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Optimising shea parklands for climate mitigation in West African drylands: Spatial suitability and carbon sequestration trade-offs in Burkina Faso

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Abstract

Background

Agroforestry parklands are increasingly promoted as Nature-based Solutions for climate mitigation and land restoration in the West African drylands. However, approaches that quantify trade-offs between carbon sequestration efficiency and intervention extent remain scarce. This study aimed to identify where shea (*Vitellaria paradoxa*) parkland enrichment and savanna restoration would deliver the greatest carbon gains in Burkina Faso, and how efficiency declines as intervention area expands. Ecological suitability was modelled with a maximum-entropy approach from 559 spatially thinned occurrence records, using a target-group bias layer to reduce sampling bias, and combined with land-cover transitions and modelled vegetation and soil organic carbon gains. Pareto optimisation was applied to 930 distinct intervention scenarios.

Results

Forty-one scenarios were Pareto-optimal, forming two segments separated by a gap in which no scenario was optimal; no balanced scenario was Pareto-optimal. The conservative regime (minimum suitability 0.70–0.80) selected 0.68–3.34 million ha at 0.30–0.38 Mg CO_2-eq ha^{-1} yr^{-1} and delivered at most 1.0 million Mg CO_2-eq yr^{-1}. The expansive regime (minimum suitability 0.25) selected 15.6–19.0 million ha at 0.27–0.28 Mg CO_2-eq ha^{-1} yr^{-1} and delivered up to 5.1 million Mg CO_2-eq yr^{-1} (4.4 million when nationally designated protected areas were excluded). Total gain rose almost in proportion to area, and Pareto-selected areas delivered up to 1.39 times the mean gain of equal-area random selections. Per-hectare gains were highest in Sud-Ouest, Cascades and Haut-Bassins (0.31–0.39 Mg CO_2-eq ha^{-1} yr^{-1}); cropland/parklands dominated the conservative gains, whereas grassy savanna became dominant in five regions under the expansive regime. Spatial-block cross-validation of the suitability model was close to chance (area under the curve = 0.519).

Conclusions

Along the Pareto front, per-hectare gain varied little relative to the nearly thirty-fold range in intervention area, so concentrating interventions in higher-suitability cells secured a roughly proportional rather than a disproportionate share of national gain. Because suitability was weakly validated and the carbon coefficients remain uncalibrated, the results supply an indicative spatial prioritisation framework rather than estimates ready for carbon accounting. Field calibration of the coefficients and a better-validated suitability model are required before the approach can support national mitigation or restoration planning.

1. Background

Terrestrial carbon management is increasingly central to climate mitigation, both in national land-use accounting and in the Nationally Determined Contributions (NDCs) submitted under the Paris

Agreement. Burkina Faso has incorporated land restoration and agroforestry into its climate commitments (CDN-BFKA, 2021). It also participates in the Great Green Wall and in the African Forest Landscape Restoration Initiative (AFR100) under which it has pledged to restore 5 million ha of degraded land by 2030 (AUDA-NEPAD, 2023). Translating these ambitions into spatially explicit interventions remains challenging. Decisions about where restoration should occur must account for substantial spatial heterogeneity and balance carbon storage with food production, biodiversity conservation and rural livelihoods (Bargués Tobella et al., 2017; Ellison & Ifejika Speranza, 2020; Mendonça et al., 2023; Djigbe et al., 2026).

Agroforestry parklands offer a particularly relevant pathway for addressing these interconnected objectives in the West African Sudano-Sahelian zone, where they already store substantial carbon (Bayala et al., 2020; Luedeling & Neufeldt, 2012; Mendonça et al., 2022). These systems retain or establish economically and culturally valuable trees within cultivated and grazed landscapes, thereby combining woody vegetation with crop and livestock production (Akol et al., 2023; Djigbe et al., 2026). Unlike many introduced silvopastoral systems, Sudano-Sahelian parklands have developed through long-standing farmer management, particularly the selective retention of useful trees during land clearing. Shea (*Vitellaria paradoxa* C.F. Gaertn.) and African locust bean (*Parkia biglobosa* (Jacq.) R.Br. ex G.Don) are prominent examples (Pagny et al., 2026; Salako et al., 2025). Present-day tree distribution and density therefore reflect interactions among ecological conditions, land use and generations of farmer management.

Although parkland enrichment and restoration are important, it remains difficult to identify where they can deliver the greatest carbon benefits and how these benefits change as the intervention area grows. Spatial carbon assessments often evaluate individual land-cover transitions or prioritise a single objective. They therefore provide limited information on the trade-off between maximising sequestration per unit area and maximising total carbon gain (Lohbeck et al., 2020; Choungo et al., 2021; Grovermann et al., 2020). This distinction matters for land-use planning: highly efficient locations may occupy small areas, whereas extensive interventions can yield greater total benefits at lower per-hectare efficiency. Multi-objective Pareto optimisation, widely used in spatial land-use planning makes this trade-off explicit (Huang et al., 2008; Wittekind et al., 2026). Knee-point analysis identifies the best-balanced solution along the Pareto front (Christopoulos, 2019), and contrasting segments of the front can be interpreted as distinct intervention regimes. Such approaches have recently been applied to Mediterranean silvopastoral systems (Kiziridis et al., 2026), but remain rare in data-limited Sudano-Sahelian agroforestry landscapes.

This study develops a multi-objective spatial framework to prioritise shea parkland enrichment and savanna restoration in Burkina Faso. It identifies conservative and expansive intervention regimes along the resulting Pareto front. The framework introduces a methodological refinement suited to data-limited contexts: projected tree-cover targets are derived from tree cover already achieved by pixels currently mapped in the destination land-cover class within the same precipitation stratum and are then weighted

by modelled ecological suitability. This constrains projected changes to locally observed biophysical conditions while capturing spatial variation in establishment potential.

The study addresses three questions: (1) What trade-off emerges between mean per-hectare and total modelled CO_2-equivalent gains as the spatial extent of shea parkland enrichment and savanna restoration increases across Burkina Faso? (2) How can the resulting Pareto front be differentiated into intervention regimes, and which environmental and management thresholds characterise these regimes? (3) Which regions and land-cover types are consistently prioritised across alternative intervention scenarios?

2. Methods

2.1. Study design and analytical framework

This study adopted the spatially explicit multi-objective framework (Kiziridis et al., 2026), developed for Mediterranean silvopastoral systems, to evaluate the potential carbon benefits of agroforestry parkland enrichment and savanna restoration across Burkina Faso. The workflow comprised five sequential components (Fig. 1): (i) classification of baseline land cover and identification of agroforestry- and restoration-eligible areas; (ii) modelling of the ecological suitability of shea (*Vitellaria paradoxa*) using species-occurrence and environmental data; (iii) definition of land-cover transition rules and locally informed tree-cover targets over a 20-year projection period; (iv) estimation of changes in vegetation carbon and soil organic carbon (SOC); and (v) multi-objective scenario analysis to characterise trade-offs between mean per-hectare and total modelled CO_2-equivalent gains. All spatial layers were harmonised to a common 0.00833° grid (≈ 1 km; mean cell area ≈ 84 ha; 320,863 valid cells, ≈ 268,000 km²).

Input data

(0.00833° grid, ≈ 1 km)

- **Land cover (WorldCover 2021)**
- **Climate (WorldClim 2.1)**
- **Soil properties (SoilGrids 2.0)**
- **Topography (SRTM)**
- **Population density (WorldPop 2020)**
- **Tree-cover fraction (WorldCover)**
- **Shea occurrences (GBIF, n = 559)**

Figure 1. Modelling framework linking shea suitability, land-cover change, carbon estimation and scenario analysis.

