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Wolf Habitat Analysis in Graubünden

A Multi-Criteria Analysis Approach for Conflict-Sensitive Habitat Suitability Modeling

GISScience and Geodatabases Project

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Bachelor's degree programme 2023
Submission date 2026-01-18
Study direction Applied Digital Life Sciences

Imprint

Recommended Citation:

Florian Klaver (2026). *Wolf Habitat Analysis in Graubünden: A Multi-Criteria Analysis Approach for Conflict-Sensitive Habitat Suitability Modeling*. Zurich University of Applied Sciences, Department Life Sciences and Facility Management, Institute for Environment and Natural Resources.

Keywords: Wolf, Habitat Suitability, Graubünden, GIS, Multi-Criteria Analysis, Human-Wildlife Conflict, Spatial Modeling

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Abstract

The natural recolonization of the Alps by the gray wolf presents a significant conservation success but also a considerable challenge for coexistence in human-dominated landscapes. This study aims to model suitable wolf habitats in the Canton of Graubünden using a raster-based Multi-Criteria Analysis (MCA) and to quantify the spatial trade-offs between biological potential and social constraints. A Python-based geoprocessing workflow was developed to integrate environmental factors (forest cover, slope, prey availability) with anthropogenic disturbance variables (roads, settlements). Additionally, a conflict model was created to identify high-risk zones where suitable habitat overlaps with vulnerable livestock grazing areas.

The analysis revealed that while biologically suitable habitat is abundant (2225 km²), applying strict social constraints by excluding conflict zones and enforcing wide safety buffers reduces the available core habitat by approximately 73% to only 603 km². The resulting “Conflict-Minimized” scenario depicts a highly fragmented landscape likely insufficient for supporting stable wolf pack dynamics. These findings suggest that a management strategy relying solely on spatial segregation is unrealistic. Sustainable coexistence in Graubünden will require accepting a degree of overlap between wolf territories and agricultural activity, necessitating active herd protection measures rather than theoretical exclusion zones.

An interactive dashboard visualizing all results was developed to facilitate exploration and is accessible here.

Acknowledgements

I would like to acknowledge the use of AI-based tools, which helped fixing and debugging issues in the code as well as refine text.

Cover Image: “Grauer und schwarzer Wolf, der tagsüber in der Nähe eines Baumstamms steht” by Robert Larsson via Unsplash.

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List of abbreviations

MCA	Multi-Criteria Analysis
GIS	Geographic Information System
DEM	Digital Elevation Model
HSI	Habitat Suitability Index
WLC	Weighted Linear Combination
GDAL	Geospatial Data Abstraction Library
VRT	Virtual Raster Table
QGIS	Quantum Geographic Information System

1. Introduction

The natural recolonization of the Alps by the gray wolf (Canis lupus) represents one of the most significant ecological recoveries in Europe. Protected under the Bern Convention and federal legislation, wolves have returned to Switzerland after being eradicated in the 19th and 20th centuries. While a conservation success, this recovery has generated substantial social and economic conflict, particularly regarding livestock predation in alpine agricultural systems (Glenz et al. 2001). The presence of wolves in human-dominated landscapes creates a complex challenge: ensuring the long-term viability of the species while minimizing negative interactions with human activities (Llaneza, López-Bao, and Sazatornil 2012).

To manage this coexistence effectively, it is crucial to understand spatial patterns of habitat suitability. Geographic Information Systems (GIS) and Multi-Criteria Analysis (MCA) have established themselves as standard methods for predicting potential wolf territories (Belongie 2008). Early models identified road density and human population as critical limiting factors, while recent studies in the Alpine range confirm that wolf distribution is strongly shaped by the availability of refuge areas and infrastructure density (Massolo and Meriggi 1998; Falcucci et al. 2013).

However, reliance on biological suitability alone is often insufficient for management in densely populated regions like the Canton of Graubünden. A discrepancy exists between where wolves can biologically survive and where their presence is socially accepted. While large-scale models cover the Alpine arc, specific local analyses contrasting biological potential with human-defined conflict scenarios are necessary to inform local decision-making.

The objective of this project is to model suitable wolf habitats in Graubünden using a raster-based MCA. This study applies a Python-based geoprocessing workflow to integrate environmental factors with anthropogenic disturbance. Beyond standard suitability modeling, this project specifically aims to identify high-conflict zones characterized by agricultural use. Furthermore, it develops two distinct scenarios to visualize the management trade-offs: a “Potential Core Habitats” scenario, focusing purely on biological suitability, and a “Conflict-Minimized Core Habitats” scenario, which incorporates larger buffers around settlements and excludes conflict zones. The final output is an interactive map designed to allow users to toggle these overlays, facilitating the visualization of coexistence strategies.

