturbance history and transition behavior over time., and for external age-dependent carbon equation coupling.

Cells can be flagged as part of **management elements** such as fuelbreak/firebreak systems. This membership affects transition constraints, effective fire spread/suppression behavior, and age-update logic under certain policy configurations. Management membership is therefore treated as an explicit state dimension (or rather, more than one under different management scenarios) rather than an external overlay.

Finally, cells carry simple **disturbance-related indicators**, including cumulative burn history (for example, whether a cell has burned up to the current year). These indicators are used to: condition post-fire pathways, modulate eligibility for selected transitions, and support scenario diagnostics on disturbance legacy. Tracking disturbance history at cell level is essential for representing path dependency in long-term simulations.

Additional helper variables and flags have been developed by pour team to govern transition eligibility and process control, such as: candidate masks for specific conversion types, freeze masks for selected state updates, neighborhood-based allocation to prioritize land cover change, grouping rules, protected area or buffer inclusion flags, and consistency checks for process sequencing. These indices are not always reported as headline outputs, but they are critical to ensure reproducible and auditable execution of policy rules.

2.3 Spatial preprocessing and harmonization

All model inputs are **harmonized** to a common cell-based simulation grid before runtime. Preprocessing includes projection unification, extent alignment, resolution matching, and consistent cell indexing across layers. A unique cell identifier is maintained throughout the workflow to ensure one-to-one joins among land-cover, topographic, risk, and management datasets.

Land-cover reclassification is performed using an explicit crosswalk from source legends to REMAINS classes (crop, pasture, shrub, broadleaf, conifer, urban, water, other, plus transitional classes where applicable). Ambiguous classes are resolved through predefined rules and checked through consistency diagnostics. Cells outside the study domain are masked and excluded from conversion and spread operations.

Topographic and contextual layers, including slope/elevation/aspect where required, are sampled or rasterized on the same grid. Management layers (firebreak/fuelbreak masks, protected-area masks, exclusion masks, and operational buffers) are processed with the same geometry and indexing rules. The final harmonized **stack** is validated using: geometry checks, class-frequency checks, NA-mask integrity checks, and logical compatibility tests between eligibility masks and class domains. This preprocessing stage is mandatory to avoid structural artefacts in both transition allocation and wildfire spread.

2.4 Land-Use and Land-Cover Transition Engine

The LULCC engine in the modified REMAINS framework translates scenario assumptions into annual, cell-level landscape change. Its function is to determine which cells transition from one class to another, in what quantity, and under which spatial and policy constraints. Conceptually, the module combines three components: **demand**, **eligibility**, and **allocation**.

At the start of each annual step, a user-defined input imposes **transition demand**, usually as absolute target area. Typical examples include conversion from cropland to broadleaf, pasture to conifer, or inverse transitions under agricultural reinforcement scenarios. The demand table has been parameterized using region-specific observed changes from difference time slices of Corine Land Cover maps in the Alpine Space (1990-2018), following harmonization between Corine land cover labels and Remains lct classes. Demand does not directly force arbitrary conversions. It is filtered through an eligibility structure that determines where change is admissible. Eligibility integrates class compatibility, neighborhood constraints, disturbance legacy, and management exclusions. Cells in non-convertible classes (for example water or urban) are excluded, while specific scenario rules can further restrict conversion by age proxy, protected area masks, or treatment membership. Candidate cells are then ranked or sampled using suitability and stochastic selection logic. The modified version applies explicit conflict control to avoid multiple incompatible updates in the same annual cycle. A visited-cell mechanism tracks cells already transformed by one transition pathway and excludes them from subsequent pathways within the same year. This is essential when several transitions are active concurrently, because it preserves accounting consistency and prevents over-allocation.

Spatial structure is a defining element of the module. Allocation of land cover change is conditioned by **neighborhood context**, buffer logic, and patch criteria, allowing scenario designs that are not purely random but spatially targeted (Annex 1). This is especially important for prevention-oriented policies: converting a cell in isolation has different implications than converting connected cells in a fuel corridor or near critical interfaces. The transition engine therefore works as a spatial optimization-by-rules system rather than a purely tabular land-balance routine.

A second key feature is the coupling with **disturbance and recovery states**. Burn history, post-fire status and recovery lags can alter transition eligibility or priority, producing path-dependent trajectories. This means that identical initial demand can yield different realized landscapes depending on previous fire sequences and management actions.

Outputs from this module include annual transition maps, updated class rasters/tables, and transition accounting by type and area. These outputs are then passed to wildfire and post-disturbance modules, which can further modify state variables before the year closes. Because transitions are stochastic under constraints, robust scenario interpretation uses repeated runs and distributional summaries rather than single-run point estimates.