2.2. Study region and baseline land cover

The study covered the whole of Burkina Faso, a landlocked Sudano-Sahelian country of about 274,000 km² in West Africa. A pronounced north-south climatic gradient, from the drier Sahelian zone in the north to the more humid Sudanian zone in the south, shapes vegetation structure, agricultural land use and the distribution of agroforestry parklands (Neya et al., 2018). In July 2025, Burkina Faso was reorganised from 13 to 17 regions. For consistency with the GADM administrative layer used throughout the analysis, results are reported under the former names, which match the input data and figures, with the 2025 name added in parentheses where a region is highlighted. Accordingly, national-scale outputs were aggregated to Burkina Faso's former 13 administrative regions. Administrative boundaries were obtained from the Database of Global Administrative Areas (GADM).

Baseline land cover was derived from the ESA WorldCover 2021 product at 10m spatial resolution and reclassified into six functional land-cover groups representing the principal vegetation and land-use states considered in the analysis (Table 1). The role of each class in the transition model is given in Table 1 and Section 2.4. All remaining land-cover types, including built-up areas and permanent water bodies, were grouped as "Other" and excluded from intervention scenarios. For consistency with the other spatial predictors, the reclassified land-cover layer was projected to the common coordinate reference system, aligned to the national analysis grid and aggregated to the 1km modelling resolution used throughout the study.

Table 1
Reclassification of ESA WorldCover 2021 classes and their roles in the framework.

ESA WorldCover class (code)	Reclassified land-cover class	Role in the analysis	Modelled transition
Tree cover (10)	Forest/gallery forest	Stable; excluded from intervention	No transition
Shrubland (20)	Shrubby savanna	Stable reference/target class	No transition
Grassland (30)	Grassy savanna	Eligible for assisted natural regeneration	Grassy savanna → shrubby savanna
Cropland (40)	Cropland/parklands	Eligible for agroforestry enrichment	Cropland/parklands → enriched parkland
Bare/sparse vegetation (60); moss and lichen (100)	Bare/degraded land	Eligible for assisted natural regeneration	Bare/degraded land → shrubby savanna
Built-up (50); permanent water bodies (80); herbaceous wetland (90); mangroves (95)	Other	Excluded from intervention scenarios	No transition

2.3. Occurrence data and ecological suitability modelling

Ecological suitability for shea was modelled with the maximum-entropy approach (MaxEnt). Because occurrence records came from opportunistic biodiversity databases rather than a systematic national inventory, species selection, occurrence-data quality control and spatial validation were built explicitly into the workflow.

2.3.1. Selection of the indicator species

Occurrence records were initially evaluated for four tree characteristic parkland tree species: shea, African locust bean (*Parkia biglobosa*), *Faidherbia albida* and baobab (*Adansonia digitata*). A preliminary pooled model based on 839 spatially thinned records showed weak spatial-block discrimination across successive data-cleaning iterations (AUC = 0.49–0.53), despite higher performance under random cross-validation (approximately 0.65–0.75). Because pooling species with different ecological niches can obscure species-specific environmental relationships, subsequent analyses focused on *V. paradoxa*, which had the largest number of cleaned records and is a characteristic component of managed parklands in the region (Bayala et al., 2014).

2.3.2. Occurrence-data processing

Occurrence records for *V. paradoxa* were obtained from the Global Biodiversity Information Facility (GBIF). No systematic national field survey of parkland trees was available, so GBIF was the only

harmonised source of georeferenced occurrences for the species. Data were acquired through the GBIF occurrence-search API (GBIF.org, 22 October 2026, DOI: https://doi.org/10.15468/dl.9fgyvt) utilizing a custom paginated client. The search criteria specified scientific Name = "*Vitellaria paradoxa*", country = BF, and hasCoordinate = true. This methodology resulted in 1,362 records derived from 18 datasets published between 1962 and 2026. Among these, 1,206 records contained a year, with the median year identified as 1997. The records were classified as follows: human observation constituted 1,329 records (97.6%), preserved specimens comprised 30 records (2.2%), and 3 records were categorized as unspecified occurrence. Coordinate uncertainty was reported for only 365 records (27%), with a median of 31,104 m (306 records at exactly 31,104 m, apparently generalised coordinates) and only 36 records at or below 10 km. No filter on coordinate uncertainty or on basis of record was applied, records with missing or zero coordinates were removed, and duplicate coordinates were removed by the spatial thinning step described below. Records were subjected to geographic quality control before model fitting. Coordinates falling outside the verified national boundary of Burkina Faso were excluded, and the remaining occurrences were spatially thinned to a maximum of one record per approximately 5km grid cell to reduce spatial clustering and sampling redundancy. Following boundary verification and spatial thinning, 559 occurrence records were retained for model development (Fig. 2)

2.3.3. Environmental predictors and MaxEnt modelling

Nineteen candidate predictor layers describing climatic, edaphic, topographic and anthropogenic conditions were harmonised to the 1-km analysis grid (Table 2): four bioclimatic variables from WorldClim 2.1 (annual mean temperature (BIO1), temperature seasonality (BIO4), annual precipitation (BIO12) and precipitation seasonality (BIO15); Fick & Hijmans, 2017), elevation and slope from SRTM, five soil properties from SoilGrids 2.0 (Poggio et al., 2021), population density (WorldPop, 2020), tree-cover fraction (ESA WorldCover) and the six reclassified land-cover classes, coded as separate binary layers. Tree-cover fraction also defines baseline cover in the tree-cover targets (Section 2.4); this potential circularity is minor, as the variable contributed 1.1% of total model weight (Table 3).

Collinearity among numeric predictors was screened in two steps. Pairwise Pearson correlations flagged 11 pairs with $|r| > 0.7$, mostly among climate variables (strongest between BIO12 and BIO15, $r = -0.98$). Variance inflation factors (VIF) were then computed iteratively, removing at each step the variable with the largest VIF above 10: annual precipitation (BIO12; VIF = 41.8) and precipitation seasonality (BIO15; VIF = 20.1) were dropped, leaving seventeen predictors (maximum VIF = 9.1). Land-cover indicators, which sum to one, were excluded from this step. Annual precipitation is therefore represented only indirectly, through temperature, soil organic carbon and land cover.

MaxEnt models were fitted with maxnet 0.1.4 in R 4.5.1 (terra 1.8.93, sf 1.0.24), using linear and quadratic features, cloglog output and a regularisation multiplier of 0.5. These settings were selected among eight feature/multiplier combinations which differed little in performance (mean spatial-block AUC 0.566–0.587); because selection and evaluation used the same folds, the reported AUC may be slightly optimistic. Models used 559 presence records (553 with complete predictor values) and 10,000

background points drawn with a target-group design (Barber et al., 2022) to correct the sampling bias of GBIF records towards roads, towns and cultivated land: the 675 GBIF locations of other parkland species (P. *biglobosa*, F. *albida* and A. *digitata*) were counted on a ≈ 10-km grid, smoothed with a Gaussian kernel (≈ ± 45 km), rescaled to a mean of one with a 10% uniform floor, and used as sampling weights. The uniform-background model was refitted and tested against the same background to quantify this correction. Performance was evaluated by spatial-block four-fold cross-validation (quadrants defined by the median longitude and latitude of occurrences), with random four-fold cross-validation as a diagnostic of spatial-structure effects. Spatial-block AUC was 0.519 (near chance); the bias-corrected model did not outperform the uniform-background model. Suitability was therefore retained only as an illustrative weighting layer, not as a validated predictive surface.

Table 2
Predictors used to model *Vitellaria paradoxa* suitability.

