



**Universität
Zürich** ^{UZH}

Geographisches Institut

A Multi-Criteria Decision Approach to Site Selection for Photovoltaic Systems in Switzerland: Balancing Renewable Energy and Biodiversity

GEO 511 Master's Thesis

Author: Marie Hamm, 18-737-270

Supervised by: Leonhard Zwiauer (Leonhard.Zwiauer@are.admin.ch)

Faculty representative: Prof. Dr. Ross Purves

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Abstract

The ongoing climate change forces us to take effective measures to reduce greenhouse gas emissions. Switzerland has set ambitious climate targets with its "Net Zero" strategy, aiming to reduce CO₂ emissions to a minimum by 2050. Ground-mounted photovoltaic (PV) systems are at the forefront of national energy planning. However, with the expansion of large-scale *ground-mounted PV plants* (GMPP), issues of biodiversity conservation arise. Ecosystems in Switzerland are already significantly under pressure from habitat fragmentation, urbanization, intensive agriculture, and climate change, as well as additional risks from GMPP, including habitat loss, microclimatic changes, and disrupted species movement. While these developments are ecologically important, our understanding of the environmental impacts of GMPP remains limited.

This thesis addresses these challenges through an improved site selection process for GMPP that systematically integrates biodiversity considerations. The main objective is to develop a spatial decision-support tool that assists in balancing PV expansion with its impact on biodiversity conservation. Building on a geodata model developed by the Federal Office for Spatial Development (ARE), which incorporates *Utilization Criteria* and *Protection Criteria*, this study integrates biodiversity criteria such as *Species Richness*, *Species Diversity*, and *Habitat Quality* into the decision-making process. Using Geographic Information Systems (GIS), Multi-Criteria Decision Analysis (MCDA), and the Analytic Hierarchy Process (AHP), important biodiversity areas are evaluated to inform the PV suitability model developed by the ARE. The resulting spatial analyses identify potential conflicts and synergies between PV expansion and biodiversity protection in Switzerland. The results show significant overlaps between high-priority areas for PV installations and biodiversity-rich areas, especially in (sub)alpine regions. This highlights the importance of appropriate site selection to find a balance between biodiversity conservation and the PV industry. The results are based on current data, values, and land-use patterns; therefore, potential future changes (e.g., climate change) were not considered. The proposed method provides a tool to support decision-makers and spatial planners in achieving a sustainable energy transition without degrading ecological integrity.

Keywords: Sustainable Energy Transition, Ecological Planning, Ground-Mounted Photovoltaic Systems (GMPP), Biodiversity Conservation, GIS, Multi-Criteria Decision Analysis (MCDA), Analytic Hierarchy Process (AHP), Site Selection, Switzerland

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List of Abbreviations

AHP	Analytic Hierarchy Process
ARE	<i>Abteilung für Raumentwicklung</i> (Federal Office for Spatial Development)
BAFU	<i>Bundesamt für Umwelt</i>
BC1	Species Richness
BC2	Species Diversity
BC3	Red List Species
BFE	<i>Bundesamt für Energie</i> (Swiss Federal Office of Energy)
EF1	Habitat Quality
EF2	Habitat Connectivity
EF3	Pollinator Abundance
EF4	Soil Quality
EF5	Human Recreation Abundance
GBIF	Global Biodiversity Information Facility
GHG	Greenhouse Gas
GIS	Geographic Information System(s)
GMPP	Ground-Mounted Photovoltaic Plants
LUC	Land Use Change
MCDA	Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision Making
NCP	Nature's Contributions to People
PCM	Pairwise Comparison Matrices
PV	Photovoltaic
REN	Réseau Écologique National

1 Introduction

1.1 Research Relevance and Motivation

The ongoing climate change forces us to take effective measures to reduce greenhouse gas emissions. Switzerland has set ambitious climate targets with its "Net Zero" strategy, aiming to reduce CO₂ emissions to a minimum by 2050 (Bundesamt für Umwelt BAFU, 2023c). Solar energy from photovoltaic (PV) systems is one of the most promising solutions to increase the use of renewable energy and meet this goal. These systems can help to facilitate sustainable energy production and move away from fossil fuels (Bundesamt für Energie BFE, 2023b). The Swiss energy policy plans to expand solar power, as about 40% of the country's energy needs are expected to be met by solar energy in the future (Brunner et al., 2024).

This thesis focuses on ground-mounted free-standing photovoltaic systems. These are solar power installations where PV panels are installed directly on the ground rather than on rooftops or other structures. These systems are usually installed on open ground and supported by frames or mounts, and can be tilted or oriented for optimal sunlight exposure. Ground-mounted PV systems are often used for large-scale solar farms or utility projects, as they can accommodate more panels. Additionally, ground-mounted PV plants (GMPP) generate significantly more electricity than roof-mounted systems (Beylot et al., 2014; Hyder, 2024).

That is why ground-mounted photovoltaic systems, especially in alpine regions, will be important for the energy transition to cover Switzerland's future energy demand (Brunner et al., 2024). However, developing large-scale GMPP is a significant threat to biodiversity. Here, biodiversity refers to the variety of animal, plant, fungal, and microorganism species, including the genetic diversity within these species in a given area. Furthermore, biodiversity encompasses the diversity of habitats and the interactions within and between these levels (Aktionsplan des Bundesrates, 2017; Hughes et al., 2008; Purvis & Hector, 2000).

Consequently, a critical question arises: What are the ecological impacts of large PV plants, particularly on biodiversity in Switzerland?

Switzerland is home to a variety of habitats and ecosystems that range from alpine regions to wetlands and forests. According to the BAFU, half of the habitats and around a third of the species in Switzerland are classified as threatened or endangered, with the loss and fragmentation of habitats, urbanization, and the increasing intensification of agriculture being the main factors (Bundesamt für Umwelt BAFU, 2022, 2024; Uldrijan et al., 2022). The ongoing changes resulting from climate change will continue to have significant impacts on biodiversity. Greenhouse gas (GHG) emissions are increasing in Switzerland, resulting in changes in the climate, precipitation patterns, and the frequency of extreme weather events (Bundesamt für Meteorologie und Klimatologie, n.d.; Mohajan, 2017). These changes can affect

ecosystems and species, especially those that cannot adapt quickly. Reducing GHG emissions is therefore essential to mitigate the impacts of climate on ecosystems and biodiversity. However, combined with climate change, this creates a dilemma: the development of GMPP could exacerbate existing pressures on ecosystems, especially in ecologically sensitive areas. Ecologically sensitive areas are those with high conservation value, such as wetlands, alpine meadows, or biodiversity hotspots (areas with exceptional species richness or endemism). GMPP projects may create microclimatic conditions, fragment existing habitats, and disrupt species movement patterns. Importantly, the ecological effects depend on prior land uses, ecosystem type, and site management (Armstrong et al., 2016; Gasparatos et al., 2017; Gómez-Catasús et al., 2024; Montag et al., 2016; Moscatelli et al., 2022; Vervloesem et al., 2022).

Careful site selection is one of the most important mitigation techniques for reducing the ecological impact of GMPP. Many studies indicate that avoiding irreversible habitat loss and species decline is the most effective way to mitigate impacts, by selecting sites away from sensitive habitats or highly biodiverse areas. Such measures are generally seen as more effective than technical mitigation measures or design-based mitigation alone (Giamalaki & Tsoutsos, 2019; Schlegel, 2021; Stoms et al., 2013). Therefore, it is now becoming increasingly accepted that decision-support tools provide spatially explicit and biodiversity-considered information so that renewable energy can progress while impacts on ecosystems are minimal.

This thesis builds on a model developed by the Federal Office of Spatial Development (ARE) that identifies areas that have a high priority for PV installation. Their model is separated into *Utilization Criteria* and *Protection Criteria*. This thesis further refines the *Protection Criteria* by adding biodiversity indicators to evaluate biodiversity hotspots in Switzerland.

In this thesis, the multi-dimensional aspect of biodiversity is analysed by using a selection of biodiversity indicators, such as *Species Richness* and *Habitat Quality*. These indicators are analysed using a Multi-Criteria Decision Making (MCDM) framework. MCDM facilitates a systematic evaluation of multiple criteria, balancing competing priorities while highlighting their significance for biodiversity conservation. Within the MCDM framework, the Analytic Hierarchical Process (AHP) is applied to determine the relative importance of each criterion through pairwise comparisons, supported by expert judgment. This study supports spatial planning and decision-making processes for selecting sites for large PV installations by combining GIS, MCDM, and AHP.

1.1.1 Research Gaps and Problem Statement

The environmental impact of ground-mounted PV systems in Switzerland remains poorly understood, despite the urgency behind solar energy expansion. To this day, Switzerland has only a few large, free-standing solar power systems, most of which are in early development or pilot stages (Bundesamt für Energie BFE, 2023a). A particularly significant research gap exists regarding the ecological impacts of alpine GMPP. Due to their harsh environmental conditions, slow ecosystem recovery rates, and high endemism, alpine habitats are particularly vulnerable to human disturbances (Körner, 2021; Schlegel, 2021). Nevertheless, no comprehensive research has yet evaluated the impact of large-scale alpine PV installations on these fragile ecosystems. In particular, little is known about how they affect species movement, habitat fragmentation, and microclimatic conditions, such as soil moisture and temperature (Rupf & Rohrer, 2024; Vervloesem et al., 2022).

In addition to the general ecological impacts, there is also a lack of applied research on mitigation strategies that could improve the ecological compatibility of GMPP. Concepts such as *Ecovoltaics* and biodiversity-friendly PV designs exist (Boscarino-Gaetano et al., 2024; Nordberg & Schwarzkopf, 2023). However, there are no examples from Switzerland or practical guidelines for their implementation. *Ecovoltaics* refers to the design and management of PV systems to enhance ecological benefits, such as promoting native vegetation or creating habitats for pollinators beneath panels. Questions remain about how targeted measures, such as promoting site-appropriate vegetation or creating ecological niches beneath PV panels, can be designed, implemented, and monitored in an alpine context to avoid biodiversity loss.

Moreover, significant data limitations hinder the effective integration of biodiversity considerations into spatial planning. Access to reliable, high-resolution biodiversity data remains a persistent challenge due to fragmented datasets, inconsistent methodologies, and gaps in species occurrence records. This lack of standardized, open-access biodiversity data complicates efforts to conduct spatially explicit assessments of ecological risk and opportunity (Michener, 2015; Reichman et al., 2011).

Finally, there is a conceptual gap in existing planning tools: although ARE's current geodata model provides a valuable starting point for assessing technical and legal limitations on PV site selection, its limited consideration of biodiversity criteria reduces its potential to ensure ecologically sustainable decision-making. To date, there is no integrated GIS-based approach available for the systematic assessment of biodiversity indicators in PV site selection in Switzerland. For an energy transition to be environmentally responsible, these research gaps must be filled. This thesis aims to close these gaps by developing a refined, biodiversity-based decision-support model for GMPP siting, which will support Switzerland's objectives for renewable energy development and biodiversity conservation.

1.2 Research Question and Objectives

The thesis is based on the following research questions:

- 1. What are the key challenges and ecological impacts associated with ground-mounted photovoltaic (PV) systems on biodiversity in Switzerland?**

This question will establish the primary ecological risks associated with ground-mounted PV systems on biodiversity, including habitat fragmentation, local microclimate changes (e.g., shading, soil moisture, and temperature changes), impacts on wildlife movement, and species diversity. It will examine how these ecological risks and implications vary and how the ecological effects could be either negative or positive due to prior land use (Gasparatos et al., 2017; Gómez-Catasús et al., 2024).