2. Methods

2.1. Study Area and Data Description

The study area comprises the entire Canton of Graubünden, Switzerland. Located in the eastern part of the country, it is the largest canton by area and is characterized by a rugged alpine topography, extensive forest cover, and a relatively low population density compared to the rest of Switzerland. While the official area of the canton is approximately 7105 km², the analyzed area in this study was 7072.43 km², based on the precise geometry of the boundary datasets employed.

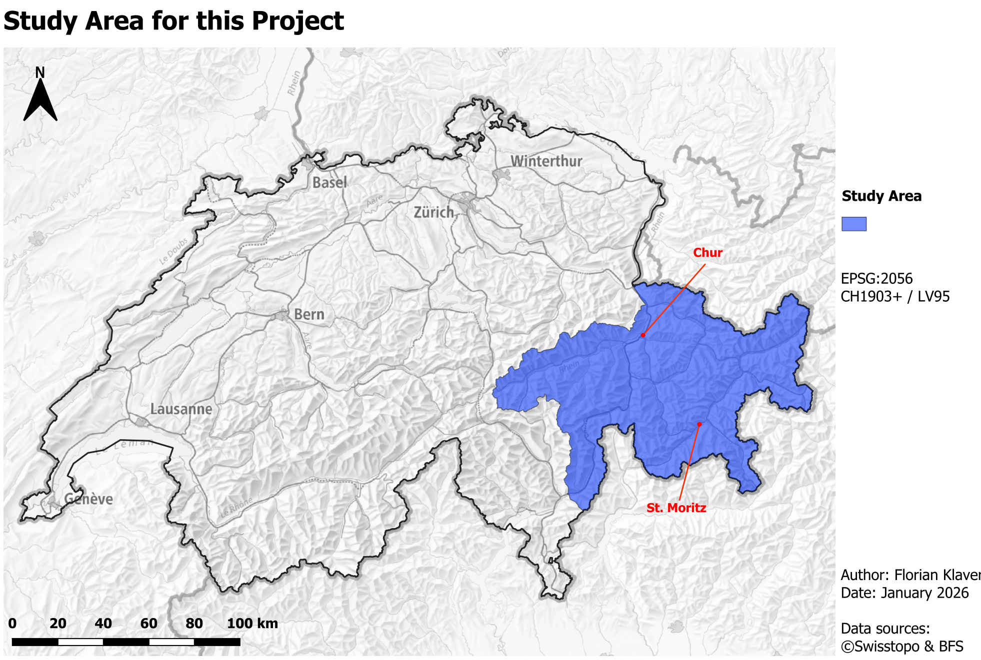

Figure 1: Map of Switzerland highlighting the Canton of Graubünden (in blue) as the study area for wolf habitat suitability analysis.

To perform the Multi-Criteria Analysis, high-resolution geospatial data were acquired from official federal sources. The specific datasets used are listed below:

- **Digital Elevation Model (DEM):** swissALTI3D (swisstopo) for elevation and slope.
- **Vector Data:** SwissTLM3D (swisstopo) for forest areas and road networks.
- **Land Use:** Arealstatistik (BFS) for settlement areas, potential prey habitats, and agricultural zones (e.g., alpine pastures).
- **Administrative Boundaries:** swissBOUNDARIES3D (swisstopo) for the study perimeter.
- **Background Maps:** Standard grey pixel map (swisstopo) for visualization.

All input data were projected in the Swiss CH1903+ / LV95 coordinate system.

2.2. Data Preprocessing

The workflow was implemented in Python using the Geospatial Data Abstraction Library (GDAL). To ensure rigorous spatial consistency, a master binary mask was created from the cantonal boundary geometry. All derived rasters were aligned to a uniform 10-meter resolution grid and strictly clipped to this mask, assigning NoData values to pixels outside the canton.

2.2.1. Digital Elevation Model (DEM) Processing

The swissALTI3D data, obtained as 7,541 individual tiles, were mosaicked and downsampled to the target 10-meter resolution using the 'Average' algorithm to minimize data noise while preserving mean elevation values. A Virtual Raster Table (VRT) was created to facilitate efficient access and processing of the large DEM dataset without generating a single massive file.

2.2.2. Derivation of Environmental and Anthropogenic Variables

Following the establishment of the reference grid, vector and point datasets were processed to generate the specific criteria layers required for the Multi-Criteria Analysis.

Topographical Criteria: Slope values (in degrees) were calculated directly from the 10-meter DEM using GDAL's DEM processing tools.

Land Cover (Forests): Forest areas were extracted from the SwissTLM3D land cover layer (tlm_bb_bodenbedeckung). Polygons classified as 'Wald' (Forest), 'Gebueschwald' (Shrub forest), 'Wald offen' (Open forest), and 'Gehoelzflaeche' (Wooded area) were rasterized into a binary grid (1 = Forest, 0 = Non-forest). A water mask was similarly generated to exclude standing water bodies ('Stehende Gewaesser') from the analysis.