Predictor group	Variables	Source	Representation
Climate	Annual mean temperature (BIO1); temperature seasonality (BIO4); annual precipitation (BIO12) and precipitation seasonality (BIO15), both removed after VIF screening	WorldClim 2.1	Continuous
Topography	Elevation; slope	SRTM	Continuous
Soil	SOC; clay; sand; pH; bulk density	SoilGrids 2.0	Continuous
Population	Population density (2020)	WorldPop	Continuous
Tree cover	Tree-cover fraction	ESA WorldCover	Continuous
Land cover	Six reclassified land-cover classes	ESA WorldCover	Binary layers

2.3.4. Predictor contributions

Relative model weight was calculated for six predictor groups (land cover, soil, topography, climate, tree-cover fraction and population density) plus a residual group of model terms not assigned to any of them as the sum of the absolute L1-regularised coefficients within each group, computed on coefficients rescaled to the observed range of each feature (0–1), normalised to 100%. Because this measure is a proxy for model influence rather than ecological importance, it was interpreted descriptively. Because land cover partly reflects human presence and sampling intensity, the suitability surface is interpreted as an illustrative weighting rather than a validated predictive map.

Table 3
Relative weight of predictor groups in the *Vitellaria paradoxa* suitability model (17 predictors; weights from L1-regularised coefficients rescaled by the feature range and normalised to 100%).

Predictor group	Variables represented	Relative model weight (%)
Land cover	Six reclassified land-cover classes	75.8
Soil properties	SOC, clay, sand, pH, bulk density	10.2
Topography	Elevation, slope	8.7
Climate	Annual mean temperature (BIO1), temperature seasonality (BIO4)	2.2
Unassigned model terms	Terms that could not be attributed to a single predictor (grouping residual)	2.0
Tree-cover fraction	Continuous tree-cover fraction	1.1
Population density	Human population density	< 0.01

2.4. Land-cover transition modelling and tree-cover targets

Two intervention pathways were simulated over a 20-year horizon: agroforestry enrichment of cropland/parklands (class 4), through retention, regeneration or establishment of shea and associated parkland trees, and restoration of grassy savanna and bare/degraded land (classes 3 and 5) towards shrubby savanna (class 2) through assisted natural regeneration (ANR). All other classes were held constant (Fig. 3). Tree-cover targets were conditioned on the cover already observed under comparable rainfall. Annual precipitation (BIO12) was divided into eight quantile groups (Table S1). In each group, the target was set to the 90th percentile of WorldCover 2021 tree cover in cropland/parkland cells (enrichment) or the 75th percentile in shrubby-savanna cells (restoration). The higher percentile for enrichment reflects that cropland parklands are actively managed systems in which well-stocked fields already demonstrate the cover attainable under farmer management, whereas a more conservative percentile was used for savanna restoration because assisted natural regeneration is slower and constrained by grazing, cultivation intensity and seed availability (Chomba et al., 2020; Lohbeck et al., 2020). This stratified approach is a simplified proxy for the k-nearest-neighbour space-for-time substitution of Kiziridis et al (2026) and allows targets to follow the climatic gradient rather than a single national value. Because a single land-cover date was used, reference cells could not be screened for stability, and some may be recently degraded or recovering. For each eligible cell *i*, the increase in tree cover was the positive difference between target and baseline cover, weighted by MaxEnt suitability:

$$\Delta\,\mathrm{T}C_i = \max(0, T_{cs}^{target} - T_{base}^{Ci}) \times\ S_i$$

1

where $\Delta\,\mathrm{T}C_i$ is the suitability-weighted increase in tree cover for pixel *i*, $T_{cs}^{target}$is the reference tree-cover target for precipitation stratum s and intervention class c, is T_{base}^{Ci}baseline tree cover, and S_i is the MaxEnt suitability index ranging from 0 to 1. Suitability weighting reduces gains in ecologically marginal pixels, where establishment risk is higher, and corrects the spatial anti-correlation between suitability (highest in the wetter south-west) and the fixed-target carbon layer (highest in the drier, tree-poor north).

2.5. Carbon sequestration estimation

Two carbon components were quantified: vegetation carbon and soil organic carbon (SOC). Both respond to the modelled interventions and together form the intervention gain used in the scenario analysis.

2.5.1. Vegetation carbon

Vegetation-carbon gain was estimated from the suitability-weighted increase in tree cover. For each eligible cell, the increase in tree cover was multiplied by an indicative coefficient of 0.7 Mg C ha⁻¹ per percentage point of tree cover, adopted from published biomass estimates for West African shea and African locust bean parklands (Dayamba et al., 2016; Dimobe et al., 2018). The same coefficient was applied to the savanna-restoration pathway in the absence of a class-specific estimate, which increases uncertainty for that pathway. The pools, allometric equations and tree densities underlying the coefficient are detailed in Additional file 1; the supporting plot-level compilation remains to be completed from primary data. The 20-year increment was:

$$\Delta\, C_{\mathrm{veg,i}} = \Delta\,\mathrm{T}C_i \,\mathrm{x}\, 0.7$$

2

Where $\Delta\, C_{\mathrm{veg,i}}$ is the vegetation-carbon gain (Mg C ha⁻¹) and $\Delta\,\mathrm{T}C_i$ is the suitability-weighted increase in tree cover (percentage points, Eq. 1). The resulting stock change was divided by 20 to obtain the annualised vegetation-carbon gain. Reaching the target cover within 20 years is optimistic for a slow-growing species such as *V. paradoxa*; it assumes that enrichment relies mainly on protecting and regenerating existing stems and rootstock rather than on new planting, and the coefficient was varied between 0.4 and 1.0 Mg C ha⁻¹ per percentage point (Section 3.7) to bound this uncertainty.

2.5.2. Soil organic carbon

Baseline SOC stock (0–30 cm) was obtained from SoilGrids 2.0 (Poggio et al., 2021) and harmonised to the 1 km grid. In cells where tree cover increased ($\Delta TC_i > 0$), SOC was assumed to increase linearly by 10% of the baseline stock over 20 years:

$$\Delta\, C_{SOC,i}, = 0.10 \times\ C_{SOC,base,i}$$

3

$$\Delta\, C_{SOC,annual,i} = \frac{\Delta\, C_{SOCi,nx}}{20}$$

4

This uniform rate is a simplification: Takimoto et al. (2008, 2009) found limited additional SOC in established parklands, so the accrual fraction was varied between 5% and 20% (Section 3.7). No business-as-usual baseline was modelled; given ongoing parkland tree loss, gains are expressed relative to current stocks rather than to a declining counterfactual.

Vegetation and SOC gains were set to zero in stable and excluded classes using a 0/1 indicator raster.

2.5.3. Integration and annualization of carbon components

Vegetation-carbon and SOC gains were expressed on a common annual basis and summed to form the intervention gain. Vegetation-carbon and SOC stock changes projected over the 20-year intervention horizon were annualised by dividing their respective changes by 20. The total annual modelled carbon gain for pixel *i* was therefore calculated as:

$$\Delta\, _{Cannual,i} = \frac{\Delta\, \mathrm{C}_{Veg,i}}{20} + \frac{\Delta\, \mathrm{C}_{SOC,i}}{20}$$

5

where $\Delta\, \mathrm{C}_{Veg,i}$ and $\Delta\, \mathrm{C}_{SOC,i}$ represent the projected 20-year changes in vegetation and soil organic carbon stocks (Mg C ha⁻¹), respectively.

Total annual carbon gain was converted to CO_2 equivalents using the molecular-weight ratio of CO_2 to elemental carbon (44/12 = 3.67):

$$\Delta\, CO_{2\mathrm{eq,i}} = \Delta\, C_{\mathrm{annual,i}} \times\ 3.67$$

6

The resulting raster, expressed as Mg CO_2-eq ha⁻¹ yr⁻¹, represented the spatially explicit annualised carbon-gain metric used in the subsequent scenario analysis and multi-objective optimisation. These values represent modelled biophysical gains under the stated assumptions rather than measured net ecosystem carbon sequestration.