- 2. How can biodiversity considerations be integrated into the planning and decision-making process for ground-mounted PV systems in Switzerland, specifically identifying how to use results from Multi-Criteria Decision Analysis (MCDA) and Analytic Hierarchy Process (AHP) to develop a decision-making framework that includes ecological priorities into the ARE model?**

The second question primarily focuses on developing the process for including biodiversity criteria (e.g. *Species Diversity*, *Habitat Quality*, and *Habitat Connectivity*) into the site selection process for PV projects in Switzerland. By using MCDA and AHP within a GIS decision support system, this study aims to refine the ARE's protection-utilization matrix to incorporate biodiversity conservation (Malczewski & Rinner, 2015a; Villacreses et al., 2022).

1.3 Research Structure

The thesis is structured as follows: Chapter 2 provides thematic context, including Switzerland's climate and plans for "Net Zero," and offers a brief overview of the state of Switzerland's biodiversity and related ecological issues. Chapter 3 is the literature review, focusing on the ecological impacts of PV systems, the definition of biodiversity, and decision-support tools such as GIS, MCDA, and AHP, as well as the issue with open biodiversity data. Chapter 4, Methodology, describes ARE's geodata model and explains how the model was refined with biodiversity criteria, including expert weighting procedures, and how biodiversity indicators were incorporated through MCDA and AHP, supported by data processing in Python and QGIS. Chapter 5 presents the results, including priority weights for biodiversity indicators and a biodiversity suitability map to help select possible PV sites. The applicability of the model is evaluated through three case studies examining regions in Switzerland to evaluate areas of ecological conflict or areas for further studies. Chapter 6 provides a critical discussion of findings, their significance for sustainable spatial planning, and existing limitations. Finally, Chapter 7 discusses key findings, responds to the research questions, and discusses possible recommendations for future research.

2 Background

2.1 Climate Strategy Switzerland

With rising temperatures, more extreme weather, and less snow cover, Switzerland is especially vulnerable to climate change, and the “Net Zero” strategy emphasizes the urgent need for action (Bundesamt für Umwelt BAFU, 2021a). On August 28, 2019, the Swiss Federal Council decided that Switzerland will reduce its greenhouse gas emissions to net zero by 2050. The Swiss Federal Council thus aligns itself with the Paris Agreement, aiming to keep global warming well below 2°C, ideally 1.5°C (Bundesamt für Umwelt BAFU, n.d., 2021b; *The Paris Agreement* | UNFCCC, n.d.). To achieve this net zero goal, emissions must be reduced as much as possible and offset by technologies with negative emissions, such as carbon capture and storage, to make up for the emissions that remain (Bundesamt für Umwelt BAFU, 2021b). To this end, the climate strategy sets out ten guiding principles focusing on accountability, reducing domestic emissions, economic and social viability, and technology openness. Buildings, industry, transportation, agriculture, finance, waste management, and aviation are among the key industries covered in the plan. In 2021, the aforementioned CO₂ law was updated along with a specific roadmap for reaching the 2050 goal, envisaging a 50% reduction in emissions by 2030 (Bundesamt für Umwelt BAFU, 2021b).

One promising solution mentioned in the roadmap is solar power, specifically through photovoltaic (PV) systems. These systems have the potential to contribute to sustainable energy production and the transition away from fossil fuels (Bundesamt für Energie BFE, 2023b). Therefore, the Swiss energy policy plans to expand solar power, with about 40% of the country's energy needs are expected to be met by solar energy in the future (Brunner et al., 2024; Bundesamt für Energie BFE, 2023b). In 2024, Switzerland could, for the first time, reach over 10% of the annual electricity consumption from solar power (*Swissolar*, 2023). Recently, photovoltaic electricity production has been increasing significantly. According to BFE, buildings have the most potential for expansion (Bundesamt für Energie BFE, 2023a). Additional expansion could also be on other types of infrastructure, such as noise barriers, dam walls and reservoirs. However, more and larger PV systems are needed to supply the growing demand for solar power. It is anticipated that free-standing ground-mounted photovoltaic plant (GMPP) installations would have enormous growth potential (Schlegel, 2021). These systems can be tilted or positioned for the best possible exposure to sunlight because they are usually installed directly on the ground and held up by frames or mounts instead of being mounted on rooftops or other structures. Furthermore, since they can hold more panels and provide a higher power output than roof-mounted systems, GMPP are frequently utilized for large-scale solar farms or utility projects (Beylot et al., 2014; Hyder, 2024). Nonetheless, there are still very few in operation and planning in Switzerland to this day. Larger PV installations are especially required to ensure a secure electricity supply in winter, to fill the “winter energy gap”. This gap is caused by fewer hours of sunshine in conjunction with increased

demand. Aiming to counter this discrepancy, the Swiss Parliament passed urgent measures in 2022 to facilitate the temporary and limited expansion of large PV installations outside designated building zones. To benefit from a correspondingly simplified approval and financial incentives, PV installations must contribute significantly to winter electricity production (Bundesamt für Energie BFE, 2023a). To do so, GMPP are planned for high-altitude alpine regions. This is because high-altitude PV systems benefit from more intense sunlight and reduced cloud cover, as well as the albedo effect, which enhances efficiency (Carigiet et al., 2021; Frischholz et al., 2024; Kahl et al., 2019; Streiff, 2021). However, there is little knowledge about large-scale alpine PV installations. Challenges include increased snow and wind loads, requiring robust anchoring and substructures; difficult access for construction and grid connection; and the need to assess their ecological impact on sensitive alpine ecosystems, which requires careful planning to balance energy needs with biodiversity protection (Bundesamt für Energie BFE, 2023a). Figure 1 displays the planned high-alpine PV plants (as of August 2025), only a few are already legally authorized.

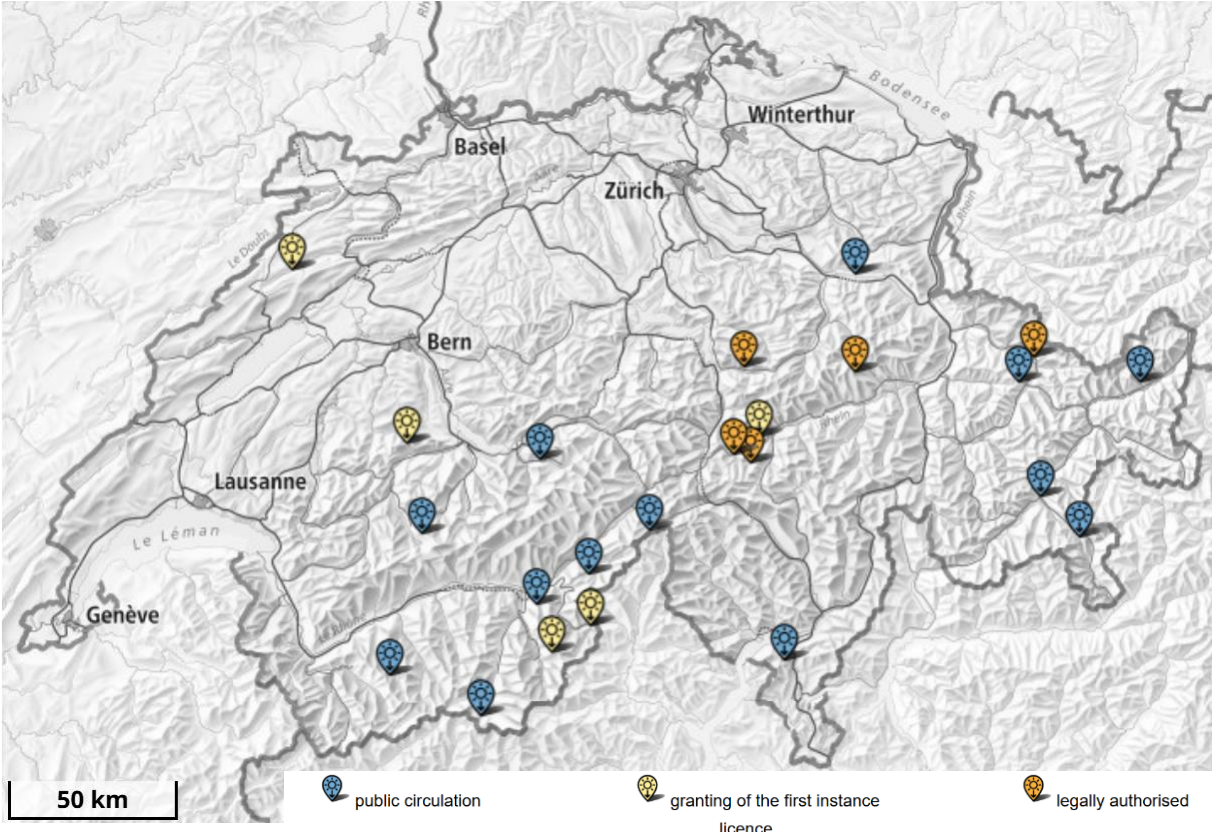


Figure 1: High-alpine Photovoltaic Installations in Switzerland (Source: (Bundesamt für Energie BFE, 2023a; Swisstopo, n.d.)

2.2 Biodiversity Challenges in Switzerland

Switzerland's biodiversity is very rich given its different biogeographic regions, such as the Alps, the Jura and the Central Plateau (see Figure 2). Each region is influenced by distinct ecosystems and species, which contribute to the country's ecological diversity. The Alpine region is characterized by mountains and glaciers, and it is also home to specialized flora and fauna that have adapted to the harsh environment. The Jura provides habitat for many woodland species. The Central Plateau, with wetlands, grasslands, and agricultural landscapes, has the highest population density. The diversity of these landscapes showcases a variety of ecosystems that support biodiversity (Bundesamt für Umwelt BAFU, 2023b).

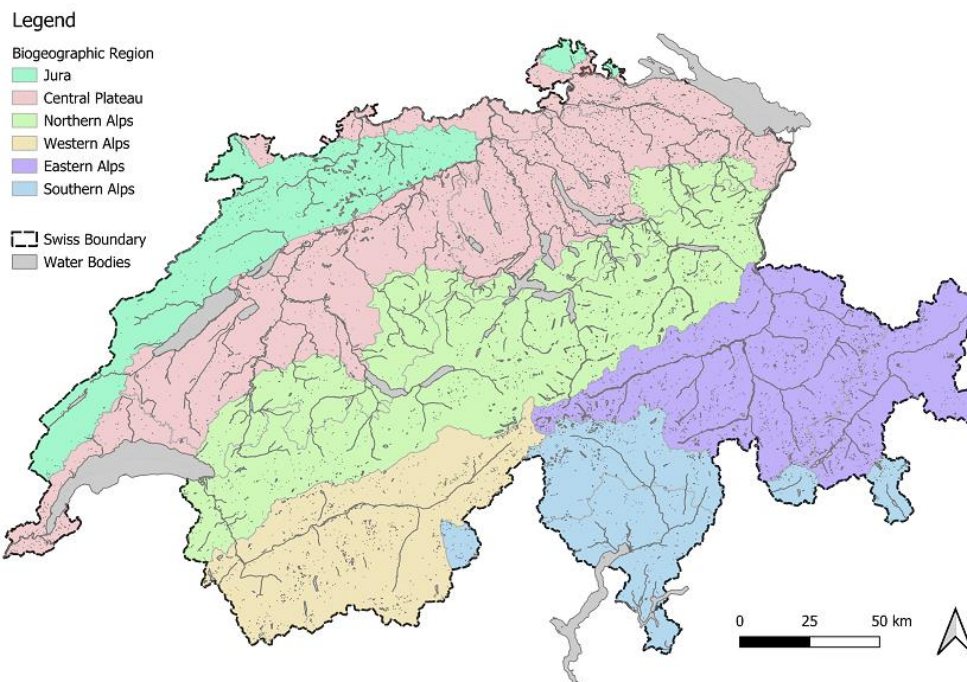


Figure 2: Biogeographic Regions of Switzerland (Source: swisstopo, BAFU)

Both international agreements and the Swiss Federal Constitution (Section 4) require the preservation of biodiversity (Bundesverfassung Der Schweizerischen Eidgenossenschaft, 1999). Switzerland has committed to protecting endangered species and enhancing the lives of the most vulnerable. Nevertheless, Switzerland's biodiversity has declined drastically over the past century. More than a third of the assessed plant and animal species, as well as nearly half of the evaluated habitat types, are now classified as endangered and listed on the Red Lists. Intensive farming has particularly affected agricultural ecosystems. High fertilizer and pesticide use, as well as uniform mechanical farming practices, are major causes of habitat and species loss (Bundesamt für Umwelt BAFU, 2023b; Schlegel, 2021). To counteract this increasing loss, a national biodiversity strategy was adopted in 2012, which was reinforced by the "Aktionsplan Biodiversität 2017" (Aktionsplan des Bundesrates, 2017; Schlegel, 2021).