Anthropogenic Disturbance (Euclidean Distance): To model human disturbance, Euclidean distance grids were generated for both roads and settlements.

- *Roads:* The road network was derived from SwissTLM3D (tlm_strassen_strasse). The dataset was filtered to include only major traffic arteries (e.g., motorways, main roads) likely to cause significant disturbance. Subterranean segments (tunnels) were explicitly excluded. The distance from every pixel to the nearest road segment was then calculated.
- *Settlements:* Settlement data were obtained from the Arealstatistik (Categories 1-13, covering industrial, commercial, and residential areas). As this dataset consists of point features, a buffer of 150 meters was applied to simulate continuous settlement zones. The Euclidean distance to these buffered areas was subsequently calculated.

Prey Availability: Potential prey habitats were identified using the Arealstatistik dataset. This selection included home pastures (Codes 43-44), alpine pastures (Codes 45-49), and unproductive vegetation (Code 65) suitable for wild game such as chamois and ibex. These point features were rasterized to create a baseline layer for prey potential.

2.3. Multi-Criteria Analysis (MCA)

The core analysis employed a Weighted Linear Combination (WLC) to calculate a Habitat Suitability Index (HSI). This method involves three distinct steps: standardization of criteria scores, weighting of factors, and final aggregation. The complete process model is visualized in Figure 1.