2.6. Scenario construction

A threshold-based scenario framework was used to identify areas suitable for agroforestry enrichment or savanna restoration under alternative biophysical and land-use constraints. Candidate pixels were restricted to the three intervention classes (grassy savanna, cropland/parklands and bare/degraded land); forest/gallery forest, shrubby savanna and the residual class were not eligible. Within these classes, cells were selected using four criteria:

- - a minimum shea suitability, to avoid ecologically marginal cells (0.25–0.80 in steps of 0.05);
- - a maximum slope, to exclude steeper, erosion-prone and less accessible land (0, 1, 2, 4, 6, 8, 12 and 16°). Because Burkina Faso is mostly flat, apart from escarpments such as around Banfora, this criterion has limited effect;
- - a maximum baseline tree cover, because already wooded cells offer little scope for gain (10, 20, 30, 40 and 50%);
- - a protection regime, strict or relaxed. Under the strict regime, cells inside nationally designated protected areas (national parks, wildlife and game reserves, classified forests and ecological corridors) were excluded, using the polygons of the World Database on Protected Areas (WDPA; UNEP-WCMC & IUCN, 2026; November 2026 release, site type PA). Ramsar, biosphere-reserve and World Heritage polygons were not treated as exclusions because they are overlay designations without land-use restrictions, and designation rather than IUCN category was used because most Burkinabè classified forests are not assigned a category. These areas cover 15.9% of the valid cells (4.26 million ha). Under the relaxed regime no exclusion was applied.

Of the 960 threshold combinations (12 × 8 × 5 × 2 protection regimes), 940 produced a non-empty area of interest; 10 strict-regime scenarios were identical to their relaxed counterparts (no protected area intersected the selection) and were removed, leaving 930 distinct scenarios. For each threshold combination, pixels satisfying all criteria were retained as the scenario-specific area of interest. Three summary metrics were then calculated: selected area (ha), mean annual modelled CO_2-equivalent gain (Mg CO_2-eq ha^{-1} yr^{-1}), and total annual modelled CO_2-equivalent gain (Mg CO_2-eq yr^{-1}). Raster layers were extracted as numeric vectors over the valid national grid and assessed using vectorised operations. This approach, instead of repeated raster-algebra calls, reduced runtime by about two orders of magnitude without changing results and allowed for systematic comparison of the scenario space.

2.7. Multi-objective optimisation and statistical analysis

Scenario performance was evaluated using two complementary objectives: mean annual modelled CO_2-equivalent gain per unit area (Mg CO_2-eq ha^{-1} yr^{-1}) and total annual modelled CO_2-equivalent gain (Mg CO_2-eq yr^{-1}). These objectives represent the trade-off between concentrating interventions in smaller areas with high per-hectare gains and expanding interventions across larger areas to maximise aggregate carbon benefits. Non-dominated scenarios were identified using Pareto optimisation. A scenario was considered Pareto-optimal when no alternative scenario simultaneously produced both a higher mean and a higher total annual CO_2-equivalent gain. The resulting Pareto front therefore represented the set of scenarios for which improvement in one objective required a trade-off in the other.

To identify a representative compromise along the Pareto front, mean gain, total gain and selected area were min-max normalised. A composite efficiency score was calculated by combining the scaled mean and total gains while penalising increasing intervention area. The point of maximum curvature of this composite score, ordered along the Pareto front, was then located following the inflection-point approach of Christopoulos (2019). Because the realised front is discontinuous, the curvature criterion is

sensitive to the threshold grid; its result is therefore reported descriptively as the most efficient scenario rather than as a definitive knee point. Intervention regimes were defined directly by minimum-suitability bands along the front: conservative ≥ 0.60, balanced 0.45–0.55 and expansive ≤ 0.40. In the realised front, every Pareto-optimal scenario had a minimum suitability of 0.70–0.80 or 0.25, so the balanced band contained none. These bands represent increasingly broader spatial intervention strategies rather than normative policy rankings. The representative scenario of the conservative and expansive regimes is the one with the largest total gain in its band, and that of the balanced regime is the median scenario of its band. To test whether the front adds more than the dilution expected whenever a larger area is averaged, each Pareto-optimal scenario was compared with 20 equal-area random selections of eligible pixels. A generalised additive model (GAM; mgcv package) relating the efficiency score to the scenario thresholds was fitted as an exploratory check only. Because the GAM was fitted to a small, optimisation-selected set of scenarios, its explained deviance indicates overfitting rather than explanatory power and is not interpreted. Drivers along the front were instead characterised descriptively by extracting, for each Pareto-optimal scenario, the pixel-level distribution (5th -95th percentile) of each threshold variable and environmental covariate within the selected area.

2.7.1. Regional synthesis and spatial prioritisation

Scenario outputs were additionally summarised across the 13 former administrative regions (Section 2.2). Regional mean (Mg CO_2-eq ha^{-1} yr^{-1}) and total (Mg CO_2-eq yr^{-1}) annual gains were calculated from the intervention-gain layer, with totals obtained by multiplying each cell's per-hectare value by its geodesic area before summing. Pixel-level selection frequency was determined by the percentage of valid scenarios where each pixel met the specific eligibility criteria. This shows how often locations were chosen across different threshold combinations. For each region, selection frequency was summarized using two metrics: selection extent, which is the average proportion of regional area selected across scenarios, and spatial patchiness, shown by the variation in pixel-level selection frequency within the region. Lastly, land-cover contributions to the total modeled gain were compared among conservative, balanced, and expansive scenarios to see how the main intervention land-cover class changed with the scale of intervention.

3. Results

3.1. Spatial variation in modelled carbon components

The two carbon components differed in spatial pattern and magnitude (Fig. 4). Vegetation-carbon gains were concentrated where baseline tree cover was furthest below the precipitation-stratified target and shea suitability was relatively high. Consequently, stable land-cover classes showed no vegetation-carbon change, whereas eligible cropland/parklands, grassy savanna and bare/degraded land accounted for the projected increases. Projected SOC followed a similar intervention-specific pattern but remained closely related to baseline SOC because the model applied a 10% increase to the baseline stock over the 20-year projection period. Consequently, the absolute SOC increment was larger in pixels with higher

initial SOC, while stable and excluded land-cover classes showed no modelled intervention-related change. At national scale, vegetation carbon contributed 2.51 million Mg CO_2-eq yr^{-1} (48.8%) and SOC 2.64 million Mg CO_2-eq yr^{-1} (51.2%) of the 5.15 million Mg CO_2-eq yr^{-1} intervention gain, equivalent to grid means of 0.094 and 0.098 Mg CO_2-eq ha^{-1} yr^{-1}, respectively. The split was almost identical in the representative conservative and expansive scenarios (48.9% and 48.8% vegetation, respectively), so the modelled gain rests about equally on the tree-cover coefficient and on the uniform 10% SOC accrual assumption .