2.2.1 Threats to Biodiversity

Human activities primarily drive biodiversity loss, a global problem with far-reaching implications for ecosystems, human well-being, and ecosystem resilience. The key drivers include land use change and unsustainable land use practices, overexploitation of resources, pollution, and climate change (Hogue & Breon, 2022; Nordberg & Schwarzkopf, 2023). Biodiversity loss degrades ecosystem processes, reduces resilience to environmental change, and negatively impacts human societies (Hoban et al., 2020; Hughes et al., 2008). Habitat destruction is the leading cause of biodiversity loss. Habitat destruction occurs when natural ecosystems are converted into agricultural land and urban areas. Fragmentation compounds habitat destruction by splitting habitats, disrupting ecological processes, and accelerating species extinction (Chase et al., 2020). Pollution includes chemical runoff, plastic, and air pollution, and it degrades habitats, with the potential to directly affect species. Pollutants alter ecosystem processes and reduce the possibility of species survival (Jaureguiberry et al., 2022). Climate change also affects biodiversity by altering species distributions and ecosystem processes. Rising temperatures and altering precipitation regimes challenge the resilience of many species (Chase et al., 2020; Hogue & Breon, 2022). Loss of biodiversity thus reduces this resilience, which leaves ecosystems more vulnerable to climate change, pollution, and other stressors.

DPSIR Framework applied to Switzerland

The DPSIR framework is a tool for analysing and managing environmental issues, including the loss of biodiversity. It provides a structured approach by identifying the key components that influence biodiversity outcomes. DPSIR stands for *Drivers*, *Pressures*, *State*, *Impact*, and *Response*, each representing a step in understanding the causes and effects of biodiversity decline (Maxim et al., 2009).

Drivers include the fundamental causes of biodiversity loss, such as human activities (deforestation, urbanization, and agricultural expansion) and factors such as climate change (Maxim et al., 2009). In Switzerland, land use change, including the development of energy resources, infrastructure expansion, and the modification of agricultural practices are major drivers (Bundesamt für Umwelt BAFU, 2024a). These drivers lead to *Pressures* that directly impact ecosystems, including habitat destruction, pollution, overexploitation, and the introduction of invasive species. Large-scale land use, soil sealing, habitat fragmentation, and nitrogen and pesticide inputs pose a threat to biodiversity in Switzerland. The loss of agricultural land, habitat fragmentation caused by urbanization and infrastructure, and the increased use of fertilizers in agriculture (all drivers) are major contributors to this pressure. The most exposed areas are the lowlands, where land development and habitat fragmentation are most severe. The Alps are also facing growing pressures from increased agricultural intensification and tourism activities, including more ski runs and the expansion of outdoor recreational areas (Bundesamt für Umwelt BAFU, 2024a). The *State* of biodiversity refers to its current condition, including the health of ecosystems and the diversity of species that occur (Maxim et al., 2009). Unfortunately, biodiversity in Switzerland is in

rather poor condition. A third of all species, and half of the country's habitats remain threatened, despite some local successes. Losses are most noticeable in lakes, rivers, and agricultural landscapes, where the impact of habitat degradation and pollution is particularly severe. Many of Switzerland's unique ecosystems, such as marshes, alluvial zones, and dry grasslands, have deteriorated conditions over the past two decades; and some species have been lost entirely (Bundesamt für Umwelt BAFU, 2024a). As biodiversity declines, the *Impacts* on both ecological functions and human well-being become more apparent. Ecosystem services, such as carbon storage, soil fertility, water purification, and protection against natural hazards (such as avalanches and rockfalls) are at risk. Biodiversity loss diminishes ecosystem resilience, reducing the ability of ecosystems to respond to challenges such as climate change. For Switzerland, economic and social losses from biodiversity decline are significant, as the country depends on it for agriculture, tourism, and public health. Biodiversity loss endangers genetic resources that are crucial for the development of new medicines and crops (Bundesamt für Umwelt BAFU, 2024a). Finally, *Responses* refer to the actions taken to mitigate biodiversity loss. In Switzerland, the Swiss Biodiversity Strategy outlines a framework to conserve biodiversity and ecosystem services. There has been some progress, including protected areas and subsidies for sustainable farming practices. The government has committed to increasing the proportion of protected areas and improving connectivity between habitats. However, there are still challenges remain in implementing these measures effectively (Bundesamt für Umwelt BAFU, 2024a; Maxim et al., 2009).

3 Literature Review

The expansion of ground-mounted photovoltaic (PV) plants (GMPP) offers future potential for renewable energy production, but also raises important concerns regarding their ecological impacts, especially with regard to biodiversity. This chapter synthesizes the existing research to provide thorough insight into these impacts. This chapter begins with an examination of the direct potential land use impacts of PV installations on soil conditions, plants, and animals, especially with respect to loss of species intactness and competition, as well as microclimate impacts. It also examines potential mitigation efforts such as *Ecovoltaics*, and describes biodiversity, including the challenges of understanding and defining biodiversity. It identifies possible approaches for site-selection of solar farms, including Geographic Information Systems (GIS), Multi-Criteria Decision Analysis (MCDA), and the Analytic Hierarchy Process (AHP), and describes how they relate to this analysis. It also discusses the problem that there are challenges regarding open data.

3.1 Direct Impacts of PV Installations on Biodiversity

The expansion of solar PV has been important for facilitating the low carbon energy transition, but it has resulted in changes in land use. GMPP in particular require large amounts of space, creating concerns about habitat fragmentation, disruption of ecosystem functions and services, and competition with other land uses such as agriculture and nature conservation. In light of this, the following sections examine the specific ecological impacts of PV installations, with a particular focus on changes in habitat connectivity, changes in soil properties, and impacts on local flora and fauna.

3.1.1 Land Use Change

The primary environmental impact of GMPP is land use change (LUC) (Sánchez-Zapata et al., 2016). Among the various impacts of LUC due to PV installations, the disruption of landscape connectivity is particularly significant. Landscape connectivity is critical to wildlife protection and refers to the degree to which a landscape facilitates or inhibits the movement of animals between resources. This movement can be significantly changed by large-scale GMPP, because they tend to fragment habitats or, in some cases, serve as ecological corridors (Boscarino-Gaetano et al., 2024; Gasparatos et al., 2017; Gómez-Catasús et al., 2024). Furthermore, habitat fragmentation can disrupt the genetic exchange among individuals, leading to isolated populations of flora and fauna, which increases their vulnerability to environmental changes and genetic bottlenecks, and complicates conservation planning (Levin et al., 2023). Species that rely on large, contiguous habitats, such as migratory birds and wide-ranging mammals, may experience increased mortality and reduced breeding success due to these disruptions

(Levin et al., 2023). Furthermore, exposure to concentrated solar energy (heat) at solar tower facilities poses a significant risk to animals (Smith & Dwyer, 2016).

In addition to the direct impact of GMPP themselves, associated infrastructure, such as access roads and power lines, further contributes to ecological pressures. Power lines, for instance, pose collision risks for birds (Levin et al., 2023), thus exposing them to impact trauma. Therefore, PV infrastructure could be especially problematic in Alpine areas where GMPP are planned, as these regions currently lack any major infrastructure.

3.1.2 Soil Degradation

GMPP are further known to influence soil properties and microclimate. Although GMPP impacts on soil quality vary significantly across sites and depend on the local ecosystem as well as previous land use, several studies have indicated that GMPP reduce soil quality indices (Dvořáčková et al., 2024; Vervloesem et al., 2022; Zhang et al., 2023). However, the extent of these influences remains largely uncertain due to the limited amount of research available. Several factors, such as topography, former land use, and local ecosystem, determine how GMPP influence soil properties (Dvořáčková et al., 2024; Moscatelli et al., 2022). The next section summarizes key findings from existing literature, though specific effects on the soils in Switzerland remain insufficiently studied.

The study by Moscatelli et al. (2022) highlights the limited evidence for GMPP-induced changes in soil properties. It aims to expand knowledge in this area and finds that PV installations can affect physical soil properties, lowering water content and increasing temperature, most likely due to associated shifts in organic matter content. These changes are a result of modified microclimatic conditions, including shading, albedo changes, and shifts in evapotranspiration patterns (Zhang et al., 2023). An example of such soil quality impairments is the shading of open spaces by PV systems (Gasparatos et al., 2017; Zhang et al., 2023). This shading can affect soil quality, altering water content levels, daytime air temperature, albedo, and photosynthesis rates (Armstrong et al., 2016; Gasparatos et al., 2017; Gómez-Catasús et al., 2024; Schlegel, 2021; Vervloesem et al., 2022; Zhang et al., 2023). As a result, habitat degradation, ecosystem fragmentation, and limited wildlife movement may occur (Blaydes et al., 2021; Lafitte et al., 2022). Furthermore, the resulting microclimatic changes also affect soil chemistry, specifically increasing electrical conductivity and pH, which in turn negatively affect plant growth, leading to reduced biodiversity and microbial activity in soil beneath PV panels. These findings are also in line with the study of Armstrong et al. (2016), which indicated significant decreases in soil carbon and nitrogen storage, negatively impacting microbial decomposition and nutrient cycling. Microbial functional diversity and enzymatic activity similarly decline beneath PV panels as a result of these changes.

One of the factors contributing to the mentioned temperature changes is the so-called "PV Heat Island Effect", which is similar to the *Urban Heat Island Effect*. This effect describes the process of solar panels

trapping and re-radiating heat, leading to local warming. Such warming can result in substantial temperature contrasts between PV-shaded areas and surrounding environments, influencing soil nutrient cycling and water-holding capacity, and potentially accelerating degradation (Barron-Gafford et al., 2016; Armstrong et al., 2016). These microclimate changes, by increasing local temperatures, pose particular risks to sensitive habitats (Gómez-Catasús et al., 2024; Lafitte et al., 2022).

Although GMPP are generally considered reversible, long-term soil degradation raises concerns about recovery time following decommissioning. Microclimatic and soil composition alterations cause patchy soil fertility, which may take time to normalize but should not prevent eventual agricultural reconversion (Moscatelli et al., 2022).

3.1.3 Flora

While GMPP installations have environmental consequences that apply to soils, they also have ecological implications for local flora. The way that these impacts, whether positive or negative, may combine to influence plant growth, biodiversity, and ecosystem health is complex. A negative impact is that PV panels create shading and reduce sunlight, decreasing the amount of light available for photosynthesis. The shading would limit growth for any vegetative plant species growing underneath the PV panels (Armstrong et al., 2016; Zhang et al., 2023). Additionally, changes to soil moisture and temperature can affect evapotranspiration, which can lead to changes to water distribution patterns and can make some areas become too dry and other areas become too wet which causes further changes to plant species composition and arrangement (Moscatelli et al., 2022). Collectively, all of the foregoing effects can have negative impacts on biodiversity through displacing sensitive plant species, degrading habitats and limiting opportunities for native vegetation to develop (Vervloesem et al., 2022). Similarly, changes to nitrogen and carbon sequestration due to, for example, changes to the microbial communities in the soil beneath the GMPP, can disrupt nutrient cycles which have further negative impacts on plant diversity and productivity (Armstrong et al., 2016).