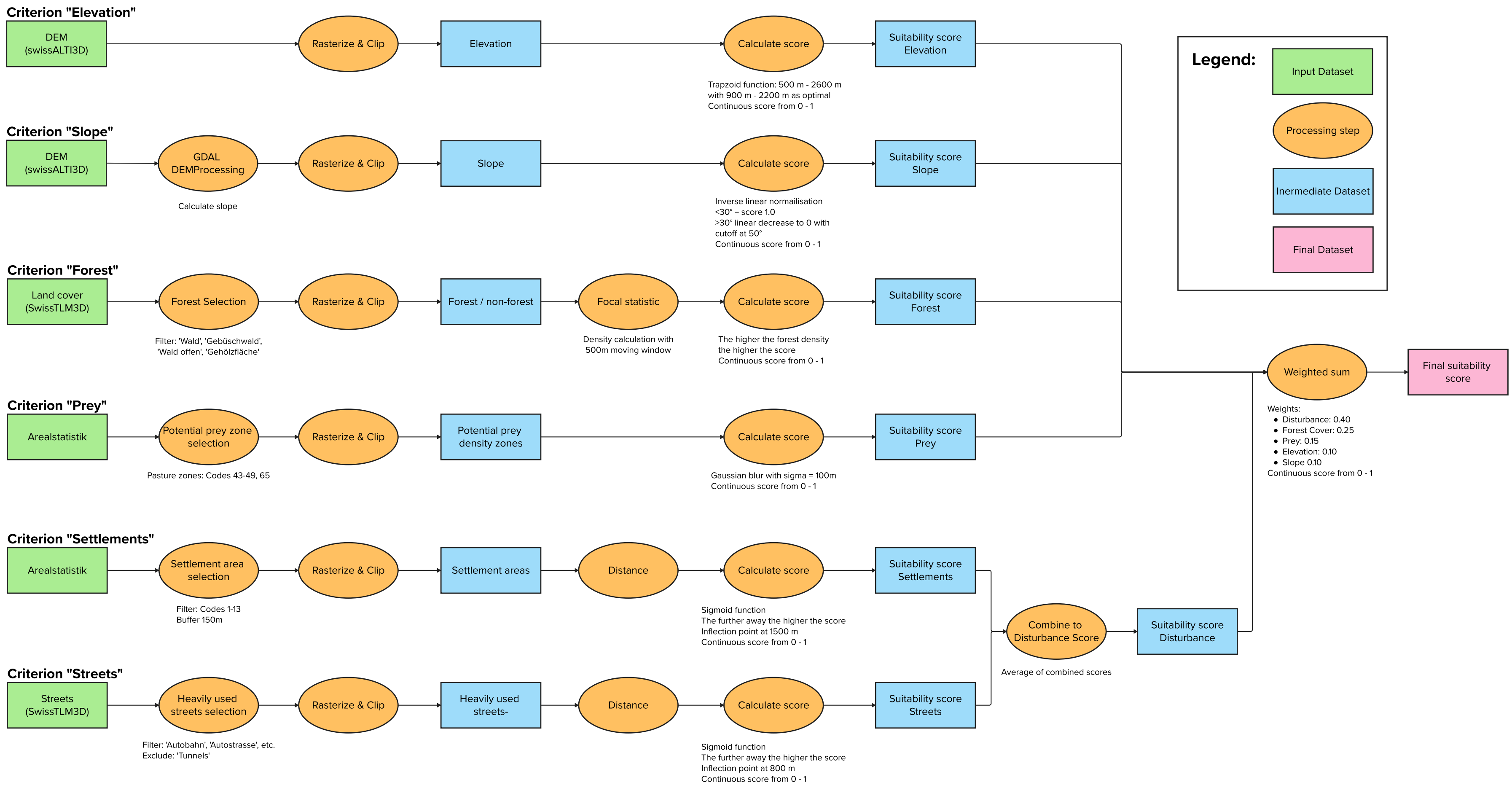

Figure 1: Process Model of the Multi-Criteria Analysis (MCA), illustrating input data, transformation steps, and weighting scheme.

2.3.1. Standardization (Scoring)

Input variables, originally measured in diverse units (degrees, meters, binary presence), were transformed into a standardized suitability score ranging from 0 (unsuitable) to 1 (highly suitable). The definition of these suitability ranges and optimal thresholds was derived from literature to reflect documented ecological requirements and utilized fuzzy logic membership functions rather than strict binary thresholds to reflect the gradual nature of ecological preference.

Elevation: A trapezoidal function was applied to model the wolf's altitudinal preference. The suitability score increases from 500 m, reaches an optimal plateau between 900 m and 2200 m (Score = 1.0), and decreases back to zero at 2600 m.

Slope: An inverse linear normalization was used. Slopes below 30° were considered ideal (Score = 1.0), while suitability linearly decreased to zero at a cutoff of 50°.

Forest Cover: To account for the density of cover rather than mere presence, a moving window filter (500 m size) was applied to the binary forest raster. This generated a score representing the proportion of forest cover within the immediate vicinity.

Prey Availability: The sparse point data for possible prey habitats were smoothed using a Gaussian blur (sigma = 100 m) to create continuous "hunting zones" rather than isolated points.

Anthropogenic Disturbance: A logistic sigmoid function (S-curve) was used to model the avoidance of human activity. This function provides a soft transition where suitability remains low near the source of disturbance and increases rapidly after a specific inflection point.

- *Roads:* Inflection point at 800 m.
- *Settlements:* Inflection point at 1500 m.
- The final disturbance score was calculated as the average of the road and settlement scores.

2.3.2. Weighting and Aggregation

Weights were assigned to each criterion based on their relative importance to wolf ecology, summing to a total of 1.0. The weights were distributed as follows:

- *Disturbance:* 0.40
- *Forest Cover:* 0.25
- *Prey Availability:* 0.15
- *Elevation:* 0.10
- *Topography (Slope):* 0.10

The final Habitat Suitability Index (HSI) was calculated by summing the weighted scores of all factors. Water bodies were explicitly masked out. The result is a continuous raster surface where higher pixel values indicate a higher probability of suitable wolf habitat based on the defined biological and anthropogenic constraints.

2.4. Conflict Zone Identification

To assess the potential for human-wildlife conflict, specifically regarding livestock predation, a separate conflict model was developed. This model integrated the calculated Habitat Suitability Index (HSI) with agricultural land use data.

Data Classification: Agricultural zones were extracted from the Arealstatistik dataset and classified into two risk categories based on livestock vulnerability:

- *High Risk (Sheep Alpages):* Areas designated as sheep pastures (Code 49). Sheep are particularly vulnerable to wolf predation, representing the highest conflict potential.
- *Medium Risk (General Pastures):* Areas including home pastures, scrub pastures, and general alpine meadows (Codes 43-48), typically used for cattle or mixed grazing, which represent a lower but significant conflict risk.

Spatial Modeling: Since the land use data were point-based, a buffer of 200 meters was applied to all pasture points to simulate realistic grazing ranges. A conflict zone was defined not merely by the presence of livestock, but by the overlap of these grazing buffers with suitable wolf habitat. A threshold of HSI ≥ 0.50 applied to this overlap. This threshold was deliberately set lower than the core habitat definition for the two scenarios (0.60) to account for the mobility of wolves, who frequently traverse sub-optimal habitats while foraging. Adopting this precautionary principle ensures that pastures located in marginal but accessible areas are included in the risk assessment, whereas areas in completely unsuitable habitat (e.g., dense urban centers or extreme slopes) remain excluded.

2.5. Scenario Definition and Spatial Analysis

Finally, two distinct suitability scenarios were derived to quantify the spatial trade-off between maximizing ecological potential and minimizing social conflict.

Scenario 1: Potential Core Habitats: This scenario identifies all areas that meet the biological requirements, regardless of conflict zones. It is defined as any area with an HSI score ≥ 0.60.