3.2. Scenario performance and Pareto trade-offs

Of the 960 threshold combinations, 940 produced a non-empty area of interest; after removing 10 strict-regime scenarios identical to their relaxed counterparts, 930 distinct scenarios remained (470 relaxed, 460 strict). Across them, mean modelled annual gain ranged from 0.17 to 0.38 (median 0.27) Mg CO_2-eq ha^{-1} yr^{-1}, selected area from about 170 ha to 19.0 million ha (median 11.9 million ha), and total annual gain reached 5.11 million Mg CO_2-eq yr^{-1} without exclusion and 4.41 million with exclusion of protected areas. Forty-one scenarios were Pareto-optimal (Fig. 5a), 37 relaxed and 4 strict. The front consists of two segments separated by a gap, between 3.34 and 15.6 million ha, in which no scenario was optimal. The lower segment (33 scenarios; minimum suitability 0.70–0.80) spans 0.68–3.34 million ha, with mean gain falling from 0.38 to 0.30 Mg CO_2-eq ha^{-1} yr^{-1} and total gain rising from 0.25 to 1.0 million Mg CO_2-eq yr^{-1}. The upper segment (8 scenarios; minimum suitability 0.25) spans 15.6–19.0 million ha at 0.27–0.28 Mg CO_2-eq ha^{-1} yr^{-1} and 4.4–5.1 million Mg CO_2-eq yr^{-1}. The curvature criterion selected a scenario of the lower segment (minimum suitability 0.70, maximum slope 4°, maximum tree cover 10%, no protection exclusion), covering 3.23 million ha at 0.30 Mg CO_2-eq ha^{-1} yr^{-1} and 0.97 million Mg CO_2-eq yr^{-1}; because of the discontinuity this is reported descriptively. Total gain scaled almost in proportion to area: the largest conservative scenario selected 17.6% of the area of the largest expansive scenario and delivered 19.5% of its total gain, at a mean gain only 10% higher (0.298 versus 0.270 Mg CO_2-eq ha^{-1} yr^{-1}). Relative to 20 equal-area random selections of eligible pixels, Pareto-selected areas delivered 1.00–1.39 times higher mean gain (mean 1.20; 1.00–1.28 for scenarios above 1 million ha; Fig. 5b). The advantage was largest for the smallest areas (×1.39 at 0.68 million ha) and vanished for the expansive regime (×1.00), whose largest scenario covers 99.7% of the 19.0 million ha of eligible land. The protection regime had a measurable cost. For identical thresholds, excluding nationally designated protected areas reduced the selected area by a median of 17% (up to 50%) and the total gain by a median of 14%; the largest strict scenario selected 15.8 million ha for 4.41 million Mg CO_2-eq yr^{-1}. In the lower segment, strict scenarios were dominated by relaxed ones; four strict scenarios were retained in the upper segment because their mean gain was slightly higher (0.279 versus 0.270 Mg CO_2-eq ha^{-1} yr^{-1}) despite a lower total. The two intervention regimes, defined by minimum-suitability bands, are summarised in Table 4.

Table 4
Intervention regimes along the Pareto front, defined by minimum-suitability bands. Ranges refer to Pareto-optimal scenarios; no Pareto-optimal scenario fell in the balanced band. Representative scenario: largest total gain in the band.

Regime	Minimum-suitability band	Pareto-optimal scenarios	Selected area (million ha)	Mean gain (Mg CO_2-eq ha^{-1} yr^{-1})	Representative scenario (million ha; million Mg CO_2-eq yr^{-1})
Conservative	≥ 0.60	33	0.68–3.34	0.30–0.38	3.34; 1.00
Balanced	0.45–0.55	0	—	—	—
Expansive	≤ 0.40	8	15.6–19.0	0.27–0.28	18.96; 5.11

3.3. Drivers along the Pareto front

Scenario characteristics changed systematically along the Pareto front (Fig. 6a). Mean per-hectare gain declined, in steps, as total gain and selected area increased, illustrating the progressive dilution of carbon benefits as interventions expanded. Minimum suitability was the dominant structuring threshold: Pareto-optimal scenarios used 0.80, 0.75 or 0.70 in the conservative regime and 0.25 in the expansive regime, with none in between, and the median suitability of the selected cells fell from about 0.84 to 0.74 within the conservative regime and to about 0.62 in the expansive regime. Maximum tree cover (10–50%) and maximum slope (1–6° in the conservative regime, 6–8° in the expansive regime) acted as secondary constraints; because the median slope of the selected cells stayed near 0.3° and their median tree cover below about 1% in every scenario, tightening these thresholds at fixed suitability barely changed the outcome, consistent with the near planar relief and sparse woody cover of the country. Environmental conditions shifted concurrently: the median elevation of the selected cells rose from about 200 m to about 300 m, annual precipitation fell from roughly 860 to 740 mm and mean annual temperature declined slightly (about 28.6 to 28.2°C), whereas topsoil clay stayed near 21%. Increasing intervention scale therefore progressively incorporated less suitable land at slightly higher elevation and with lower rainfall.

Land-cover composition reinforced this transition (Fig. 6b). The conservative scenarios selected relatively small areas in which cropland/parklands made up about 60% (about 2.0 of the 3.3 million ha of the largest conservative scenario). In the expansive regime, grassy savanna became the largest class (about 10.8 of 19.0 million ha), with cropland/parklands covering about 7.5 million ha and bare/degraded land under 1 million ha. The sharp increase in selected area towards the expansive end therefore resulted primarily from extending intervention eligibility from agricultural parklands into broader savanna landscapes, whereas forest/gallery forest, shrubby savanna and the residual class were excluded from selection at every threshold combination (Section 2.6).

3.4. Regional patterns of modelled gain and spatial selection

Regional patterns varied markedly depending on whether performance was expressed as per-hectare carbon gain, total carbon potential, or consistency of selection across scenarios (Table 5). Raster-based mean annual gains were highest in Sud-Ouest (Djôrô; 0.394 Mg CO_2-eq ha^{-1} yr^{-1}) and Cascades (Tannounyan; 0.393), followed by Haut-Bassins (Guiriko; 0.313), Centre-Sud (0.237) and Centre-Est (0.235). Regional totals, computed by weighting each cell by its geodesic area, were largest in Haut-Bassins (0.79 million Mg CO_2-eq yr^{-1}), Est (0.77 million), Cascades (0.71 million) and Sud-Ouest (0.62 million) and sum to the national total of 5.15 million Mg CO_2-eq yr^{-1}. However, these regions did not necessarily have the greatest spatial extent of intervention, indicating that high carbon-gain intensity and broad intervention potential were spatially distinct.

Across the scenario ensemble, Centre-Est had the highest mean selection extent, with 55.8% of its area selected, followed by Plateau-Central (48.4%) and Est (46.0%) (Fig. 7). In contrast, scenario-averaged total contributions were highest in Est (465,332 Mg CO_2-eq yr^{-1}), Haut-Bassins (376,245), Sud-Ouest (332,946) and Boucle du Mouhoun (273,054). These contrasts show that regional contribution depended on both the carbon-gain intensity of selected pixels and the amount of land repeatedly satisfying the scenario constraints.

The Sahel had the lowest raster-based mean gain of any region, 0.077 Mg CO_2-eq ha^{-1} yr^{-1}, and a mean selection extent of 32.2%, but only the ninth-largest scenario-averaged total contribution (99,647 Mg CO_2-eq yr^{-1}). Spatial patchiness was highest in the south-west, in Cascades (CV = 1.31), Sud-Ouest (1.05) and Haut-Bassins (1.00), where selection was concentrated in a minority of cells, and lowest in Centre-Nord (0.52) and Centre-Est (0.54). The south-western regions therefore combine the highest per-hectare gains with the most spatially concentrated opportunities, whereas the Sahel offers little gain per hectare over a moderately extensive area.

Table 5
Regional annual CO_2-eq gain and scenario-based selection. Mean (Mg CO_2-eq ha^{-1} yr^{-1}) and total (Mg CO_2-eq yr^{-1}) gains refer to the intervention gain; other metrics summarise the scenario ensemble.