REMAINS also uses **transitional land-cover classes,** i.e., explicit **intermediate states** used to represent the time lag between a disturbance or management action and the attainment of a stable land-cover condition. Rather than converting a cell immediately from one mature class to another, the model routes it through temporary classes that preserve the legacy of recent change, such as post-fire reorganization or post-intervention recovery. This is essential in annual simulations, because ecological structure, fuel properties, and management status do not reset instantaneously. Operationally, transitional classes are activated when a cell undergoes a major state shift (for example, wildfire impact, prevention-driven conversion, or recovery entry). The cell then remains in a transient state for one or more time steps, after which exit rules move it toward stable classes according to regeneration/recovery logic. This approach allows the model to separate **newly transformed** cells from **mature** cells even when both are nominally linked to the same broad vegetation type.

Methodologically, these classes improve realism and model stability in four ways. First, they represent delayed succession and recovery trajectories. Second, they avoid abrupt class jumps that would otherwise create artificial step changes in area statistics. Third, they preserve coupling between wildfire, regeneration, recovery, ageing/freeze rules, and future transition eligibility. Fourth, they reduce short-term output artefacts by ensuring that early-stage stands are not treated as equivalent to mature stands in spread and transition logic.

2.5 Wildfire module

The wildfire module simulates fire occurrence and spread every year as an endogenous process interacting with landscape configuration. The modified REMAINS implementation follows a five-step logic that links scenario-based fire regime assumptions with spatially explicit propagation dynamics:

Step 1: Flammability assignment. Each land-use/land-cover class is assigned a flammability value or effective spread-related coefficient. This provides the baseline combustibility structure of the landscape. Management features and scenario options can alter effective flammability locally, for example by reducing spread potential in designated firebreak/fuelbreak cells or in converted low-flammability mosaics. This step creates the annual fuel-behavior layer used for subsequent calculations.

Step 2: Annual burned-area target sampling. The model samples total area to burn in the year from a user-defined frequency distribution, which we calibrated merging observed fire events in each landscape and empirical modeling of climate change-induced effects on yearly burned area distribution, calibrated on observed relationships between yearly burned area and seasonal fire weather indices (see Deliverable 3.1). This does not prescribe where fire will spread but sets the stochastic disturbance pressure for that annual step. Using a distribution instead of a fixed value captures interannual variability in disturbance burden, which is necessary for realistic long-horizon scenario testing.

Step 3: Number of fires by size class. The module samples the number of events across fire-size classes from scenario-defined distributions. This controls event structure, distinguishing many small events from fewer large events, or mixed regimes. The annual combination of burned-area target and event-size structure shapes the realized spread pattern and fragmentation effect.

Step 4: Fire risk. A risk index is computed per cell from land context plus additional modifiers (e.g., orography, hazard components). This layer is used to bias where ignitions are placed. In operational terms, it translates static and dynamic landscape properties into a spatial field where higher-risk cells have higher probability of ignition and/or contribute to faster spread pathways in subsequent fire simulation steps. The risk module is executed at each annual time step after land transitions and before ignition/spread simulation.

The risk index is computed per cell $i$as a combination of components:

$$Ri=f\,(Si,\ Hi,\ Di,\ Oi,\ Mi),$$ where:

- S_i: structural susceptibility linked to current land-cover class (fuel type proxy),
- H_i: hazard-related contribution (propensity of the cell to support fire occurrence),
- D_i: potential damage/exposure component (if included in the project settings),
- O_i: orographic modifier (terrain influence) – typical effects include slope-related spread facilitation and terrain-driven exposure patterns,
- M_i: management modifier (e.g., suppression-oriented masks, if active in risk stage).

Step 5: Ignition placement, spread and suppression. Ignitions are placed probabilistically with higher likelihood in higher-risk cells, based on a fire-risk layer and eligibility conditions. Cells with higher risk index $R_i$receive higher selection probability when annual fire events are generated. A generic formulation is:

$$P_i^{ign} = \frac{g(R_i)}{\sum_{j\in\Omega} g(R_j)}$$

with $g(\cdot)$a monotonic transform and Ω the set of ignitable cells.

Spread then proceeds according to local flammability and neighborhood connectivity, while suppression-related effects of management features at individual pixels or groups of pixels can reduce propagation probability or continuity. Once ignited, fire spreads from a source cell to its **8 neighboring cells** (Moore neighborhood). Each neighbor receives a spread-rate value, and the order of burning emerges from those rates. The spread rate toward each neighbor is computed from a polynomial model combining three main explanatory components:

1. **Dynamic land-cover fire proneness** (flammability/fuel-related term, updated with landscape dynamics)
2. **Slope relative to fire front** (using elevation information)
3. **Aspect** (terrain orientation effect)

These components are weighted by model parameters inside the polynomial formulation. A small random term is added to propagation speed, so fire perimeters are not unrealistically regular. This preserves directional control from topography/fuels while producing more realistic shapes. Several active fronts may target the same cell, but the cell burns **once**, by the front that arrives first (minimum travel time logic). **Secondary ignitions / spotting is not simulated** in the base spread algorithm.