However, there are potential ecological benefits provided by GMPP installations. For example, providing shade and shelter may provide opportunities for shade tolerant species to establish, hence potentially increasing plant biodiversity in localized areas (Gómez-Catasús et al., 2024). Additionally, carefully locating GMPP may exclude land from intensive land use opportunities like heavy grazing, excessive use of fertilizers and pesticides, and create a space for native and less competitive plants to establish (Evans et al., 2023).

3.1.4 Fauna

Beyond their impact on soil and vegetation, GMPP installations also influence the fauna within and around the project sites. As with flora, GMPP can have both negative and positive impacts on fauna, affecting habitat availability, animal behaviour, and population dynamics. On the negative side, the shading and structural changes caused by GMPP disrupt habitats for a variety of species. Thus, the destruction of open spaces and changes in vegetation reduce food availability and alter the breeding ground for certain fauna (Armstrong et al., 2016). Additionally, human activity, noise, and traffic associated with the installation and operation of PV systems can disturb wildlife and create stress for local animal populations (Evans et al., 2023). Furthermore, PV arrays may also form barriers to movement for species reliant on open landscapes or extensive territories to feed or mate (Schlegel, 2021; Vervloesem et al., 2022).

Insects are one of the animal groups that PV installations affect. Insects play an important role in pollination and thus contribute significantly to ecosystem services and food production (Blaydes et al., 2021). Studies have shown a lower abundance and diversity of pollinators beneath PV panels, which is attributed to changes in vegetation structure (Gómez-Catasús et al., 2024; Lafitte et al., 2022). However, if GMPP are integrated into agricultural landscapes, they may have positive effects on pollinators. Because the leading causes of pollinator decline include intensive local agricultural practices, use of insecticides, and climate change, properly managed PV installations could serve as refuges for pollinators (Blaydes et al., 2021). Secondly, higher temperatures could also have beneficial effects on insects, and GMPP could create a diversity of microclimates that can support different species (Blaydes et al., 2021). Montag et al. (2016) observed a higher abundance of butterflies and bumblebees in GMPP compared to control locations. However, GMPP can also pose risks to specific insect populations and water birds. The so-called "Lake Effect" can serve as an ecological trap for aquatic insects, leading them to mistake PV panels for water surfaces (Gómez-Catasús et al., 2024; Lafitte et al., 2022; Smith & Dwyer, 2016).

Birds are another species affected. Reflections from panels can cause collisions and injury (Gasparatos et al., 2017; Gómez-Catasús et al., 2024; Sánchez-Zapata et al., 2016; Schlegel, 2021; Taylor et al., 2019). Despite these risks, evidence suggests that well-regulated GMPP can facilitate enhanced biodiversity, particularly on formerly degraded or intensively used land. Properly planned GMPP can offer refuge to various species by reducing the impacts of intensive agriculture as well as by forming corridors for habitat (Boscarino-Gaetano et al., 2024; Montag et al., 2016; Nordberg & Schwarzkopf, 2023; Schlegel, 2021; Stoms et al., 2013). Because most of the area beneath the GMPP remains usable, it can be used for the promotion of biodiversity if utilized correctly (Schlegel, 2021; Taylor et al., 2019). For pollinators, on which many ecosystem services depend, GMPP may even serve as refuges by minimizing the effects of intensive agriculture, pesticide use, and climate change (Uldrijan et al., 2022).

Furthermore, amphibians and reptiles could benefit from a high insect density (Schlegel, 2021). Strategically placed GMPP might decrease temperature extremes in certain habitats, providing cooler microclimates, which can be beneficial for species that struggle with heat stress (Zhang et al., 2023). Moreover, the simultaneous use of PV systems and farming and agricultural areas (so-called *Agrovoltaics*) can support diverse fauna by maintaining ecological corridors and reducing land fragmentation, allowing animals to move more freely across the landscape (Evans et al., 2023). In this way, GMPP can offer both challenges and opportunities for fauna, depending on their design, location, and integration with local ecosystems.

3.1.5 Lack of Research

Even though numbers of GMPP are growing, there remain large research gaps concerning their ecological impact. One important area for further research is wildlife utilization of GMPP, including how species utilize them and whether they act as refuges or barriers (Gómez-Catasús et al., 2024). Additionally, the influence of single PV configurations, for example the landscape type, on biodiversity and ecosystem functions is not well documented. There is also a need to assess the effectiveness of management, mitigation, and compensation measures both within and outside of GMPP to maximize biodiversity benefits (Gómez-Catasús et al., 2024). The size of GMPP is a key driver of their environmental impact, but its effects have not yet been sufficiently studied (Gómez-Catasús et al., 2024). More broadly, ecosystem functions and services related to PV infrastructure have been studied insufficiently (Zhang et al., 2023). Also, there is a mismatch between the geographic region covered by the literature and the regions where PV is installed most around the world; most studies are conducted in areas that do not reflect the dominant deployment regions (Gómez-Catasús et al., 2024; Lafitte et al., 2023). Yet another underexplored issue is the impact of GMPP on grasslands and agricultural landscapes particularly regarding the effects of PV deployment on biodiversity and ecosystem services (Gómez-Catasús et al., 2024). Experimental setups, such as Before-After-Control-Impact (BACI) studies are scarce. Schlegel et al. (2021) suggest that the scarcity of experimental setups prevents researchers from quantifying the true ecological consequences of GMPP. Further research is necessary to understand the local impacts on biodiversity, particularly in alpine areas where the planning of GMPP is increasing (Schlegel, 2021). Additionally, there is a spatial mismatch between areas best suited for PV production which consider environmental constraints and those with the greatest energy demands, which is also a concern that has been observed in several contexts (Hermoso et al., 2023). Addressing these knowledge gaps is necessary to ensure that the development of solar energy infrastructure aligns with biodiversity conservation goals.

3.2 Potential Mitigation Strategies

There are several strategies to mitigate the impacts PV installations have on biodiversity. The easiest way is to locate PV installations in places already impacted by humans (e.g., parking lots, rooftops) (Hernandez et al., 2015; Schlegel, 2021). While this approach offers significant potential, it is not the focus of this study. Another key strategy is to avoid areas of high biodiversity value or protection status as well as areas where the ecological impact would be too severe (Stoms et al., 2013). These high-conservation-value areas must be mapped and protected by systematically collecting and analysing biological data (Stoms et al., 2013). In a simplified manner, this approach has been applied in this thesis. Areas of high value for the ecosystem are generally excluded from the analysis; see Section 4.1 for a detailed description of the exclusion criteria.

A more applicable mitigation strategy involves the design and management of the GMPP itself. So-called *Ecovoltaics* can provide ecological benefits to ecosystems while minimizing negative impacts by adequate sitings, construction techniques and land management practices (Carvalho et al., 2024; Nordberg & Schwarzkopf, 2023). Figure 3 illustrates the implementation of *Ecovoltaics* as a mitigation strategy for GMPP. This strategy adds additional structures and ecological niches to the area designated as B, which promotes biodiversity.

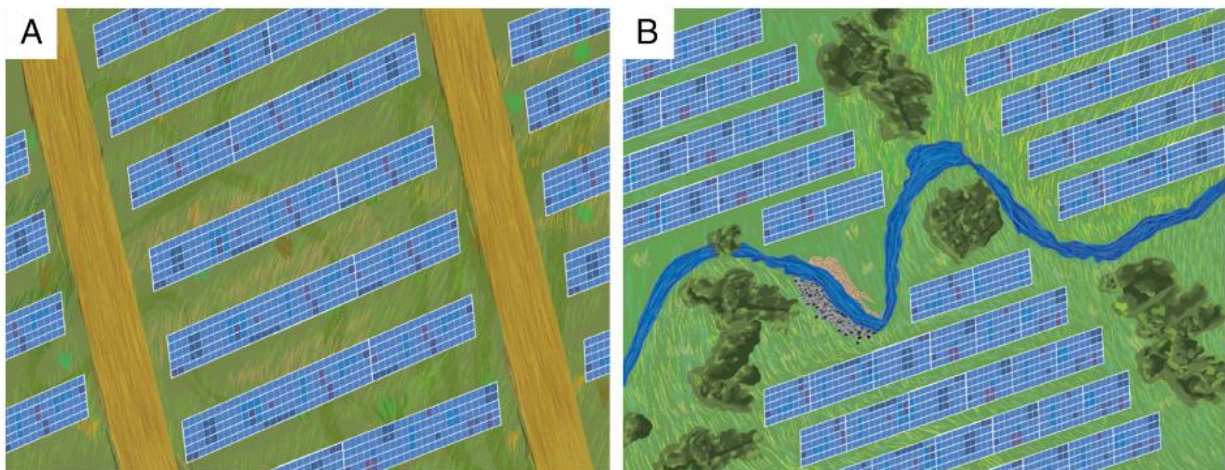


Figure 3: Application of *Ecovoltaics* in GMPP Design for Ecological Mitigation (from Boscarino-Gaetano et al. (2024), p. 1858)

PV site planning should include and plan for ecological corridors, buffer zones with native vegetation, and undeveloped strips of land between installations to reduce habitat fragmentation. Not using impermeable fencing, or using a wildlife-friendly designs with openings at the bottom, can also enhance species movement. Studies show that mobile wildlife is affected less in space when alternative habitats are within easy reach (Schlegel, 2021).

GMPP can also generate opportunities to enhance biodiversity, particularly in intensively used agricultural landscapes. Studies in Germany showed that extensively managed solar parks supported valuable bird habitats, so it is feasible to sustainably support biodiversity (Schlegel, 2021). Moreover, the presence of shelter and nesting sites in PV arrays can support high population levels in certain species. For example, gaps of at least three meters between panel rows can provide more sunlight exposure, benefiting potentially reptile populations. Enclosed PV sites can even provide reptiles and small mammals protection against human disturbances and predators (Schlegel, 2021).

Blaydes et al. (2021) offer ten evidence-based recommendations for optimizing pollinator habitats in GMPP, for example, to boost food and reproductive resources, improve microclimatic diversity, and improve habitat heterogeneity while preserving connectivity with surrounding landscapes. Similarly, the most efficient biodiversity-enhancing PV designs modify artificial habitat structures to species-specific requirements (Boscarino-Gaetano et al., 2024). Consequently, research shows that sustainable land management practices can balance renewable energy production and conservation without fully utilizing the negative impacts of disturbance while still harnessing solar energy (Gómez-Catasús et al., 2024).

3.3 Biodiversity: Definition and Challenges

The previous chapter repeatedly discussed biodiversity without providing a clear definition or explanation. The aim of this chapter is to clearly define this term and outline the difficulties that arise with these definitions. Biodiversity is a contraction of "biological diversity" and refers to the natural variability of living organisms, and the ecological complexes of which they are a part. These include genetic diversity within species, the diversity of animals, plants, fungi, and microbes, as well as the diversity of habitats and ecosystems in which these organisms live. This multidimensional concept reflects the complexity and interdependence of life on Earth, involving interactions among organisms, as well as between organisms and their physical environment. Biodiversity is necessary to maintain ecosystem functions and services that are essential to human well-being and environmental health. While its importance is widely accepted, the term does not have a universally accepted definition and is often applied with varying implications in scientific and policy contexts (Feest et al., 2010; Hamilton, 2005; Kaennel, 1998; Mendoza & Prabhu, 2001; Purvis & Hector, 2000; Redford & Richter, 1999; Regan et al., 2007). This chapter provides an overview of these challenges and sets the stage for discussing the impacts of photovoltaic installations on biodiversity (see the definition of key terms in the Glossary).