Region	Raster mean (Mg CO_2-eq ha^{-1} yr^{-1})	Raster total (Mg CO_2-eq yr^{-1})	Selection extent (%)	Patchiness (CV)	Scenario mean total (Mg CO_2-eq yr^{-1})
Sud-Ouest	0.394	623,702	28.7	1.05	332,946
Cascades	0.393	710,864	13.3	1.31	232,545
Haut-Bassins	0.313	792,297	27.2	1.00	376,245
Centre-Sud	0.237	269,290	42.7	0.74	157,571
Centre-Est	0.235	338,459	55.8	0.54	243,388
Centre-Ouest	0.185	395,162	43.0	0.69	237,220
Est	0.169	772,472	46.0	0.65	465,332
Boucle du Mouhoun	0.143	487,227	37.2	0.76	273,054
Plateau-Central	0.140	119,698	48.4	0.57	75,588
Centre	0.114	31,174	38.8	0.75	18,230
Centre-Nord	0.099	194,358	41.2	0.52	98,682
Nord	0.091	142,888	35.7	0.61	68,562
Sahel	0.077	273,075	32.2	0.61	99,647

3.5. Regional prioritisation and shifts in dominant intervention land cover

Regional intervention potential varied substantially across Burkina Faso and depended on whether priority was expressed as selection extent, spatial consistency, or total modelled carbon contribution (Fig. 8a–c). These maps reproduce the indicators reported in Section 3.4, Table 5 and Fig. 7. The dominant land-cover contributor also changed with intervention regime (Fig. 8d–e; no balanced scenario was Pareto-optimal). Under the representative conservative scenario (3.34 million ha), cropland/parklands dominated twelve of the thirteen regions (57–100% of regional gain), whereas grassy savanna dominated only in Est (65%), which also had the largest conservative total (about 0.46 million Mg CO_2-eq yr^{-1}), followed by Centre-Est (about 0.17 million) and Sud-Ouest (about 0.09 million). Under the representative expansive scenario (18.96 million ha), grassy savanna became the dominant contributor in five northern, eastern and south-western regions (Sahel 80% of regional gain,

Est 69%, Centre-Nord 63%, Sud-Ouest 63% and Nord 54%), while cropland/parklands remained dominant in the other eight (52–75%), led by Haut-Bassins (about 0.78 million Mg CO_2-eq yr^{-1}), Cascades (about 0.70 million) and Boucle du Mouhoun (about 0.49 million).

3.6. National patterns of agroforestry suitability and carbon gain

Spatial-block cross-validation of the bias-corrected suitability model gave a mean test AUC of 0.519 (north-east 0.441, south-east 0.528, north-west 0.552, south-west 0.555), close to chance and no higher than the 0.532 obtained with the uniform-background model (Fig. 10b); the north-east block performed worst. Land cover carried by far the largest share of model weight (75.8%), followed by soil properties (10.2%), topography (8.7%) and climate (2.2%), whereas tree-cover fraction (1.1%) and population density (< 0.01%) contributed little (Table 3; Fig. 10a). Correcting the sampling bias also changed the suitability surface considerably: its rank correlation with the uniform-background surface was moderate (Spearman $\rho = 0.42$), and the overlap of cells with suitability ≥ 0.75 was low (Jaccard index 0.09; 0.41 for ≥ 0.60). Agroforestry suitability showed a clear north-south gradient (Fig. 9a), with low values across much of the Sahelian north and higher values across the southern two-thirds of Burkina Faso, although cells with suitability ≥ 0.65 within the eligible land-cover classes still cover up to about 6.7 million ha. In contrast, modelled carbon gains were more spatially concentrated (Fig. 9b). Most areas remained below 0.5 Mg CO_2-eq ha^{-1} yr^{-1}, while hotspots reaching approximately 2.8 Mg CO_2-eq ha^{-1} yr^{-1} occurred mainly in Tannounyan (former Cascades) and southern Djôrô (former Sud-Ouest). This contrast shows that high suitability alone did not necessarily translate into high carbon gain. The 20-year projection (Fig. 9c–d) illustrates the corresponding landscape transition, with eligible cropland/parklands shifting towards enriched parklands and eligible savanna and degraded areas towards restored savanna. Overall, the results indicate that the strongest intervention opportunities are spatially concentrated where favourable suitability coincides with greater potential for tree-cover increase.

(a) Agroforestry parkland suitability – Burkina Faso

Figure 10. Suitability model diagnostics: (a) relative contribution of predictor groups (%); (b) spatial-block test AUC per quadrant for uniform- and target-group-background models (dashed line: AUC = 0.5).

3.7. Sensitivity of modelled gains to the uncalibrated carbon coefficients

Two coefficients in the intervention-gain model are standard values used nationwide: the tree-cover-gain-to-carbon ratio (0.7 Mg C ha^{-1} per percentage point) and a fixed 10% SOC accrual fraction over 20 years. Since each main figure is a deterministic multiplicative function of these two constants, their impact was measured using a one-at-a-time sensitivity analysis (Table 6). This involved changing each within a range informed by literature while keeping the other and all scenario thresholds constant. Their combined

effect was then assessed using a Monte Carlo analysis (2,000 uniform draws of both coefficients) for the representative conservative (3.34 million ha) and expansive (18.96 million ha) scenarios.

Across the tested ranges, the vegetation coefficient (0.4–1.0 Mg C ha^{-1} per percentage point) changed total sequestration symmetrically by ± 20.9%, identically at national scale and in both representative scenarios, whereas the SOC accrual fraction (5–20%) changed it by − 25.6% to + 51.2% (Table 6; Fig. 11a). Each response equals the relative change in the coefficient multiplied by that component's share of the gain (about 49% vegetation and 51% SOC; Section 3.1); the SOC response is asymmetric because its range extends twice as far above the 10% baseline as below it. Neither coefficient dominates, so both would need field constraint. The joint Monte Carlo propagation gave a median of 0.34 Mg CO_2-eq ha^{-1} yr^{-1} (90% interval 0.21–0.47) and 1.13 million Mg CO_2-eq yr^{-1} (0.70–1.56 million) for the conservative scenario, and 0.31 Mg CO_2-eq ha^{-1} yr^{-1} (0.19–0.42) and 5.80 million Mg CO_2-eq yr^{-1} (3.63–8.01 million) for the expansive scenario (Fig. 11b). In both, the deterministic value (0.30 and 0.27 Mg CO_2-eq ha^{-1} yr^{-1}) lay near the 34th percentile of the draws, because the mean of the uniform SOC distribution (12.5%) exceeds the 10% baseline. These ranges should be read as the minimum plausible uncertainty in every headline figure reported above: they hold scenario thresholds fixed and therefore exclude the additional uncertainty that would arise from re-optimising the Pareto front under each coefficient draw (Section 4.5).

Table A2
Tree cover implied by published carbon stocks for three values of the coefficient k (implied cover = stock / k). This is an internal plausibility check, not a validation: pools and cover measurements were not harmonised across sources, and plot-level calibration of k is left for future work.

Source (carbon pools)	**Reported stock (Mg C ha^{-1})**	**Implied cover, k = 0.4 (%)**	**Implied cover, k = 0.7 (%)**	**Implied cover, k = 1.0 (%)**
Dimobe & Bayala (2023), shea parklands	12.8	32.0	18.3	12.8
Sanou et al. (2025), Sahel zone (aboveground)	2.3–3.4	5.8–8.5	3.3–4.9	2.3–3.4
Sanou et al. (2025), Sudan zone (aboveground)	6.1–8.1	15.3–20.3	8.7–11.6	6.1–8.1

Table 6
One-at-a-time sensitivity of sequestration estimates to the two uncalibrated gain coefficients (thresholds fixed). National means cover 320,863 valid pixels (0.00833° grid; ≈ 268,000 km²).

Coefficient	Level	National mean (Mg CO_2-eq ha^{-1} yr^{-1})	National Δ%	Conservative Δ%	Expansive Δ%
Vegetation (Mg C ha − 1 per % tree cover)	Low (0.4)	0.152	−20.9%	−20.9%	−20.9%
Vegetation (Mg C ha − 1 per % tree cover)	Baseline (0.7)	0.192	n/a	n/a	n/a
Vegetation (Mg C ha − 1 per % tree cover)	High (1.0)	0.232	+ 20.9%	+ 20.9%	+ 20.9%
SOC accrual fraction (20 year)	Low (5%)	0.143	−25.6%	−25.6%	−25.6%
SOC accrual fraction (20 year)	Baseline (10%)	0.192	n/a	n/a	n/a
SOC accrual fraction (20 year)	High (20%)	0.290	+ 51.2%	+ 51.1%	+ 51.2%

4. Discussion

4.1. Agroforestry restoration shows a weak intensity–scale trade-off along a discontinuous Pareto front

The central result of this study is not a single optimal intervention but the shape of the trade-off itself. Along the Pareto front, mean per-hectare gain fell by less than a third (from 0.38 to 0.27 Mg CO_2-eq ha^{-1} yr^{-1}) while the intervention area increased nearly thirty-fold (from 0.68 to 19.0 million ha), and the front was discontinuous, with no Pareto-optimal scenario between 3.34 and 15.6 million ha. Returns therefore diminish, but only weakly: the first hectares selected combine high suitability, a large tree-cover deficit and good soils, yet each additional hectare is only slightly less productive. Global restoration analyses rest on the same logic and report up to 13-fold gains in cost-effectiveness when restoration is spatially optimised rather than spread uniformly (Strassburg et al., 2020); within a single Sudano-Sahelian country and a single intervention type, the equivalent gain is much smaller because per-hectare carbon gain varies within a narrow range. Part of the decline is mechanical, as lowering thresholds necessarily reduces the average. Pareto-selected areas nevertheless outperformed equal-area random selections by up to 1.39 times at small extents, so the front captures environmental structure rather than simple dilution; this advantage disappeared as the selection approached all eligible land.