Scenario 2: Conflict-Minimized Core Habitats: This scenario restricts the suitable habitat to areas that are both biologically viable and minimize conflict. It applies the same biological threshold (HSI ≥ 0.60) but enforces strict exclusion criteria:

- *Exclusion of Conflict Zones:* All identified High and Medium risk conflict zones were removed.
- *Enhanced Safety Buffers:* Additional safety distances were applied, excluding all areas within 750 meters of settlements and 250 meters of major roads, to ensure a high degree of separation between wolf territories and human activity.

For both scenarios, a minimum patch size filter of 1000 pixels (equivalent to 10 hectares) was applied to remove very small small, fragmented habitat patches (despeckling). The resulting areas were calculated in square kilometers to assess the reduction in available habitat imposed by social constraints.

2.6. Visualizations and Dashboard

The results of the analysis were synthesized into both static and interactive visualization products. Static cartographic outputs for the report were generated using QGIS (Quantum Geographic Information System). For better user engagement and scenario exploration, a web-based interactive dashboard was developed using the Python framework Streamlit. This application integrates the processed raster layers (HSI, conflict zones, and scenarios), allowing users to toggle individual criteria and compare the spatial extent of the two management scenarios in more detail. The dashboard can be accessed here.

3. Results

3.1. Habitat Suitability Index (HSI)

The Weighted Linear Combination (WLC) model produced a continuous Habitat Suitability Index (HSI) for the entire Canton of Graubünden. The calculated suitability scores in the study area range from a minimum of ~0.18 to a maximum of ~0.85. To enhance visual contrast and interpretability, the color ramp is scaled to the range 0.15 - 0.85 rather than the theoretical 0-1 interval. The visualization of the suitability scores (Figure 2) reveals a distinct spatial pattern driven by the topography and the distribution of anthropogenic infrastructure. Highly suitable areas are concentrated in the forested, mountainous regions away from the main valley floors. The major valleys, such as the Rhine Valley (Chur to Disentis) and the Inn Valley (Engadin), appear as distinct barriers with low suitability scores due to high settlement density and major transit routes.

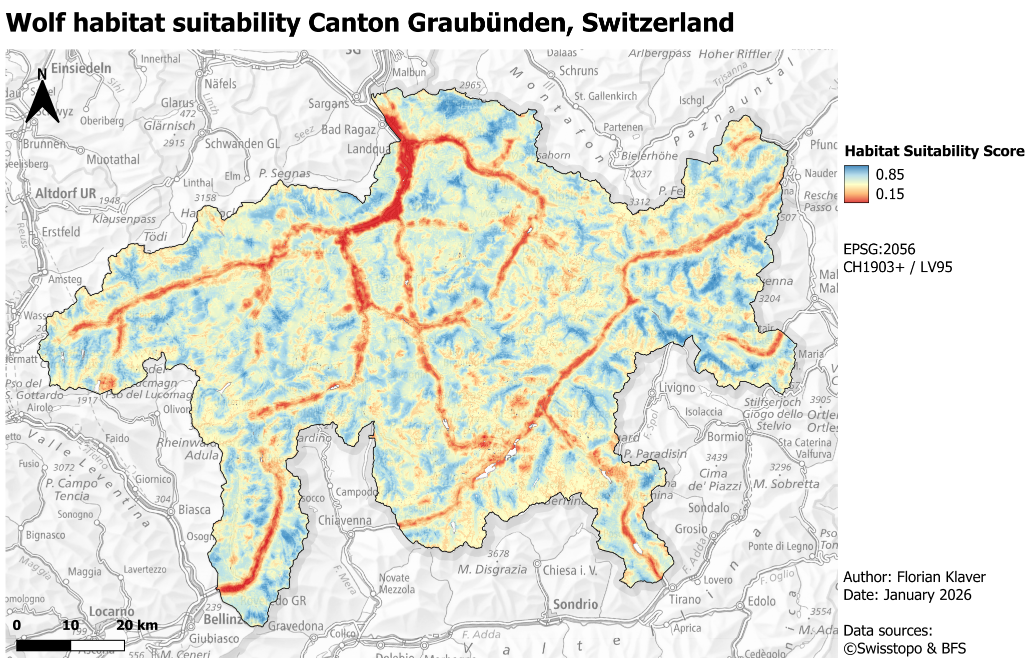

Figure 2: Habitat Suitability Index (HSI) Map of Graubünden, illustrating spatial variation in suitability scores from 0.15 (unsuitable, red) to 0.85 (highly suitable, blue). High suitability areas are predominantly located in remote, forested regions away from human infrastructure.

3.2. Conflict Zones

The conflict analysis identified specific zones where moderate to high habitat suitability (score ≥ 0.5) overlaps with vulnerable agricultural use. Figure 3 illustrates the spatial distribution of these conflict areas.

- **Medium Risk Zones (Brown):** These zones, representing cattle and general pastures within suitable wolf habitats, cover a large amount of the potential habitat areas, particularly in the mid-altitude regions.