Fire fronts can be **suppressed** according to the suppression strategy in the scenario. As a result, final burned area can be smaller than potential event size The model distinguishes **Fuel-based suppression** and **Mosaic-based suppression.** A fire stops when one of the following occurs: (1) It reaches its **potential target size** from the fire-size draw, (2) It cannot spread to additional burnable cells, (3) All active fronts are suppressed. In the modified REMAINS configuration, suppression is implemented as a **single harmonized control system** based on two threshold parameters, replacing region-specific legacy logic. Suppression effectiveness is governed by two main threshold controls:

- **fuel.th (fuel threshold)**: Controls how fuel conditions influence the probability that spread is contained. Conceptually, when local fuel conditions are below or around this threshold, suppression has higher success. As fuels become more conducive to spread, suppression effectiveness decreases.
- **mosaic.th (landscape mosaic threshold)**: Controls how landscape heterogeneity/discontinuity influences containment. More fragmented, less connected fuel patterns increase suppression success; highly continuous fuels reduce it. This parameter captures the structural advantage of a fire-smart landscape mosaic.

On top of threshold logic, each scenario applies a specific suppression intensity profile:

- **BAU (Business as Usual):** Suppression remains at the reference historical level used as baseline.
- **Strict Rewilding + Fire-control**: Suppression is increased by **+0.1** relative to BAU. This represents stronger tactical effort/capacity and tests whether higher control pressure can offset fire-risk effects generated by stricter rewilding constraints.
- **Fire-smart Rewilding + Direct Prevention**: Suppression remains at **BAU level** but is coupled with **targeted direct prevention** (fuelbreak/firebreak and risk-aware landscape intervention). The underlying hypothesis is that structural prevention reduces spread pressure, so similar suppression effort can achieve better outcomes.

The final annual burn pattern emerges from interaction among fire regime statistics, risk-based ignition location, class-specific flammability, spatial configuration, topography, suppression, and local stochasticity. A major strength of this module is that disturbance is not external post-processing. Burn outcomes modify state variables that feed forward into subsequent years, influencing eligibility, landscape composition, and future spread conditions. This creates endogenous feedback loops central to long-term prevention assessment.

From an output perspective, the module generates annual burned-cell pixel status layers (burned/unburned/suppressed), event-level summaries, and aggregate metrics such as per-fire and total burned area, event counts, and size distribution. In planning applications, the wildfire module is especially valuable for testing whether a given landscape strategy remains effective under repeated annual disturbance, and what are the trade-offs between certain fire prevention strategies and carbon stock dynamics (including both avoided fire emissions, avoided forest stock losses, and feedbacks through changes in land cover type and age).

2.6 Territorial fire prevention policies

In the modified REMAINS framework, fire prevention policies are encoded as explicit parameters that alter either transition dynamics, pixel-level effective flammability, or both. This makes interventions testable within the same simulation logic as baseline dynamics and allows direct comparison of outcomes under controlled assumptions.

Policy representation follows three principles. First, interventions must be **operationally translatable** into model rules, such as conversion quotas, eligibility masks, buffer constraints, or local flammability adjustments. Second, interventions must be **spatially explicit**, because prevention efficacy depends on location and connectivity, not only on treated area totals. Third, interventions must be **time-consistent**, meaning they are applied within annual simulation cycles so cumulative and path-dependent effects can emerge.

Prevention actions are implemented as explicit spatial rules that modify transition **eligibility** and/or effective **fire behavior**. The workflow combines hard masks (non-convertible or non-treatable zones), soft targeting masks (priority intervention areas), and buffer-based candidate selection around strategic elements such as roads or predefined treatment corridors. Candidate cells must satisfy class eligibility and all active mask constraints before allocation. Two policy families are central in this project configuration:

A. Linear or patch-based suppression structures (fuelbreak/firebreak systems). These are represented as managed features that disrupt spread continuity and/or modify local suppression behavior. Depending on scenario settings, firebreak membership can also influence state variables (i.e., reduction of one age class) and update rules (i.e., freezing ageing) for treated cells. The main policy function is not to eliminate ignition risk everywhere, but to reduce contagion probability, lower fire intensity facilitating direct firefighting, and limit expansion into large connected burns. Their effectiveness is therefore topology-dependent: design and placement relative to dominant spread pathways and high-risk interfaces determine performance more than nominal treated area.