The ecological nature of that structure is consistent with a north–south climatic gradient. Independent field evidence from Burkina Faso shows that aboveground carbon in agroforestry systems rises from 2.3–3.4 Mg C ha^{-1} in the Sahel zone to 6.1–8.1 Mg C ha^{-1} in the Sudan zone (Sanou et al., 2025), and parkland stocks measured across three climatic zones follow the same gradient (Neya et al., 2020). Extending restoration targets northwards therefore tends to encounter lower woody-biomass ceilings (Bayala & Harmand, 2023; Dimobe et al., 2020; Fané et al., 2024). In absolute terms, the gain of the most efficient scenario (0.30 Mg CO_2-eq ha^{-1} yr^{-1}, ≈ 0.08 Mg C ha^{-1} yr^{-1}) lies at or below the lower end of accumulation rates reported for West African parklands (Bayala et al., 2020; Dayamba et al., 2016; Luedeling & Neufeldt, 2012). Two aspects of the model clarify this comparison. Field values mainly represent whole-system stocks in established parklands, whereas the model estimates only the increment possible within 20 years under locally observed cover targets. The comparison is therefore one of order of magnitude; the Monte Carlo interval confirms that the values are modelled biophysical potential rather than measured sequestration. Luedeling & Neufeldt (2012) argued that in the Sahel adaptation should take precedence over mitigation. The moderate gains found here are consistent with that position: parkland enrichment is more readily justified by its contribution to soils, food and income, with carbon as a co-benefit, than by carbon alone.

4.2. Carbon-gain hotspots occupy a narrower domain than agroforestry suitability

The national maps reveal a pronounced spatial decoupling between the ecological suitability of *V. paradoxa* and the potential for additional carbon sequestration. While climatic suitability extends across much of southern Burkina Faso the largest modelled carbon gains are confined to a narrower south-western domain. This contraction is not an artefact of the optimisation; it follows from the fact that carbon gain is a residual quantity. High projected gains require both favourable conditions for tree growth and a substantial deficit relative to the precipitation-stratified reference tree cover, together with contributions from baseline soil organic carbon (Zomer et al., 2022). In many areas of high suitability, existing parkland densities already approach or exceed these reference levels, so that the incremental biomass that can still be accumulated is limited (Bayala et al., 2020; Chomba et al., 2020).

Field evidence supports this interpretation. Inventories across Sudanian parklands show that aboveground carbon stocks are controlled primarily by stem density, diameter structure and the presence of large individuals rather than by climatic suitability alone (Neya et al., 2020; Sanou et al., 2025; Yabi et al., 2025). Moreover, many shea stands lack recruitment: trees frequently exhibit DBH > 24 cm with few or no juveniles, indicating that current densities reflect historical management and past regeneration rather than present climatic potential (Dimobe & Bayala, 2023; Dayamba et al., 2016; Ouoba et al., 2019). Under such conditions, further densification may be constrained by competition, farmer preferences or the absence of protective institutions, even where the climate remains favourable. Size-dependent carbon allocation further modulates the outcome: root-to-shoot ratios decline with increasing crown area, so that additional large trees store proportionally less below-ground carbon than the same biomass added as smaller stems.

The south-western concentration of gains is consistent with higher measured stocks in the Sudanian zone (Neya et al., 2020). Yet the optimisation demonstrates that the locations maximising suitability, carbon gain and intervention extent do not coincide. Continental restoration targets that treat high suitability as a proxy for high restoration opportunity therefore risk both over-targeting already wooded landscapes and underestimating residual deficits in more open systems (Bond et al., 2019). An additional source of uncertainty is the systematic under-detection of isolated parkland trees in coarse tree-cover products. Sub-metre mapping has revealed more than 1.8 billion individual trees across the West African Sahara, Sahel and sub-humid zone, many of them larger in managed farmlands than in unmanaged savannas (Brandt et al., 2020). Where baseline layers miss these trees, modelled deficits and gains should be regarded as upper-bound estimates. Collectively, these findings argue for spatially differentiated strategies that prioritise residual deficit and structural opportunity rather than suitability alone.

4.3. Scaling restoration changes the dominant intervention pathway

As intervention scale increases, the dominant pathway shifts from parkland enrichment to the restoration of grassy savanna (Section 3.5). At restricted scales, the model mainly identifies opportunities to increase tree cover within managed cropland, building on the defining feature of West African parklands, where useful trees are retained, protected or regenerated in fields (Fané et al., 2024; Lohbeck et al., 2020). Larger targets exhaust these opportunities and require assisted natural regeneration across savanna landscapes (Goffner et al., 2019; Haglund et al., 2011; Weston et al., 2015). The two pathways are not equivalent. Regeneration in savannas is constrained by grazing and cultivation intensity and by distance to seed trees (Chomba et al., 2020; Lohbeck et al., 2020), so the second pathway is slower and less certain than the enrichment of existing parklands. The Pareto trade-off is therefore a change not only in intervention area but also in the landscape process required to obtain additional carbon. This shift raises an ecological question that carbon accounting alone cannot answer. Grassy savannas are not necessarily degraded woodlands; many are long-standing ecosystems maintained by fire and herbivory, whose biodiversity and services depend on an open canopy (Bond et al., 2019; Veldman et al., 2015). Increasing their tree cover can therefore reduce rather than restore their ecological value. The grassy savanna mapped by WorldCover in Burkina Faso is likely to include fallows and degraded former cropland, where woody regeneration is a legitimate goal, but also functional open savanna and rangeland on which pastoral livelihoods depend. The expansive regime should therefore not be read as a mandate to densify all grassy savanna: distinguishing degraded land from naturally open grassland, through field verification and with local land users, is a precondition for that pathway. Gains in the conservative regime, which come mostly from cropland already managed as parkland, are much less exposed to this concern. Finally, the negligible contribution of forest and gallery forest shows that modelled gains come from working landscapes rather than from the conversion of remaining woody ecosystems, so they complement rather than replace forest protection.

4.4. Regional contrasts argue against a single national restoration strategy

Regional contrasts show that per-hectare potential, intervention extent and total contribution are distinct dimensions of opportunity (Table 5). A national programme guided by a single carbon map would therefore misallocate effort (Strassburg et al., 2020). The Sahel illustrates the problem at the margin. Across scenarios it was selected over about a third of its area, with low patchiness (CV = 0.61), yet it had the lowest mean gain of any region (0.077 Mg CO_2-eq ha^{-1} yr^{-1}), so extensive intervention there would deliver little carbon per unit of effort, whereas the south-western regions combine the highest per-hectare gains with spatially concentrated opportunities. The conservative and expansive regimes, separated by a gap in which no scenario was Pareto-optimal, are best read as alternative planning envelopes, each suited to a different policy objective, rather than as a ranking.