- **High Risk Zones (Black):** These areas, representing sheep alpages located within suitable wolf habitats, are more concentrated but pose a significant risk due to the high vulnerability of sheep to predation.

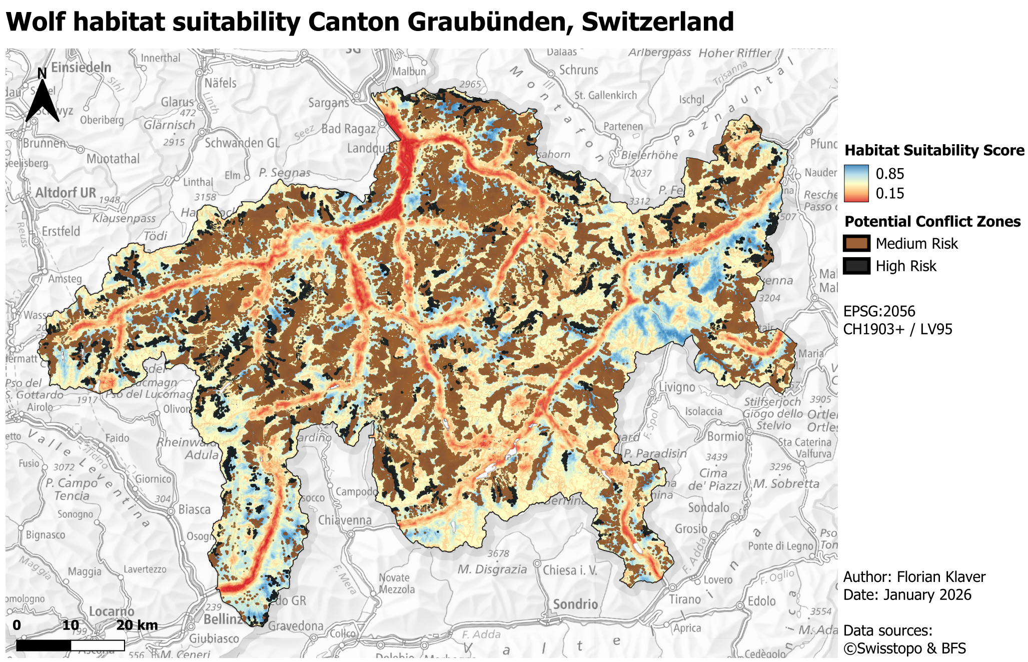

Figure 3: Conflict Zones Map, highlighting High Risk (Black) and Medium Risk (Brown) agricultural areas overlapping with at least moderately suitable wolf habitat (HSI > 0.50).

3.3. Scenario Analysis

The spatial analysis of the two defined scenarios visualized in Figure 4 and Figure 5 revealed a substantial trade-off between biological potential and safety constraints.

Scenario 1: Potential Core Habitats This scenario, which considers only biological requirements (HSI > 0.60) without regard for agricultural conflict, identified a total suitable habitat area of 2225 km². As shown in Figure 4, theses habitats cover a significant portion of the canton and are primarily located in dense forested areas with low human disturbance.

Scenario 2: Conflict-Minimized Core Habitats When applying the conflict exclusion criteria and enhanced safety buffers, the available suitable habitat was drastically reduced to 603 km². As illustrated in Figure 5, the remaining core habitats are much more fragmented and isolated, primarily located in more remote alpine regions. This represents a reduction of approximately 73% in suitable habitat area compared to scenario 1, highlighting the significant impact of human-wildlife conflict considerations on habitat availability.