B. Targeted conversion toward lower-flammability mosaics. This policy modifies land-use transitions to create strategic landscape mosaic heterogeneity, often by increasing low-flammability patches (i.e., croplands) in key zones. The mechanism acts through landscape structure: reduced fuel continuity can lower the probability of large-event propagation even when ignition pressure remains high. In REMAINS, this is implemented through conversion rules and candidate selection criteria, allowing planners to test different intensities, locations, and sequencing options.

Firebreak deployment and mosaic conversion can be complementary or partially redundant depending on spatial arrangement and annual disturbance patterns. Combined scenarios are therefore essential for identifying synergies and diminishing returns. The model supports this by keeping policy levers modular: each lever can be activated alone or in combination, with consistent annual accounting.

Fire-smart rewilding in REMAINS is implemented as a **rule-based, hierarchical allocation process** and not as random expansion. Each scenario defines a quantitative target (for example, a percentage of the landscape or of the eligible domain) and then allocates rewilding through a priority cascade. Potential management masks were defined as **15% of forest (broadleaf + conifer) within a 150 m forest-road buffer, plus 10% of pasture and 10% of sparse vegetation selected with a paddock-style clustered geometry.** This mask architecture ensures operational realism, spatial coherence, and explicit traceability of management and rewilding decisions. Cells are selected tier by **tier**: the model first fills the target using the highest-priority domains, and only if the target is not met does it move to lower-priority tiers. This structure turns rewilding into an explicit planning strategy with traceable choices, rather than a diffuse increase in natural cover. The priority order for scenario implementation is as follows:

- **Priority 1**: unmanaged/indefinite ageing areas inside protected areas already suitable for passive or low-intervention recovery (Rw)
- **Priority 2**: managed cells inside protected areas converted to rewilding if Rw is insufficient, i.e., adjacent or connected cells that increase continuity of Priority 1 nuclei and reduce edge fragmentation (Rwm)

- **Priority 3**: secondary eligible cells in managed matrices where rewilding can improve mosaic structure without violating explicit exclusions, i.e., unmanaged cells outside protected areas within expanding buffer (up to 1 km and beyond if required by target logic) when Rw+Rwm are insufficient (Rwu).

Within each priority tier, tie-breaking is usually performed with additional spatial criteria: contiguity to existing natural patches, neighborhood support, minimum patch size thresholds, and distance-based penalties/bonuses. This ensures that selected cells contribute to functional connectivity and avoids checkerboard patterns that would be ecologically weak and methodologically unstable.

Evaluation is based on comparative scenario outputs, including burned area trajectories, large-fire frequency, landscape composition, and configuration indicators. Where carbon-related modules are coupled, policy effects on sink trajectories can also be tracked. This supports a more rigorous prevention planning process, where interventions are assessed as adaptive portfolios in changing landscapes rather than as static one-off treatments.

3. Input, output and model workflow

3.1 Software architecture and script roles

The implementation is modular within the R statistical framework, with one main orchestrator and multiple process-specific scripts:

- **land.dyn.mdl.R:** Main orchestration engine. It controls runs, annual looping, module activation/deactivation (LULCC, wildfire, post-fire, recovery, afforestation/encroachment), ageing/freezing rules, and output writing.
- **default.params.R**: Central parameter definition. It stores default settings for time horizon, annual time step, cell size, regional mappings, scenario switches, and key thresholds.
- **internals.R:** Internal utility layer. It includes helper functions for validation, safe sampling, edge-case handling, logical coercion, mask operations, and output safety checks.
- **land.cover.change.R:** LULCC transition module. It builds eligible candidate pools, allocates annual transition demand, applies neighborhood-based front expansion, and prevents same-year conflicts.
- **fire.risk.R:** Cell-level fire risk computation from land cover and contextual factors (including topographic/orographic components where configured).
- **wildfire.R:** Annual ignition and spread simulation. It handles event generation, ignition probability allocation on risk surfaces, spread logic, suppression-related behavior, and burn tracking.
- **postfire.rege.R:** Post-fire transition/regeneration module. It applies disturbance-conditioned class updates and recovery trajectories after fire.
- **forest.recover.R:** Forest recovery progression module. It governs multi-year transition from transient post-disturbance states toward stable forest classes.
- **direct_prevention.R:** Direct prevention policy module. It applies targeted preventive conversions (for example in firebreak buffers), including state changes (such as a reset or reduction in time since change) where required.
- **interface.R:** Landscape-interface classification module. It derives interface classes (urban–rural–forest combinations) for diagnostics and reporting.

3.2 Input data structure

3.2.1 Core spatial inputs

1. Initial land-use/land-cover grid (e.g., crop, pasture, shrub, broadleaf, conifer, urban, water, other).
2. Topography/orography layers (if used in risk computation).
3. Fire-risk map (or the variables needed to build it).
4. Management layers (e.g., firebreak/fuelbreak masks, buffers, exclusion masks).