4.5. Uncertainty and limitations

The results should be interpreted in light of several modelling constraints. Spatial-block validation of the suitability model was modest and geographically variable (Section 3.6), indicating limited spatial transferability. Because suitability weights projected tree-cover gains, this uncertainty propagates through the carbon and optimisation results. Land cover accounted for the largest share of model weight (75.8%; Section 3.6); given that shea occurrence partly reflects long-term farmer management, the model may partly identify existing parkland landscapes rather than purely biophysical suitability. The strong contribution of cropland/parklands to projected gains should therefore not be read as independent evidence of intrinsic superiority. Additional uncertainty arises from the additive treatment of vegetation carbon and SOC, from literature-derived coefficients applied nationally, and from residual sampling bias (spatial-block AUC did not improve after bias correction: 0.519 versus 0.532). Because the corrected block AUC is close to chance, suitability is best read as a relative prioritisation index used to weight tree-cover gains, not as a predictive map of shea occurrence. The tree-cover fraction is both a predictor and the baseline of the target, a further minor source of circularity. The precipitation-stratified tree-cover target remains a modelling proxy rather than an empirically demonstrated endpoint. These limitations do not negate the spatial trade-offs identified, but absolute carbon values should not yet be treated as MRV-ready estimates. For carbon-accounting use, three further issues apply. Permanence: the modelled gains are stock changes over a fixed 20-year horizon under an assumption of continued management and are not tested against reversal through drought, fire, tenure change or renewed clearing; projected climate change is also expected to reduce the area favourable to shea by about 12–13% by 2070 (Dimobe et al., 2020). Leakage: scenarios are defined pixel by pixel without a landscape-level land-use constraint, so gains in selected areas could be offset by displaced activity elsewhere. Uncertainty: the Monte Carlo propagation covers only the two carbon coefficients for a fixed scenario; a full envelope would require jointly varying the tree-cover targets and suitability surface and re-deriving the Pareto front. Finally, the analysis represents biophysical opportunity rather than implementation feasibility. Protected areas were handled through a strict/relaxed protection regime based on nationally designated protected areas (WDPA, November 2026). Without exclusion, 25.2% and 16.5% of the area of the largest conservative and

expansive scenarios fell inside these areas (8.2% and 2.3% inside IUCN categories Ia–III only), so the relaxed regime overstates what is implementable; for identical thresholds, the strict regime reduced the selected area by a median of 17% and the total gain by a median of 14%. The strict regime is a legal-designation filter only: it does not consider management effectiveness, and it does not remove cells that lie outside designated areas but are subject to other restrictions. Farmer preferences, tenure, labour and security constraints were not incorporated. Livestock-mediated carbon and grazing pressure were also not modelled: manure carbon is a present-day flux that the interventions do not change, and high grazing pressure may limit natural regeneration (Lohbeck et al., 2020), so the expansive regime may overstate what savanna restoration can achieve. Insecurity is particularly binding in Burkina Faso: terrorist violence has reduced farmed plots and short-term investment (Kafando & Sakurai, 2025), making the long-term tree management assumed here unlikely to be sustained, especially under the expansive regime. The framework is therefore most useful as a first-stage spatial decision-support tool.

5. Conclusions

This study linked shea suitability, land-cover transitions and carbon gains through multi-objective optimisation to prioritise parkland enrichment and savanna restoration across Burkina Faso. Of 930 distinct scenarios, 41 were Pareto-optimal, forming a conservative segment (0.68–3.34 million ha; up to 1.0 million Mg CO_2-eq yr^{-1}) and an expansive segment (15.6–19.0 million ha; up to 5.1 million Mg CO_2-eq yr^{-1}) separated by a gap with no optimal scenario. Per-hectare gain differed only modestly between them (≈ 0.30 versus 0.27 Mg CO_2-eq ha^{-1} yr^{-1}), so total gain scaled almost in proportion to area, and excluding nationally designated protected areas reduced the maximum total gain by 14%. Because the suitability model performed near chance under spatial-block validation and the carbon coefficients are uncalibrated, absolute values and spatial rankings are indicative only. Field measurements of parkland biomass and soil carbon, completion of the coefficient derivation, and a better-validated suitability model are required before the framework can support measurement, reporting and verification or carbon finance.

Abbreviations

AFR100
African Forest Landscape Restoration Initiative
AUC
area under the receiver operating characteristic curve
CV
coefficient of variation
GBIF
Global Biodiversity Information Facility
IUCN
International Union for Conservation of Nature
MaxEnt

maximum entropy
MRV
measurement, reporting and verification
NDC
Nationally Determined Contribution
SOC
soil organic carbon
SRTM
Shuttle Radar Topography Mission
VIF
variance inflation factor
WDPA
World Database on Protected Areas.

Declarations

Competing interests

The authors declare that they have no competing interests

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Author Contribution

AS conceived the study, developed the methodology and code, performed the analyses, and wrote the original draft. KD supervised the work and reviewed and edited the manuscript. BZD, DK and JO contributed to interpretation and reviewed and edited the manuscript. All authors read and approved the final manuscript.

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Data Availability

The R code implementing the full analysis pipeline (data acquisition, suitability modelling, carbon accounting, scenario analysis and figure generation) and the output rasters (suitability, carbon gain and scenario selections) are publicly available in Zenodo at DOI: 10.5281/zenodo.24292162. Occurrence data are third-party GBIF records subject to GBIF's data-sharing terms (GBIF.org, 22 October 2026, https://doi.org/10.15468/dl.9fgyvt); the derived, spatially filtered and thinned occurrence sets used in model training are included in the code repository.

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48. Additional file 1. Consistency check of the tree-cover-to-carbon coefficient (0.7 Mg C ha^{-1} per percentage point).
49. Purpose. The vegetation-carbon gain is $\Delta C_{veg,i} = \Delta TC_i \times k$, with k = 0.7 Mg C ha^{-1} per percentage point of tree cover applied uniformly to all eligible cells. The value is an indicative coefficient adopted from published parkland biomass estimates (Dayamba, Dimobe et al. 2018); it was not calibrated against plot data from this study. This file makes explicit what k implies and checks it against independent stock values, so that reviewers can judge it.
50. Definition. For a parkland with N trees ha^{-1}, a mean crown area ac (m^2 $tree^{-1}$) and a mean carbon stock per tree ctree (kg C $tree^{-1}$, aboveground plus belowground, i.e. biomass from the allometric equation × root-to-shoot expansion × carbon fraction), tree cover is TC = N·ac/100 (%) and the stock is C = N·ctree/1000 (Mg C ha^{-1}). Hence k = C/TC = 0.1 × ctree/ac. The coefficient depends only on the carbon held per unit of crown area, not on tree density; k = 0.7 corresponds to 7 kg C per m^2 of crown (for example, about 210 kg C for a tree with a 30 m^2 crown).
51. Consistency with published stocks. Dividing reported carbon stocks by k gives the tree cover they would imply: (i) about 12.8 Mg C ha^{-1} at 32–45 trees ha^{-1} in shea parklands (Dimobe & Bayala, 2023) implies about 18% cover; (ii) aboveground carbon of 2.3–3.4 Mg C ha^{-1} in the Sahel zone and 6.1–8.1 Mg C ha^{-1} in the Sudan zone. (Sanou 2025) implies about 3–5% and 9–12% cover, respectively. These cover values are plausible for open parklands, but they are an internal plausibility check, not a validation, because the carbon pools included in each source (aboveground only or total) and the cover measurements were not harmonised. If k were 0.4 or 1.0, the 12.8 Mg C ha^{-1} stock would imply about 32% or 13% cover, respectively; this range is the one explored in the one-at-a-time sensitivity analysis (Table 6).
52. Applicability. The coefficient comes from shea and African locust bean parklands and is applied here also to enrichment of cropland/parklands and to restoration of grassy savanna and bare/degraded land towards shrubby savanna, where carbon per unit crown area may differ (species composition, wood density, root-to-shoot ratio and stem size classes). The vegetation-carbon gain of the savanna-restoration pathways is therefore more uncertain than that of parkland enrichment, and the national vegetation total should be read as indicative.