3.3.1 Defining Biodiversity

It is difficult to define biodiversity since the term can be used in different contexts. Swingland (2001) argues that the three main factors of biodiversity are endemism (geographical uniqueness), species diversity (number of species), and the level of threat to species and habitats. These factors help to address the multidimensional aspect of biodiversity by emphasizing both its biological and geographical uniqueness, along with its vulnerability. Endemism is a term used to denote a species or an ecosystem that is unique to a given geographic area, for instance, an island, mountain range, or other isolated ecosystem (Swingland, 2001). These species do not exist elsewhere in the world. Endemism adds a geographical component to biodiversity. High-endemism regions are typically considered biodiversity hotspots because they harbour species that cannot be replaced anywhere else in the world. Conservation of endemic species is crucial because their extinction means an irreversible loss of biodiversity that cannot be made up for by species elsewhere (Purvis & Hector, 2000). Species diversity is the quantity of species (species richness) in a specific area and their relative abundance (evenness). It is one of the best-documented components of biodiversity (Kaennel, 1998; Purvis & Hector, 2000; Redford & Richter, 1999). Species diversity encompasses the diversity of ecosystems and their ability to provide important functions, such as pollination, nutrient cycling, and carbon sequestration. Most species-diverse regions are more resilient to disturbances, such as climate change or invasive species, because they contain a broader set of organisms that promote ecosystem resilience (Hoban et al., 2020; Hughes et al., 2008). Swingland's (2001) focus on species diversity aligns with traditional approaches to measuring biodiversity, but also encourages the consideration of additional factors such as endemism and ecological processes. The threat to species and habitats highlights the degree to which species or ecosystems are at risk of extinction or degradation due to human actions or natural changes. Examples of threats include habitat destruction, climate change, pollution, overexploitation, and the introduction of invasive species (Hoban et al., 2020; Swingland, 2001). The determination of threat status for species and habitats is a means for prioritizing conservation efforts and deciding where to spend resources. Without identifying and mitigating threats, we can neither maintain nor restore biodiversity. This factor underscores the significance of concentrating conservation efforts in areas most in need (Hogue & Breon, 2022). Each factor is valuable, but the relationships between them are important to capture total biodiversity (Regan et al., 2007).

According to DeLong (1996), biodiversity has the following three main attributes. Composition provides the "raw materials" of biodiversity and is the easiest to quantify. It serves as the basis for many biodiversity assessments, such as species richness (the number of species in a given area) or genetic diversity. Composition includes the identity and richness of biotic components, such as genes, organisms, populations, age classes, species, taxonomic categories, and trophic levels, along with their relative abundance. Structure refers to the arrangement of biotic elements within ecosystems, including horizontal and vertical elements of a community or landscape. Structure determines how organisms interact with their environment and influences processes. Function represents the ecological roles and

processes that organisms and ecosystems perform, such as nutrient cycling, energy flow, and pollination. Functional biodiversity supports ecosystem services that are critical for human well-being and environmental stability. The loss of functional diversity can destabilize ecosystems. DeLong (1996) defines biodiversity in his paper as follows: “Biodiversity is a state or attribute of a site or area and specifically refers to the variety within and among living organisms, assemblages of living organisms, biotic communities, and biotic processes, whether naturally occurring or modified by humans. Biodiversity can be measured in terms of genetic diversity and the identity and number of different types of species, assemblages of species, biotic communities, and biotic processes, and the amount (e.g., abundance, biomass, cover, rate) and structure of each. It can be observed and measured at any spatial scale ranging from microsites and habitat patches to the entire biosphere” (DeLong, 1996, p. 745). This variability can be measured at multiple scales, from genes and species to communities and ecosystems (Kaennel, 1998), and across different spatial scales, ranging from microsites to the entire biosphere (DeLong, 1996).

With reference to these findings, biodiversity can be defined as follows: Biodiversity is the variety among living organisms at every level of biological organization, that is, at the genetic, species, and ecosystem levels. It involves the composition (identity and diversity of biotic components), structure (spatial arrangement and patterns of these components), and function (the roles and processes supporting ecosystems). Biodiversity operates over a spectrum of spatial scales ranging from local ecosystems and microsites to the world biosphere and is shaped by both human and natural processes. Although ecological and evolutionary processes are responsible for maintaining biodiversity, they are not considered part of biodiversity itself (DeLong, 1996). Conservation of biodiversity in human-altered landscapes requires a trade-off between consumptive and non-consumptive use to maintain its structural, functional, and compositional attributes. This is especially relevant where native biodiversity is low or where human modification has severely altered ecosystems (Redford & Richter, 1999).

3.3.2 Challenges when defining Biodiversity

While biodiversity is a widely accepted concept, a clear definition of that term remains rather unclear (Swingland, 2001). Understanding biodiversity is challenging due to its complexity, the numerous subject matter areas involved, the spatial and temporal contexts involved, and the sociopolitical contexts in which it is discussed (e.g., urban planning and development, climate change adaptation, resource extraction) (Hamilton, 2005; Purvis & Hector, 2000). The complexity derives not only from the various characteristics of biodiversity, per se, but in part from the social and political issues associated with its discussion (Hamilton, 2005; Purvis & Hector, 2000). There are three basic components of biodiversity, including genetic diversity, species diversity, and ecosystem diversity (Hoban et al., 2020; Hughes et al., 2008; Kaennel, 1998). Each occurs at a different biological level and requires different measurements. Given the definition of DeLong (1996), biodiversity also involves the structure (e.g., spatial patterns),

function (e.g., nutrient cycling), and composition (e.g., identity of species and genes) of the system (DeLong, 1996). Therefore, incorporating all of these factors in a single definition is difficult. Biodiversity occurs across multiple spatial and temporal scales, microsites to the biosphere (DeLong, 1996; Purvis & Hector, 2000). What defines biodiversity at one spatial or temporal scale (e.g., the genetic diversity of a population) may or may not describe biodiversity at another scale (e.g., the biodiversity of an ecosystems across a region). Additionally, biodiversity is often discussed in the context of human-altered ecosystems, where defining “native” versus “modified” biodiversity is complex (DeLong, 1996). Human activities, including habitat changes, resource extraction, and pollution, all affect biodiversity because they all represent a redistribution of flows of matter and energy at some, albeit measurable, level (Redford & Richter, 1999). Such alterations often result in genetic loss, species loss, community reorganization, and disruption of ecosystem processes. Conservation, therefore, must address both natural and human-altered systems, as purely "native biodiversity" is increasingly rare in a human-dominated world (DeLong, 1996; Redford & Richter, 1999). Therefore, human activities blur the line between what is "natural" and what is "artificial," making it difficult to define the baseline state of biodiversity. Definitions must accommodate both the preservation of biodiversity in undisturbed ecosystems and its sustainable use in human-dominated landscapes (Redford & Richter, 1999). Balancing these goals often introduces ambiguity. Biodiversity is closely tied to abiotic ecological processes (e.g., nutrient cycling, energy flows) that maintain it, yet these processes are not inherently “biotic” (DeLong, 1996). Including abiotic factors in biodiversity definitions risks conflating biodiversity with ecosystem functions and services. Furthermore, biodiversity is relevant across disciplines such as ecology, genetics, conservation biology, politics, and economics. Each field prioritizes different aspects (Purvis & Hector, 2000). While ecologists would highlight species interactions and ecosystem processes, geneticists might highlight intraspecific variation. Policymakers would likely highlight the economic and cultural significance of biodiversity. Emphasising different aspects creates multiple definitions that are useful for specific purposes but may not be universally applicable. Biodiversity is now a political phrase and is widely used in policy circles to initiate action towards conservation (Redford & Richter, 1999). Effective political definitions must be broad and thus less scientifically specific and harder to quantify. DeLong (1996) argues that a definition must be clear, consistent, and meaningful to facilitate effective communication and cooperation between countries, disciplines, organizations, and individuals who are working on conservation. It needs a semantic and etymological foundation to be consistent with the meanings of other ecological terms and not to incline towards any particular discipline (DeLong, 1996).

Overall, the complexity, multidimensionality, and context-dependence of the term biodiversity ensure that any definition remains inherently contested and requires a flexible and precise framework for effective conservation and policy application.

3.4 Methods for Solar Farm Site Selection

Geographic Information Systems (GIS) are powerful decision-making tools that facilitate the identification, analysis, and visualisation of spatial data. They enable comparisons between different spatial units by integrating both qualitative and quantitative assessments (Uyan, 2013; Villacreses et al., 2022). Through mapping and analysing ecological data, GIS supports informed decision-making about the ecological significance of an area. These processes provide both ecological and numerical analysis; interpretation often becomes an integral part of anticipating multidimensional environmental concerns, such as the effect of GMPP on biodiversity. GIS also provides greater precision in making well-informed decisions, including decisions about where to locate renewable solar energy photovoltaic (PV) installations (Uyan, 2013). GIS facilitates spatial data analysis through two principal representation modes: raster (pixel-based, storing uniform-resolution data such as location or altitude) and vector (geometric objects such as points, or polygons that describe spatial boundaries) (Villacreses et al., 2022). The mapping process involves taking a geographic overview, collecting data, standardising data, defining scale and resolution, and ensuring consistency throughout the process (Villacreses et al., 2022). GIS provides decision-makers with assessments of ecological and technical suitability by overlaying different spatial datasets. This facilitates the identification of optimal locations for solar farms.

Multi-Criteria Decision Making (MCDM) is a support model for decision-making that evaluates multiple factors simultaneously and compares the trade-offs among different alternatives (Adem Esmail & Geneletti, 2018). The method is particularly useful in complex decision-making problems, for instance, site selection for solar farms, where multiple and often conflicting objectives, ranging from environmental constraints to technical and economic feasibility, must be considered (Adem Esmail & Geneletti, 2018). MCDM helps in organizing decision problems, particularly when it is not possible to reduce them to a single goal. It follows a structured approach that includes (Adem Esmail & Geneletti, 2018):

- **Problem structuring** – Defining the objective and identifying key criteria.
- **Analysis** – Comparing and analysing criteria, aggregating results, and performing a sensitivity analysis.
- **Decision-making** – Integrating results to make a final decision.

The engagement of stakeholders is a fundamental aspect of MCDM, as they contribute to the process by collecting data (Adem Esmail & Geneletti, 2018). Within energy planning, MCDM is considered one of the most effective methods of decision-making, particularly in biodiversity-sensitive areas where there are conflicting land-use priorities that need to be adequately balanced, as it includes practical methods that can be used to evaluate and plan energy projects and focus on improving either one or several key factors (Marques-Perez et al., 2020).

The Analytic Hierarchy Process (AHP) is a hierarchical decision-making model developed by Thomas Saaty in the 1970s (Saaty, 1977, 1987). AHP is one of the most widely used methods in MCDM to evaluate complex problems through a systematic method: the AHP method allows complex problems to be broken down into manageable hierarchy. AHP is based on pairwise comparisons to weight each of the various criteria based on expert judgement. As a result, stakeholder engagement facilitates a transparent and participatory decision-making process (Marques-Perez et al., 2020; Villacreses et al., 2022).

AHP follows these key steps (Mu & Pereyra-Rojas, 2017; Saaty, 1977, 2008):

- **Decision on criteria** - Identification and selection of relevant criteria that influence the decision
- **Assignment of weights** – Experts assign weights to determine the relative importance of each criterion.
- **Calculation of consistency ratio** – Ensures that decision-makers’ judgments remain logically consistent.
- **Sensitivity analysis** – Evaluates how robust the assigned weights are.