3.2.2 Scenario and transition parameters

1. Time settings (simulation years, annual step).
2. Transition matrix/rules (allowed source-target class conversions).
3. Annual transition demand (lcc.demand) by transition type, in absolute area units.
4. Neighborhood/expansion parameters (e.g., exponent k, distance threshold).

5. Module switches

3.2.3 Fire-regime inputs

1. Class-specific flammability values.
2. Distribution for annual total burned area.
3. Distribution for number of fires by fire-size class.
4. Spread/suppression parameters, including management effects.

3.2.4 Prevention-policy inputs

1. Scenario switches (direct_prev, use.firebreaks, freeze_cols as applicable).
2. Preventive conversion settings (eligible classes, quotas, patch filters, buffer geometry).
3. Age/successional thresholds for candidate selection.

3.2.5 Carbon-related inputs (external equations, coupled)

1. State variables linked to stand development or disturbance legacy (land cover type, age, burn history).
2. Carbon equation parameters for different carbon pools
3. Lookup settings (including scenario-specific pathways such as proforestation when enabled in the project workflow).

3.3 Annual operational workflow

The simulation year is executed as a state-update sequence (Table 1, Figure 2).

Step 0. Initialization (pre-run)

- Load parameters (default.params.R or scenario-specific overrides).
- Import spatial layers and harmonize class schema.
- Initialize trackers (visited cells, burned cells, annual diagnostics).
- Optionally apply pre-scenario prevention (direct_prevention.R).

Step 1. LULCC allocation (land.cover.change.R)

For each active transition type:

1. Build eligible candidate pool.
2. Assign initial weights/suitability.
3. Select initial seed cells.
4. Expand conversion through neighborhood front propagation.
5. Allocate until annual demand is met (or candidates are exhausted).
6. Enforce conflict control via visit.cells.

Result: updated land-cover class map and related cell state updates.

Step 2. Fire-risk update (fire.risk.R)

Compute/update cell-level fire risk based on current land configuration and contextual variables. Result: annual risk surface for ignition/spread logic.

Step 3. Wildfire simulation (wildfire.R)

1. Sample annual burned-area target.
2. Sample fire-event counts by size class.
3. Allocate ignitions probabilistically (higher chance in higher-risk cells).
4. Simulate spread under flammability, connectivity, and suppression constraints (including firebreak effects where active).
5. Record burned cells and event diagnostics.

Result: annual burn footprint and event statistics.

Step 4. Post-fire transitions (postfire.rege.R)

Apply disturbance-conditioned state transitions and regeneration pathways. Result: post-fire class/state updates.

Step 5. Recovery progression (forest.recover.R)

Advance transient recovery classes toward stable forest classes according to model rules. Result: multi-year recovery dynamics reflected in yearly state.

Step 6. Ageing/freezing and consistency (land.dyn.mdl.R)

The model updates age/proxy state annually for eligible cells, but this update can be altered or suspended through freeze logic in selected scenarios. A frozen management class represents sustained intervention state, whereas ageing classes represent progressive succession/recovery. Freeze behavior is controlled by explicit mask rules and parameter switches. **Firebreak** cells and regularly **managed forests** and pastures are **excluded from ageing**. In addition, state resets can occur after specific transitions or prevention operations, including cases where age-related variables are set to baseline values or **downgraded by one age class** (e.g., as a result of burning). This behavior has direct implications for trajectory realism and downstream interpretation of vegetation and carbon dynamics.

- Apply annual age/proxy increment where allowed.
- Exclude frozen classes/features (including firebreaks under specific scenario logic).
- Run consistency checks before writing outputs.

Step 7. Output writing

- Export annual maps and tabular diagnostics.
- Aggregate per run and per scenario for downstream comparison.

3.4 Output structure

Outputs are produced at three levels.

3.4.1 Annual spatial outputs

- Updated LULC raster.
- Burned and suppressed cell raster (and event/perimeter layers if configured).
- Optional diagnostic maps (risk, interfaces, management masks).

3.4.2 Run-level tabular outputs

- Converted area by transition type.
- Annual and cumulative burned and suppressed area.
- Number of fire events and size-distribution metrics.
- Composition/configuration indicators by class.