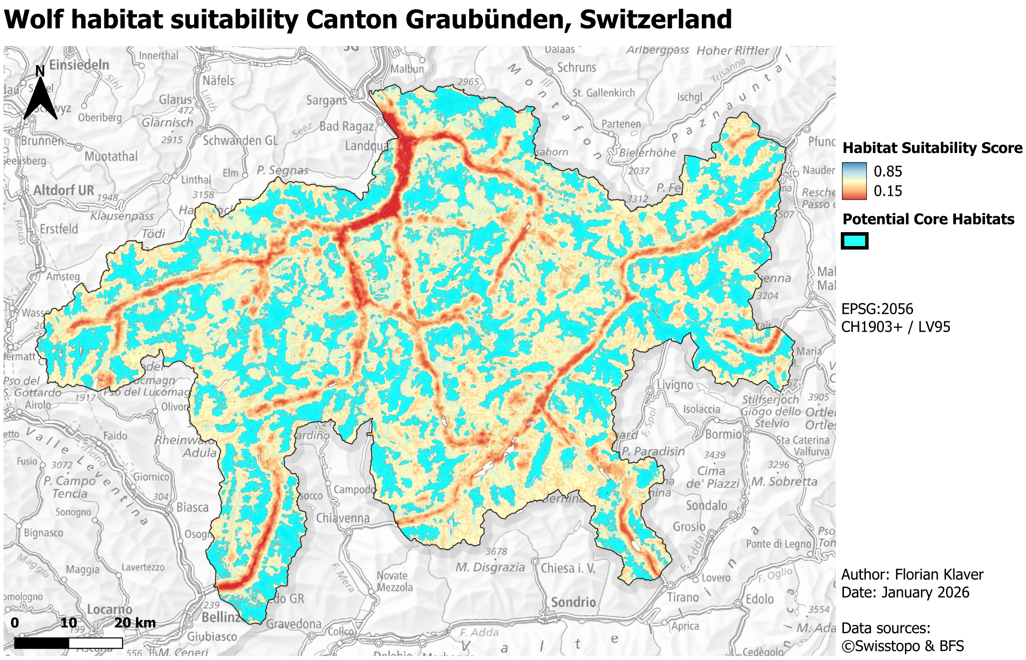

Figure 4: Potential Core Habitats Scenario Map, showing all areas with HSI ≥ 0.60 (cyan). These areas represent the potentialcore habitats with high suitability for wolves disregarding conflict zones.

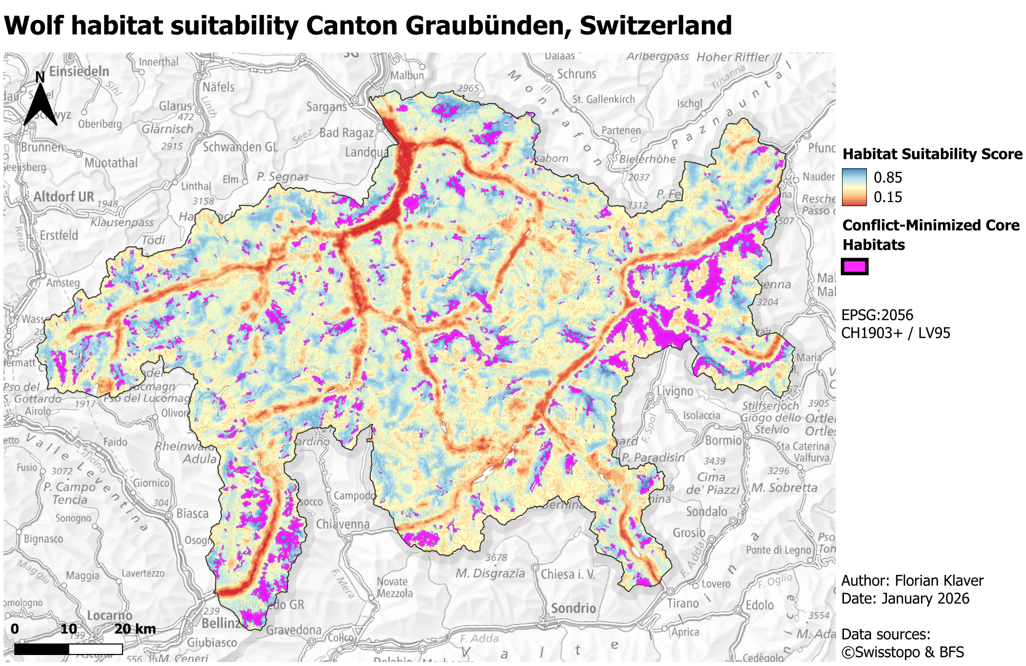

Figure 5: Conflict-Minimized Core Habitats Scenario Map, showing suitable habitats (HSI ≥ 0.60) after excluding conflict zones and applying enhanced safety buffers (Magenta).

4. Discussion

The results of this Multi-Criteria Analysis highlight the critical tension between the biological potential for wolf recovery in Graubünden and the sociopolitical constraints imposed by human land use. The analysis confirms that while the Canton offers extensive ecological suitability for wolves, the realization of this potential is severely limited by the requirement for conflict-free coexistence.

4.1. Interpretation of Habitat Availability and Fragmentation

The most significant finding of this study is the 73% reduction in suitable habitat when moving from a biological suitability model (Scenario 1) to a socially constrained model (Scenario 2). While the "Potential Core Habitats" scenario identifies 2225 km² of suitable land, sufficient to support multiple wolf packs, the "Conflict-Minimized Core Habitats" scenario leaves only 603 km².

Crucially, the impact is not just in total area, but in spatial configuration. As observed in the results, the "Conflict-Minimized Core Habitats" scenario results in a highly fragmented landscape. The resulting map shows that there are only two large, suitable, conflict-free areas to the east and south-east of Zernez. Wolves are territorial animals with home ranges often exceeding 100-300 km² in the Alps (Glenz et al. 2001). The small, isolated patches identified in Scenario 2 are insufficient to support stable pack dynamics. This suggests that a management strategy based on the strict avoidance of all conflict zones and wide safety buffers is incompatible with a viable wolf population. Realistic coexistence will require accepting a degree of overlap between wolf territories and agricultural zones, necessitating active herd protection measures rather than spatial segregation.