AHP can combine both quantitative and qualitative criteria, which is an advantage and suggests it is an especially good candidate for complicated site selection problems (Günen, 2021). Still, there are disadvantages since it is an anthropocentric method that only relies on experts’ judgment resulting in a possibility of bias or inconsistency. Weights are based on subjective judgments and form the basis for the final decision (García Márquez et al., 2017). Regardless, AHP is mostly considered a valid method for solar energy planning, including systematic evaluation and the ability to facilitate public participation (Günen, 2021).

The integration of GIS and AHP in an MCDM framework is a good method for determining appropriate locations for solar farms, as this is a classic MCDM problem: site selection must be based on multiple factors including technical infrastructure, land use and environmental constraints (Uyan, 2013; Villacreses et al., 2022). The general procedure consists of:

- **GIS-based site screening** – GMPP require vast land areas. GIS helps identify potential sites by analysing spatial constraints such as land availability, terrain slope, and solar radiation levels (Marques-Perez et al., 2020). *(This step was mostly done by ARE)*
- **Factor evaluation using MCDM** – Various criteria (e.g., environmental impact, proximity to grid infrastructure, and economic feasibility) are assessed to ensure a well-rounded decision.
- **AHP for site suitability ranking** – Expert judgement is used to give weight to criteria.
- **GIS and AHP integration for final selection** – Combining GIS-based spatial analysis with AHP allows for efficient decision-making.

3.5 Open Data in Ecological and Biodiversity Science

At the beginning of this thesis, it was an important step to find suitable data. It was not possible to collect primary data due to the time constraints and complexity of a master's thesis. However, it was harder than anticipated to find adequate biodiversity data, which indicates underlying issues with data availability. This issue led to the decision to include this chapter, which explores the role of open data, its challenges, and its limitations in the field of ecology and biodiversity science. Through a literature review, this chapter examines the principles of open data, barriers to data sharing, and strategies to enhance transparency and collaboration in scientific research.

The open data philosophy has two contrasting meanings: *libre* access and *gratis* access (Murray-Rust, 2008). *Libre* access grants users the right to freely inspect, modify, and redistribute data without technical or legal restrictions. *Gratis* access provides data free of charge but with restrictions in use or resubmission, which can hinder its transformative potential (Murray-Rust, 2008). As Murray-Rust (2008) notes, the open access movement in science has a predisposition towards *gratis* access, which can limit the full potential of *libre* data. "True" open science requires data to be freely accessible and reusable to maximize its scientific and societal impact.

Data are a key component of ecological research. They allow scientists to explore hypotheses, validate models, and address environmental problems (Reichman et al., 2011). Despite their importance, ecological data are often not publicly available. Reichmann et al. (2011) estimate that less than 1% of ecological data collected are shared publicly after publication (p. 703). Most datasets are either lost, kept privately or poorly documented. Instead of sharing raw data, researchers typically publish interpretations of data in the form of journal articles or presentations, limiting opportunities for reproducibility and data synthesis (Reichman et al., 2011).

There are several reasons why biodiversity data are limited. Ecological data are inherently scattered and usually stored in small, independently managed datasets owned by individual researchers or institutions (Reichman et al., 2011). These datasets are highly heterogeneous and cover a wide range of taxa, ecosystems, methodologies, and time periods. This heterogeneity complicates attempts to standardize and combine data, as datasets differ in format, quality of metadata, or measurement protocols (Michener, 2015). Additionally, data can be transformed multiple times through aggregation, modelling, or analysis and thus it may become difficult to trace their origins or ensure their accuracy (Reichman et al., 2011). For example, data on species occurrence may be inaccurately georeferenced, while data on ecological features may lack essential metadata. This limits their usefulness for large-scale analyses (Bowker, 2000). Cultural and institutional factors further exacerbate the problem. Many researchers are reluctant to share data before they have gained the maximum scientific benefit from it because they fear that others may publish findings first, thereby diminishing their academic recognition (Reichman et al., 2011). Concerns about intellectual property, potential misuse of data, and lack of recognition for data contributions also discourage sharing. Biodiversity science compounds these challenges as it relies on

the integration of datasets from different disciplines such as taxonomy, ecology, genetics, and climatology. Each discipline applies different methodologies and assumptions, resulting in databases that are often incompatible or insufficiently documented (Bowker, 2000).

Technologically and culturally we need changes to reduce these issues. Technology must be robust and comprehensive enough to improve data management systems, and subsequently improve accessibility and interoperability. The Global Biodiversity Information Facility (GBIF) is one such platform that demonstrates the possibilities of centralized access to data and a robust suite of metadata standards for biodiversity data (GBIF, n.d.). These standards allow data to be discoverable and interoperable and, as well as enable researchers to synthesize datasets across studies and disciplinary scales (Costello et al., 2013; GBIF, n.d.). For example, looking at GBIF for a biodiversity analysis allows aggregation of data from multiple sources, and enables researchers to analyse data on a greater scale to investigate and reveal patterns or trends that are not apparent in more localized research. Additionally, using standard data formats and complete metadata protocols can also help limit data heterogeneity issues and problems with data traceability (Michener, 2015).

While technology-based approaches to addressing the management, sharing, and preservation of ecological and biodiversity data are important, they may be inadequate if the institutional and cultural barriers are not also addressed. Reichman et al. (2011) propose that a reward system which links data publication either to funding conditions or demarcation of academic quality that is recognized by the academic community, would help make data sharing easier and more attractive to the researcher. Journals, for example, can provide data with a digital object identifier (DOI) to the datasets thereby allowing authors accessing the datasets to receive formal citation and acknowledgement, while at the same time providing the original author(s) with credit for their product (Costello et al., 2013; Michener, 2015). Funding organisations, too, can use conditional grant awards, one of which logistically is the development of data management plans that promote sharing and openness. Proposing the notion of a collaborative culture can eventually lead to change in attitudes to data sharing and highlight the potential benefits of data sharing to research progress and the overall benefit to our society (Michener, 2015; Reichman et al., 2011).

Effective management of ecological and biodiversity data, including their sharing and reuse, is necessary to promote knowledge and research progress and to address many of the global challenges we face today. Open data offers opportunities for collaboration and improved reproducibility. This allows for the identification of patterns and trends that are normally not possible when research results or datasets exist in isolation (Costello et al., 2013; Reichman et al., 2011).

4 Methodology

In order to mitigate the trade-off between renewable energy and biodiversity, there is a need for a solid, systematic approach for siting ground-mounted photovoltaic (PV) plants (GMPP). This chapter describes the process followed to create a spatial decision-support tool to account for biodiversity and species in the site selection of PV systems across Switzerland. Based on the geodata model developed by the Federal Office for Spatial Development (ARE), the methodology incorporates biodiversity indicators including *Species Richness*, *Species Diversity*, and *Habitat Quality* with the use of Geographic Information Systems (GIS), Multi-Criteria Decision Analysis (MCDA), and the Analytic Hierarchy Process (AHP). This chapter describes the data sources, expert weighting methods, and analytical steps with reliance on Python and QGIS for the spatial analysis.

4.1 ARE Model Description

ARE is a Swiss federal agency. It plays a central role in planning and shaping Switzerland's spatial development and ensuring that the country's spatial resources are used sustainably. The ARE's responsibilities include spatial planning such as sustainable urban development, and promoting balanced economic, social, and environmental development in Switzerland. The ARE aims to promote compact, resource-efficient, and climate-adapted urban development while protecting landscapes, natural habitats, and cultural heritage (Bundesamt für Raumentwicklung ARE, n.d.). In this context, ARE developed a geodata model to identify potential locations for free-standing PV systems within cantonal planning frameworks. The model uses a protection-utilization matrix and takes sensitive and protected locations into account.

Utilization Criteria assess the suitability of locations for PV installations based on factors such as global radiation, slope inclination, or infrastructure synergy. *Protection Criteria* evaluate ecological, cultural, and natural importance as well as their legal protection status. Datasets are categorized by the responsible authority (e.g., the Federal Office for Spatial Development, the Federal Office for the Environment, or the Federal Office for Agriculture), protection category (such as biotope conservation, landscape protection, or water reserves), and the respective area type (e.g., raised bogs, forest reserves, or water protection zones). Protection levels are categorized from "Not considered (90)" or "Generally excluded zones (60)" to "Medium protection interest (30)" and "High protection interest (10)". This approach highlights key areas of ecological and cultural importance, including biotopes, amphibian habitats, UNESCO World Heritage Sites, landscapes of national significance, and zones critical for agriculture, forestry, or water management.

Table 1 illustrates examples of utilization criteria. For instance, slope inclination > 40° is considered unsuitable, whereas areas with strong infrastructure synergies are rated highly suitable.

Table 1: Example of Utilization Criteria table developed by ARE (see all criteria in Appendix A; Status September 2024)

<i>Thematic Area</i>	<i>Geospatial Dataset</i>	<i>Usage Interest</i>	<i>Description / Details on Dataset Usage</i>
<i>Technology/Natural Hazards</i>	Slope inclination	Not relevant for usage	Slope inclination > 40°
<i>PV Production Potential</i>	Specific yield, winter semester	Variable usage interest	Expected production per year
<i>Synergy with other Infrastructures</i>	Presence of important transport, tourism, or energy infrastructure	High usage interest	Existing load present

Table 2 shows the protection-utilization matrix, where both protection and utilization criteria are ranked from low to high. Sites with low protection and low utilization values are prioritized for PV development. Within the black rectangle in Table 2 are locations that are “areas worth examining” from a federal perspective. Pink squares indicate Priority 1, orange Priority 2, turquoise Priority 3, and grey Priority 4.

This classification provides a nationwide first estimation of PV suitability. It should be noted that ARE’s analysis is a first estimate based on available nationwide data and does not consider other important factors such as economic efficiency, natural hazards, or electrical grid connections.

Table 2: Protection-Utilization Matrix developed by ARE.

<i>Utilization</i>	<i>Sum of high Utilization Interests (1)</i>	<i>Sum of average utilization interests (2)</i>	<i>Sum of below-average utilization interests (3)</i>	<i>Utilization not a priority (4)</i>	<i>Utilization uninteresting (5)</i>
<i>Protection</i>					
<i>No protection Interests (10)</i>	11	12	13	14	15
<i>Low Protection Interests (20)</i>	21	22	23	24	25
<i>Medium Protection Interests (30)</i>	31	32	33	34	35
<i>High Protection Interests (40)</i>	41	42	43	44	45
<i>Generally Exclusion Area (60)</i>	61	62	63	64	65
<i>No Interest Assessment (70)</i>	71	72	73	74	75
<i>Not Considered (90)</i>	91	92	93	94	95

4.2 Criteria Development

The methodology of this thesis builds upon the model and findings presented by ARE in chapter 4.1. However, it aims to enhance the analysis by emphasizing biodiversity, by defining important biodiversity indicators by integrating results, and therefore by further refining the model developed by ARE.

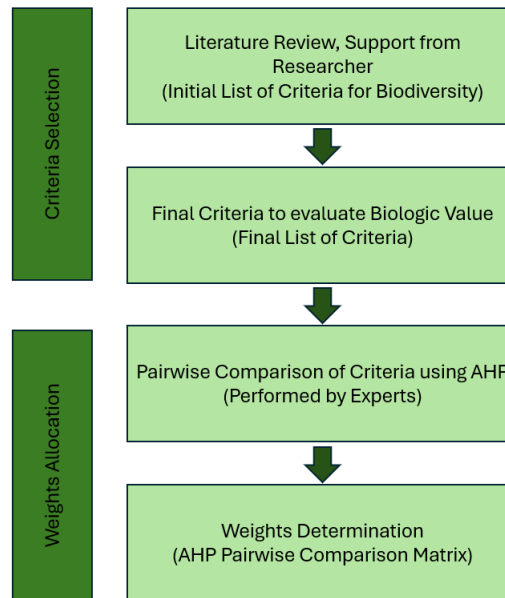


Figure 4: Workflow in AHP for evaluating biodiversity value

Biodiversity encompasses a number of dimensions, including species and ecosystem diversity. Multi-Criteria Decision Analysis (MCDA) is used to systematically assess these complex factors. MCDA makes it possible to weigh up various factors. This facilitates informed decision-making by evaluating trade-offs between competing criteria (Geneletti, 2019). MCDA uses the Analytic Hierarchical Process (AHP) to determine the relative importance of each criterion. The AHP is based on pairwise comparisons of criteria and the derivation of weights that reflect the priorities in a given decision problem. This method relies on expert judgments to determine priority measures (Saaty, 1977; Villacreses et al., 2022).