Table 1. Companion mapping of workflow steps, scripts, and outputs

Workflow step	Main script(s)	Key operations	Primary outputs
0. Inputs (maps + parameters)	default.params.R, scenario input files, spatial layers	Load baseline LULC, topography/orography, fire-risk inputs, management masks, transition demand and switches	Harmonized model inputs (grids/tables), active parameter set
0. Initialization	land.dyn.mdl.R, internals.R	Build simulation objects, initialize run/year trackers, normalize fields, set flags and masks	Initialized landscape state, run metadata, tracking structures
1. LULCC transitions	land.cover.change.R	Build eligible candidates, apply transition demand (trgt.dmnd), allocate changes using neighborhood front expansion, enforce visit.cells conflict control	Updated annual LULC map, transition logs (area/cells by transition type)
2. Fire-risk update	fire.risk.R	Recompute cell-level fire risk from current land state and contextual modifiers (including orography where configured)	Annual fire-risk surface (cell-level risk index/weights)
3. Wildfire simulation	wildfire.R	Sample annual burned-area pressure and fire events, risk-weighted ignition allocation, cell-to-cell spread, suppression/firebreak effects, event tracking	Burned-cell map, event list, annual burned area, fire-size metrics
4. Post-fire regeneration	postfire.rege.R	Apply disturbance-conditioned transitions and post-fire state updates	Updated post-fire land states/classes
5. Forest recovery	forest.recover.R	Advance transient recovery pathways toward stable forest classes across years	Recovery-updated forest state and class trajectories
6. Ageing checks	land.dyn.mdl.R (with masks/flags from params)	Increment age proxies where allowed; exclude frozen cells/features (including firebreak conditions when active); consistency checks	Final end-of-year state (age/class/masks coherent)
7 Annual outputs	land.dyn.mdl.R, internals.R, optional interface.R	Write annual maps/tables; derive interface diagnostics where required	Yearly rasters/tables (LULC, burned area, diagnostics)

Module activation is scenario-dependent and controlled in land.dyn.mdl.R through model switches (e.g., LULCC, wildfire, post-fire regeneration, forest recovery, prevention settings).