4.2. Validation with current Distribution and Literature

The robustness of the "Potential Core Habitats" model (Scenario 1) is supported by comparisons with both scientific literature and current field observations.

Comparison with Alpine-Scale Models: The spatial patterns of suitability identified in this study show a strong correlation with the large-scale predictive model for the Alpine range developed by Falcucci et al. (Falcucci et al. 2013). Both models identify the Surselva, the Calanda massif, and mountainous areas east of Zernez as suitable habitats. However, a visual comparison reveals that the model of this project's local-scale analysis depicts a much more fragmented landscape than Falcucci's regional model. This discrepancy is likely attributable to the higher resolution of our input data, which captures finer-scale barriers such as minor roads and settlement sprawl that are generalized in coarser, pan-Alpine studies.

Validation with Observed Wolf Pack Locations: A comparison with the official 2026 distribution map of the 12 known wolf packs in Graubünden provides a critical real-world validation. The observed pack territories largely overlap with the areas identified as suitable in our biological model (Scenario 1), confirming the model's predictive power regarding ecological requirements. However, these real-world territories are not restricted to the "Conflict-Minimized" zones identified in Scenario 2. The packs successfully inhabit areas that the second scenario excluded due to conflict risks or proximity to infrastructure. This observation reinforces the conclusion that the “Conflict-Minimized” scenario is an idealized theoretical construct. In reality, wolves in Graubünden demonstrate a higher tolerance for anthropogenic structures and conflict potential than the strict parameters of Scenario 2 allow, further emphasizing that coexistence is defined by management of conflict rather than spatial avoidance of it.

4.3. Limitations and Uncertainties

While the model provides robust spatial insights, several limitations must be considered. First, the “Prey Availability” criterion relied on the location of alpine pastures as a proxy for wild ungulate presence (deer, chamois) and livestock. While summer grazing livestock is a food source, the primary prey base consists of wild game, whose density was not directly modeled due to data limitations.

Second, the model represents a “static” view of the landscape, largely reflecting summer conditions (when pastures are active). It does not account for seasonal dynamics, such as snow depth, which forces both wild prey and wolves into lower elevations during winter. This seasonal migration brings wolves closer to human settlements, potentially increasing conflict risks that are not fully captured in a static model. Future iterations could improve accuracy by incorporating seasonal snow cover data and dynamic prey density maps.

4.4. Conclusion and Outlook

This project successfully developed a reproducible, Python-based workflow to model wolf habitat suitability in Graubünden. The findings demonstrate that biologically suitable habitat is abundant, but socially acceptable habitat is scarce and fragmented. The interactive map developed in this study provides a valuable tool for stakeholders to visualize these trade-offs. Ultimately, the results suggest that the long-term presence of the wolf in Graubünden will depend not on finding “conflict-free” space, but on managing the inevitable overlap between human agricultural activity and ecological reality.

Given the identified limitations, future iterations of this model should aim to incorporate dynamic seasonal variables and other additional criterias. Specifically, integrating snow depth data would allow for a more accurate assessment of winter habitat suitability and potential conflict hotspots during the cold season, when predator-prey dynamics shift towards valley floors. Furthermore, replacing the proxy-based prey layer with actual prey density data from a separate habitat data for relevant animals would significantly refine the ecological component of the model. Finally, the “social tolerance” parameters could be improved by incorporating stakeholder feedback directly, moving from theoretical buffer distances to values negotiated with local agricultural and conservation interest groups.

5. Statement of Reproducibility

All code developed for data processing, MCA modeling, and dashboard deployment is fully available in the project's GitHub repository. While the specific raw geospatial data (SwissTLM3D, swissALTI3D) cannot be redistributed directly due to licensing restrictions and data size, the code structure allows for the reproduction of the workflow using the standard datasets available from Swisstopo and the Swiss Federal Statistical Office. The source data can be obtained via swisstopo and geocat.ch.

To ensure reproducibility, maintainability, and simple reusability, the codebase was refactored into documented, modular scripts. This prevents code duplication and allows specific steps, such as the rasterization of vector features, the calculation of suitability scores, or the scenario generation, to be reused independently. Key configuration variables and model parameters (e.g., criteria weights, fuzzy logic inflection points, and safety buffer distances) are declared at the top of the scripts to facilitate adaptation to new research questions.

Project version control was managed via GitHub. All computational tasks, including data preprocessing and spatial analysis, were optimized to run on standard local hardware using open-source Python libraries.

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List of figures