4.2.1 Selection of the Biodiversity Indicators

In this study, criteria selection is based on a review of relevant literature, especially Regan et al. (2007) and the help of expert insight. The lack of available open data was also a restriction when choosing biodiversity indicators. Regan et al. (2007) separates biotic composition from ecological context and condition; hence, the following indicators were selected to represent the biological value of an area. These indicators are categorized into two main groups:

- **Biotic Composition:** Species Richness, Species Diversity, and Red List Species
- **Ecosystem Function:** Habitat Quality, Habitat Connectivity, Pollinator Abundance, Soil Quality, and Human Recreation Potential

Biotic Composition

Species richness describes the diversity of species in an environment. Species richness refers to the number of different species present within an area or habitat, regardless of their abundance. A high species richness usually signifies a diverse and resilient ecosystem (Purvis & Hector, 2000).

Another useful measure is species diversity, which accounts for not only for the quantity of species but also for their relative abundance (Peet, 1974; Swingland, 2001). Whereas species richness captures the breadth of biodiversity, species diversity illustrates the ecological relevance of certain species in maintaining the structure and function of ecosystem (Colwell, 2009). The Shannon Index is often used for evaluating species diversity. The Shannon (Diversity) Index measures how many distinct species there are (richness) and how evenly they are distributed (evenness). If there are many species in a community and they are spread evenly, then the index is higher (= more diversity) than if one species is dominant (= lower diversity) (Duelli & Obrist, 2003; Peet, 1974).

In addition to these indices, red-listed species are considered. The Swiss Government has divided the species into threatened or endangered categories (Cordillot & Klaus, 2011). Presence of red-listed species is a key measure of conservation value, as red-listed species are often highly sensitive to environmental changes and habitat disturbances. The identification of areas with high densities of threatened species helps prioritize sites for conservation and inform decision-making regarding where PV installations should be avoided (Myers et al., 2000; Regan et al., 2007).

Ecosystem Function

DeLong (1996) argues that ecological attributes are not primarily “bio” (= life), and, thus should be excluded from a biodiversity assessment. However, the functional differences between the lowland and alpine region of Switzerland means that ecological features must be included in defining the selection criteria. Each regions’ structure demonstrates unique biodiversity patterns that lead to varied ecosystem processes such as nutrient cycling, energy flow, and habitat connectivity.

Lowland regions typically support more consistent environmental conditions, milder climates, and for the most part, have multiple varied habitat types: forests, wetlands, and grasslands (Bundesamt für Umwelt BAFU, 2023b). However, human activities such as urbanization, agriculture, and infrastructure development have dramatically impacted habitat quality through land use changes and through the disruption of natural ecological processes (Aktionsplan des Bundesrates, 2017). Habitat connectivity remains a key issue in lowland areas. The BAFU recognizes the current situation as a threat to biodiversity. Where habitat connectivity is impaired, the critical ecosystem functions are impacted, and biodiversity loss leads to losses in productivity (e.g., pollination, seed dispersal and wildlife movement). To address this, BAFU outlines the importance of extending ecological infrastructure (= connectivity) (Aktionsplan des Bundesrates, 2017). The establishment of “sites of connectivity” could reconnect functional links between ecosystems and increase resilience to human influences (Regan et al., 2007).

The alpine biome has extreme and harsh environments, with organisms capable of surviving cold conditions, high UV stresses and short growing seasons. Limitations of organic matter decomposition, low primary productivity and short growing seasons may predispose alpine ecosystems to lower nutrient cycling. These alpine ecosystems include habitats such as meadow, scree, and glacier forelands, many of which harbour a variety of unique flora and fauna, and endemism due to the geographic isolation. As a generalization, alpine habitat would have higher habitat quality as anthropogenic disturbance is lower than temperate lowlands (Bundesamt für Umwelt BAFU, 2023b; Körner, 2021).

Examples related to habitat quality and connectivity show that multiple other processes in an ecosystem also influence biodiversity. Soil quality is a fundamental component on which organic matter depends. Soil has strong influence on plant growth, microbial communities, and overall ecosystem stability (Armstrong et al., 2016; Blaydes et al., 2021). Such soil ecosystem services support nutrient cycles, carbon storage, and water filtration, which benefit and sustain biodiversity in different landscapes. Degradation through erosion, compaction, and pollution can potentially reduce soil fertility and have a negative impact on plant diversity and species relying on these plants for food and shelter (Van Der Plas, 2019).

The *Human Recreation Potential* indicator is associated with biodiversity in many complicated ways. Natural landscapes can be important places for recreational activities and maintain people’s awareness and appreciation of the environment at high levels. High human recreation potential with human presence indicates that ecosystems are functioning well. Typically, bad conditions diminish the possibility of pleasant and sustainable recreation. Therefore, human recreation potential can be assessed as an indicator of ecosystem health and success for biodiversity conservation (Burger, 2000; Külling et al., 2024; Siikamäki et al., 2015).

Table 3 summarizes the indicators used for determining biological value (see the AHP Survey in Appendix B for further detail):

Table 3: Biodiversity Indicators used for AHP Survey

	Indicator	Description
Biotic Composition		
BC1	Species Richness	Species richness refers to the number of different species present in a given area or ecosystem. It is a measure of biodiversity, focusing solely on the count of species, without considering their abundance or distribution.
BC2	Species Diversity	Species diversity is a measure of biodiversity that accounts for both the number of different species (species richness) and the relative abundance of each species in an area or ecosystem. Metrics such as the Shannon Index (see chapter 4.3.3.8) is used to quantify species diversity.
BC3	Red List Species	Red List Species are those identified as threatened and classified on the Swiss Red List, which includes species categorized as vulnerable, endangered, or critically endangered. These species face a high risk of extinction and are recognized as priorities for conservation efforts.
Ecosystem Function		
EF1	Habitat quality	Habitat quality describes the distribution of habitats and their state of degradation, such as the extent of vegetation loss, soil erosion, or pollution. High-quality habitats support biodiversity and sustain essential ecosystem functions.
EF2	Habitat Connectivity	Habitat connectivity refers to the degree to which different habitats are linked, allowing wildlife to move freely between them. It enables species to migrate, find food, reproduce, and adapt to environmental changes. Connectivity is crucial for maintaining biodiversity, supporting healthy ecosystems, and preventing habitat fragmentation, which can lead to isolated populations and decreased genetic diversity.
EF3	Pollinator Abundance	Pollinator abundance reflects the potential presence of wild pollinator species, such as bees and butterflies, based on habitat nesting suitability and the availability of floral resources within their flying range.
EF4	Soil Quality	Soil quality refers to the ability of soil to perform essential functions effectively, including supporting plant growth, regulating water, cycling nutrients, and sustaining biodiversity. High-quality soil is fertile, well-structured, and resilient to degradation. Key aspects include nutrient retention, which prevents the leaching of essential nutrients, and sediment retention, which helps prevent soil erosion and maintains water quality.
EF5	Human Recreation Potential	This indicator represents areas with minimal human disturbance, emphasizing visually undisturbed landscapes, natural water bodies, and sparse human activity. These zones are critical for recreation, mental well-

		being, and the preservation of peaceful natural environments, particularly on the Swiss Plateau.
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4.2.2 Data Collection

This subchapter provides a detailed description of the data sources and types. The data collected for this research were from various sources, including biodiversity databases, Geographic Information System (GIS) datasets, and expert input.

GBIF: A Resource for Biodiversity Data

The Global Biodiversity Information Facility (GBIF) is an international network and data infrastructure that provides *libre* and open access to biodiversity data worldwide. GBIF collects data about species distribution via a network of contributors from museums, research institutions, governmental organisations, and citizen science initiatives. GBIF provides occurrence records with spatial and temporal distribution data for each species. The data comes from field-based observation data or collection data or published papers. GBIF offers several tools to explore, visualize, and download data (GBIF, n.d.).

In this thesis, GBIF was used as a source of secondary data. More specifically, GBIF was used to access data to evaluate species richness and diversity in Switzerland. The data collected from GBIF were filtered to account for:

- **Taxonomic Groups:** The target species groups, including mammals, reptiles, amphibians, and breeding birds, are especially sensitive to habitat changes caused by PV installations.
- **Geographic Scope:** Data within and relevant to Switzerland. Each observation is stored with a coordinate. It should be noted that reptile and breeding bird observation points are recorded in a 10x10 km, respectively 5x5 km, grid cell (for data protection).
- **Temporal Range:** Recent occurrence data (1950 - 2024) to reflect current biodiversity trends.

Table 4: Data from GBIF and its corresponding authors (find full citation in References)

Databank Name	Authors
Swiss National Mammal Databank	Hummel et al. (2025)
Swiss National Reptile Databank	Andreas & Ursenbacher (2025)
Swiss National Amphibian Databank	Schmidt et al. (2025)
Swiss National Breeding Bird Databank	Wechsler et al. (2023)

Spatial Data Overview: Mapping NCP Indicators and Biodiversity across Switzerland

In addition to data from GBIF, this study uses data from Külling et al. (2024). Külling et al. (2024) mapped the contribution of nature to people and biodiversity across Switzerland. The datasets contain records of biodiversity patterns, ecosystem services, and important environmental factors, such as land use and climate factors. The data was collected through a combination of field surveys and environmental models. Külling et al. (2024) focused particularly on mapping biodiversity at a regional scale, providing researchers with valuable information on areas that could be impacted by human activities. In their work, Külling et al. (2024) mapped the supply of 15 NCP indicators and one biodiversity indicator. The study provided spatially explicit outputs in the form of raster maps with a 25 m resolution for the whole of Switzerland. Further details on the data can be found in the paper published by Külling et al. (2024).

The following datasets were selected for this research due to their comprehensive coverage of biodiversity patterns and their relevance to the Swiss context.

Table 5: Detailed description of the Biodiversity Indicators used from Külling et al. (2024)

Indicator	Description
Red List Species	Consists of terrestrial species that have been identified as threatened and classified in the red list by the Swiss Government (Cordillot & Klaus, 2011).
Habitat Quality	The habitat quality index for Switzerland scores each 25m area based on how natural it is, how sensitive it is to threats, and how close it is to things such as roads, rural homes, cities, and farms. Scores came from a land-use map and expert ratings (0 to 1). Threat effects were figured out from studies on distance and impact strength.
Pollinator Abundance	The pollinator study picked species and mapped habitat suitability. It looks at nesting spots and flower resources within each pollinator's flight range. Input data comes from a literature review of studies in Switzerland or similar areas.
Soil Quality (Nutrient Retention & Sediment Retention)	Two modules were used to evaluate soil quality in Switzerland to assess how well the environment filters nitrogen each year and to estimate yearly sediment retention per pixel in the Swiss landscape. Together, these measure soil quality by analysing nitrogen filtration and sediment retention.
Human Recreation Potential	This indicator shows the potential for outdoor recreation in a landscape. It is based on three features: naturalness of land use, natural protected areas, and water components. Features come from habitat scores assigned to land use types, protected areas in Switzerland, and by measuring distance from lakes.