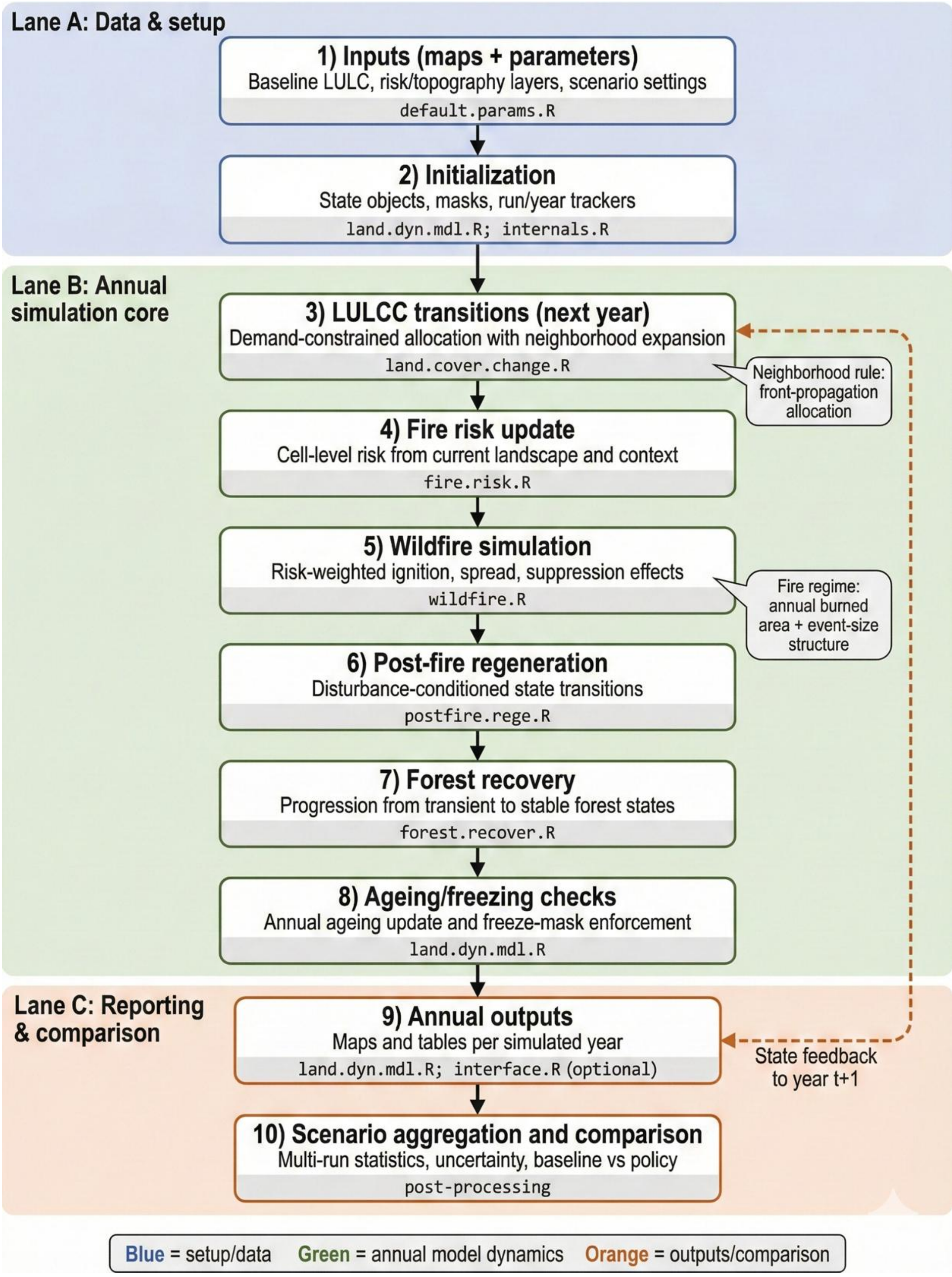

Figure 2. Operational workflow of the modified REMAINS model. The model integrates annual land-use transitions, fire-risk update, wildfire spread, post-fire regeneration, and recovery dynamics in a single simulation loop. Inputs include harmonized spatial layers and scenario parameters. At each yearly step, state updates are applied sequentially, with management constraints (including prevention settings) affecting eligibility, spread, and ageing/freeze behavior. Annual outputs are aggregated across runs to compare scenarios and quantify uncertainty.

4. Discussions

4.1 Strengths

The modified REMAINS framework provides a strong platform for analyszing coupled landscape dynamics under alternative governance strategies. Its core contribution is the **endogenous integration** of land-use and land-cover change, wildfire processes, and policy interventions within a single annual simulation loop. This integration is methodologically relevant because it captures feedbacks that are often treated as external in separate models. Land transitions alter fuel continuity and ignition context, wildfire reshapes eligibility and recovery pathways, and policy choices influence both transition allocation and fire control. The result is a dynamic system where outcomes emerge from interactions, not from isolated modules.

A second strength is **architectural transparency**. The workflow is modular, with explicit process separation across transition allocation, fire risk and spread, post-fire regeneration, and recovery updates. This modularity improves interpretability, supports reproducibility, and enables targeted adaptation of individual components without redesigning the whole framework. It also facilitates scenario diagnostics, because changes in outcomes can be linked to specific model blocks and parameter sets. For applied planning, this is critical: stakeholders can evaluate the consequences of increasing suppression, shifting rewilding priorities, or introducing direct prevention while maintaining a coherent modeling backbone.

A third strength is **scenario-comparison capacity**. REMAINS is well suited to comparative policy analysis because it can represent alternative intervention logics, temporal schedules, and spatial masks under shared baseline assumptions. This supports decision-oriented questions such as whether a higher suppression intensity outperforms landscape prevention, or whether a given rewilding strategy reduces risk or shifts it spatially. The model is particularly useful in contexts where policy options have strong spatial selectivity and path dependence, since annual feedbacks can reveal delayed or counterintuitive effects that static analyses cannot detect.

4.2 Limitations

At the same time, several limitations must be acknowledged. Fire outcomes depend on predefined **stochastic distributions** for annual burned area and event-size structure. If these distributions are weakly constrained or not representative of local regimes, downstream dynamics can be biased even with sound transition logic. The framework is also sensitive to key transition and spread parameters, including neighborhood allocation controls, class-specific flammability settings, and suppression thresholds. Small parameter shifts can produce meaningful differences in long-horizon trajectories, especially when compounded through annual feedback loops.

Another limitation concerns **process abstraction**. Compared with process-based forest simulators, REMAINS uses a simplified representation of eco-physiological mechanisms. This is a reasonable trade-off for integrated landscape-scale policy experiments, but it restricts mechanistic interpretation of growth, mortality, and physiological stress responses. Carbon dynamics derived from class and state trajectories remain informative for scenario comparison, yet they should not be interpreted as substitutes for detailed stand-level physiological modeling.

Data quality and harmonization are additional structural constraints. Model performance depends on the consistency of initial land-cover layers, mask geometry, reclassification rules, and risk-related inputs. Misalignment in spatial resolution, class coding, or temporal harmonization can propagate through multiple modules and alter both aggregate and spatial outputs. The integrated architecture increases analytical value, but it also increases the importance of disciplined pre-processing and configuration control.

Uncertainty propagation is a central issue. In REMAINS, uncertainty does not remain local to one module. It travels through the coupled chain of transitions, fire events, recovery pathways, and policy constraints. This effect is amplified over long horizons, where stochastic variability becomes substantial and scenario divergence can be large. For this reason, outputs should be read as probabilistic trajectories conditioned by assumptions, parameterization, and scenario design, not as deterministic forecasts of future landscapes. This interpretative point is fundamental for policy use. **The model is most informative when used to compare relative behavior across scenarios under a shared assumption set**. It is less appropriate for point prediction at single-year, single-cell resolution. A robust reading focuses on directional changes, risk trade-offs, and confidence envelopes across ensembles. In practice, this means discussing distributions, not only means, and emphasizing where conclusions are stable versus assumption sensitive.

4.3 Methodological recommendations to improve robustness in future versions

To strengthen inference quality and policy relevance, **five practices are recommended**.

1. Conduct global **sensitivity analysis** on the most influential parameters, including transition demand, neighborhood spread controls, class flammability, and suppression thresholds. This is necessary to identify dominant drivers and avoid overconfidence in single calibrations.
2. Maintain complete **traceability** of all adaptations introduced relative to the baseline implementation. Each modification should be linked to rationale, script location, parameter changes, and expected process effect. This improves reproducibility and external review.
3. **Validate** against historical evidence at two levels: annual aggregates and spatial patterns. Aggregate validation should include burned area and class composition trajectories. Spatial validation should test hotspot location, fragmentation metrics, and treatment placement realism.
4. Run **ensemble simulations** for every scenario and report uncertainty intervals systematically. Scenario results should include central tendency plus dispersion metrics, with clear statements on overlap and separation among distributions.
5. Separate **mechanistic statements** from scenario-driven statements in reporting. Mechanistic results describe model-internal process responses under fixed assumptions. Scenario-driven results describe comparative outcomes under different policy configurations. Keeping this distinction explicit improves scientific clarity and decision support credibility.

4.4 Final synthesis

The modified REMAINS framework is a strong comparative tool for integrated territorial policy analysis under wildfire risk. Its value lies in explicit coupling, annual feedback representation, and scenario testing flexibility. Its limits are real but manageable through rigorous calibration, transparent parameter reporting, ensemble-based uncertainty treatment, and multi-scale validation. Under these conditions, the model can provide robust support for strategic planning by clarifying which policy combinations are consistently favorable, where trade-offs are unavoidable, and how uncertainty affects confidence in decision pathways.

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Annexes

Annex 1 – Neighborhood algorithm for land use change allocation

To reproduce spatial contagion in land-use transitions, the modified REMAINS implementation uses a **front-propagation neighborhood rule**. The rule is applied within each transition type and annual time step, after eligibility filtering and before final allocation closure. Let:

- $\mathcal{C} = \{c_1, \ldots, c_n\}$: set of eligible candidate cells for one transition,
- $w_i^{(0)}$: initial suitability weight of candidate c_i,
- D_t: annual demand (number of cells or equivalent area) for this transition,
- $\mathcal{V}_t$: set of cells already converted in the same annual step, used to prevent double conversion.

At initialization, REMAINS samples an initial converted set $\mathcal{F}_0 \subset \mathcal{C}$, called **front**. For each front cell $f \in \mathcal{F}_k$, neighbors are searched among candidate coordinates using nearest-neighbor indexing. The algorithm retrieves up to 9 nearest points (including the focal point), removes the focal point itself, and retains neighbors with distance $0 < d < 200$map units. Thus, the active neighborhood of $f$at iteration k is: $\mathcal{N}(f) = \{c_j \in \mathcal{C}: 0 < d(c_j, f) < 200\}$.

This yields an effective local expansion set of up to 8 neighbors per front cell, constrained by the distance threshold. Each neighbor inherits the seed suitability from its parent front cell. If $w_f^{(0)}$is the initial suitability of front cell f, each candidate neighbor $j \in \mathcal{N}(f)$receives an expansion weight: $W_j = X_j \cdot \left(w_f^{(0)}\right)^k$, where $X_j \sim \mathrm{Exp}(\lambda)$is an exponential random variate, and k is an exponent controlling how strongly inherited suitability shapes expansion. Before accepting new recruits, REMAINS removes cells that violate annual consistency, such as: cells already converted by other transitions in the same year ($\mathcal{V}_t$), duplicate recruits generated by overlapping fronts, and cells no longer admissible under dynamic masks. This step ensures **one conversion per cell per year** and preserves accounting consistency across concurrent transition pathways. After filtering, selected recruits form the new front: $\mathcal{F}_{k+1} \leftarrow \mathrm{SelectedNeighbors}(\mathcal{F}_k)$. The algorithm iterates until one stopping condition is met:

1. cumulative converted cells reach demand D_t,
2. no valid neighbors remain,
3. candidate pool becomes insufficient for further expansion.

The resulting pattern is a clustered, path-dependent conversion map rather than scattered random change.

Annex 2 – R code for Remains – version used in RewildFire (available under request and in agreement with the Regos A. ECOP Landscape Ecology Lab)