Réseau Écologique National (REN) & Interregional Wildlife Corridor

Regan et al. (2007) mention *Habitat Connectivity* as a biodiversity indicator of great importance. The *Réseau Écologique National* (REN) is a national ecological network that aims to promote biodiversity in Switzerland by connecting habitats and enabling the genetic exchange of plant and animal populations (Berthoud et al., 2004). As infrastructure, settlements, and intensive agriculture increase in the landscape, many species are restricted in their freedom of movement, which threatens their survival. For this reason, REN establishes ecological corridors to link otherwise isolated populations and establish a more resilient natural environment. The REN elements consist of core zones, corridors, and buffer zones (Berthoud et al., 2004). In addition, an *Interregional Wildlife Corridors* layer captures ecological flow at a wider scale and complements REN locations. The *Interregional Wildlife Corridors* layer maps known corridors based on existing data at the cantonal level and potential corridors were detected from GIS data (Bundesamt für Umwelt BAFU, 2024b). Taken together, the layers provide a basis for the assessment of habitat connectivity in Switzerland.

Table 6: Data used for Habitat Connectivity Indicator and its Source

Name	Source
Réseau Écologique National:	
REN dry habitat	<i>National Ecological Network (REN), Dry Habitat, 2011;</i>
REN extensive agriculture	<i>National Ecological Network REN, Extensive Agricultural Area, 2011;</i>
REN forest	<i>National Ecological Network (REN), Forest Area, 2011;</i>
REN watercourses and lakes	<i>National Ecological Network (REN), Watercourses / Lakes, 2011;</i>
REN wetland site	<i>National Ecological Network (REN), Wetland Site, 2011</i>
Interregional Wildlife Corridor	<i>Interregional Wildlife Corridor, 2025</i>

AHP Survey Results

To assess how much each biodiversity indicator contributes to overall biodiversity value, a group of experts ranked the chosen indicators to assign weights to each indicator. The ranking was conducted through a survey based on the Analytic Hierarchy Process (AHP) structure. In this process, a questionnaire was designed and distributed, asking participants to compare the indicators in pairs and assign rankings that reflect the relative importance of one indicator over another.

The survey is based on the previously defined biodiversity indicators and compares these within their respective dimensions: *Biotic Composition* and *Ecologic Function*. Detailed instructions are provided to introduce the participants to the topic, define relevant terms, and explain the individual indicators, which are compared repeatedly. The survey is included in Appendix B.

Table 7: AHP Priority Ranking System

AHP PRIORITY RANK	SCALE OF IMPORTANCE
1	Equally important
3	Moderately more important
5	Strongly more important
7	Very strongly more important
9	Extremely more important
2, 4, 6, 8	Intermediate Values

The survey was distributed to 15 experts specializing in biodiversity research. The experts were scientists at Eawag (Swiss Federal Institute of Aquatic Science and Technology), the University of Zurich, and professionals at BAFU. Each participant was asked to assess the indicator pairs using a numerical scale from 1 to 9. A rank of 1 means that two indicators are deemed equally important regarding their influence on biodiversity, while a score of 9 indicates that one indicator is of extreme priority over another (Saaty, 1977).

4.2.3 AHP Analysis for Criteria Weighting

The Analytic Hierarchy Process (AHP) is used to obtain the relative importance values of the ten criteria for completing the biodiversity assessment as AHP has been successfully used for guiding multi-attribute decision problems. Developed by Thomas L. Saaty (1977, 1987, 2008), AHP provides a framework for logical decision-making by breaking down complex problems into a hierarchy of criteria and sub-criteria so that they can be compared pairwise to obtain weights that reflect priority to the decision. AHP is valuable because it allows the user to make in-depth pairwise comparisons that should strengthen the reliability of weight determination compared to direct assignment of weights. AHP is

implemented in five steps: (1) Structuring the decision problem into a hierarchy; (2) Making pairwise comparisons to assess the relative importance of each criterion; (3) Calculate priority weights via the eigenvalue method; (4) Check the consistency of the pairwise comparisons; and (5) Aggregate the weights to make the final ranking of criteria (Saaty, 2008). This section outlines the AHP approach used in the calculation of weights for the biodiversity indicators, as well as the incorporation of combining expert judgment. All processing steps were performed using Python¹ and QGIS.

In this study, the decision hierarchy was defined with the goal of assessing a biodiversity indicator at the top level. Two high-level criteria are established: *Biotic Composition (BC)* and *Ecosystem Function (EF)*. Within biotic composition, three sub-criteria are identified: *Species Richness (BC1)*, *Species Diversity (BC2)*, and *Red List Species (BC3)*. For ecosystem function, five sub-criteria were considered: *Habitat Quality (EF1)*, *Habitat Connectivity (EF2)*, *Pollinator Abundance (EF3)*, *Soil Quality (EF4)*, and *Human Recreation Potential (EF5)*. These criteria formed the hierarchical structure for the AHP analysis, as illustrated in Figure 5.

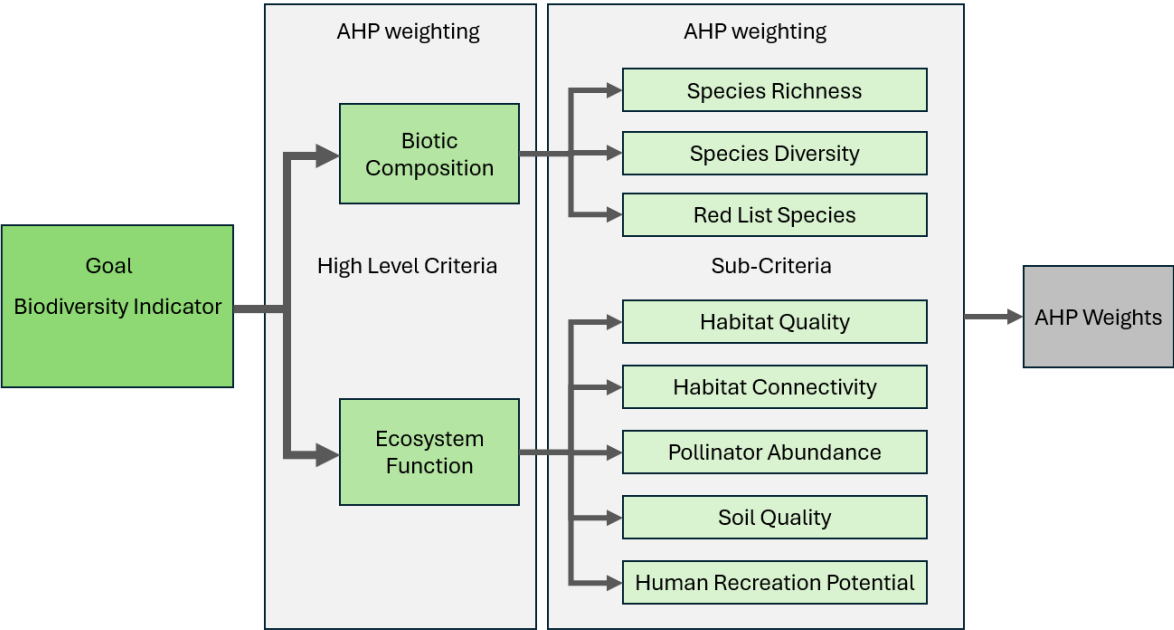


Figure 5: AHP Structure

¹ The code is available on GitHub: <https://github.com/mariehamm/thesis>

The survey responses formed the basis for constructing pairwise comparison matrices (PCMs) at the three hierarchy levels: high-level criteria (BC vs. EF), BC sub-criteria, and EF sub-criteria. Each level's criteria, denoted as

$$C = \{C_j | j = 1, 2, \dots, n\}$$

are systematically compared to establish their relative importance.

For each hierarchy level, PCMs were constructed. Each matrix A is a $n \times n$ positive reciprocal matrix, where a_{ij} represents the priority of criterion C_i over C_j :

$$A = \begin{matrix} & C_1 & C_2 & \dots & C_n \\ \begin{matrix} C_1 \\ C_2 \\ \vdots \\ C_n \end{matrix} & \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} & \text{with } a_{ii} = 1, a_{ji} = 1/a_{ij}, a_{ij} \neq 0 \end{matrix}$$

With $a_{ii} = 1$ meaning equal importance along the diagonal, $a_{ji} = 1/a_{ij}$ (reciprocity). The values a_{ij} are derived from the geometric mean of respondent ratings (Grošelj & Zadnik Stirn, 2012; Ishizaka & Labib, 2009). If C_i is seen as more important than C_j , a_{ij} ranged from 1 to 9; if less important, $a_{ji} = \frac{1}{a_{ij}}$ is used (Saaty, 1977). At the higher level, a 2x2 matrix was built comparing *BC* and *EF*, with the geometric mean of expert inputs used to determine the relative preference value and its reciprocal. For sub-criteria, larger matrices were created (3x3 for BC and 5x5 for EF sub-criteria). Each populated with geometric means of expert inputs for each pair, ensuring reciprocity (e.g., if *Habitat Quality* was rated 3 times more important than *Habitat Connectivity*, the reverse comparison received a value of 1/3) (Grošelj & Zadnik Stirn, 2012; Ishizaka & Labib, 2009).

The matrix columns were then normalized to sum to 1 using the formula:

$$r_{ij} = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}}$$

This normalization standardizes the weights and forms the basis for following calculations.

Priority weights are derived using the eigenvector method. For each PCM, the principal eigenvector, corresponding to the largest eigenvalue (λ_{max}), is calculated and normalized by dividing each element by the sum vector to ensure that the weights within each level sum to 1 (Saaty, 1977). In this study, λ_{max} is calculated using Python's NumPy library, which solves the eigenvalue problem for each PCM. This process is applied independently to the high-level criteria (*BC* and *EF*) and to the sub-criteria within each category to produce local weights for each criterion relative to its peers (Saaty, 1987).

Saaty (1980) demonstrated that the maximum eigenvalue (λ_{max}) is always greater than or equal to n , where n represents the number of indicator components at a given hierarchy level. A smaller deviation between λ_{max} and n indicates greater consistency in the weighting results. When the pairwise

comparisons are entirely consistent, λ_{max} is equal to n . Based on this principle, the consistency of the pairwise comparison judgments can be evaluated to assess the reliability of the results. The consistency is determined by the relationships among the entries of matrix A and, consequently, by the responses in the pairwise comparison questionnaire. To ensure the reliability of the expert judgments, Saaty's consistency metrics were calculated for each matrix. The Consistency Index (CI) is computed as (Mu & Pereyra-Rojas, 2017; Saaty, 1987):

$$CI = \frac{(\lambda_{max} - n)}{(n - 1)}$$

where n is the matrix size. The Consistency Ratio (CR) was then calculated as:

$$CR = CI / RI$$

where RI is the Random Index specific to the matrix size (see Table 8).

Table 8: Reference Table for RI values (from Saaty (1977)); only relevant values

n	1	2	3	4	5
RI	0	0	0.58	0.90	1.12

A CR value of 0.1 or less indicates acceptable consistency and confirms that expert judgements are reliable for decision-making. For the 2x2 high-level matrix, consistency is inherently satisfied (RI = 0), while sub-criteria matrices are evaluated against their respective thresholds.

Local weights from the sub-criteria are then combined with the high-level weights to compute global weights to reflect each sub-criterion's overall importance across the hierarchy. Specifically, the weights of BC sub-criteria ($BC1$, $BC2$, $BC3$) are multiplied by the high-level weight of BC , and the weights of EF sub-criteria ($EF1$ through $EF5$) are multiplied by the EF high-level weight. The resulting global weights for all eight sub-criteria are aggregated into a final set, with their sum equal to 1, thus confirming the integrity of the weighting process.

Additionally, a sensitivity analysis is performed. This type of analysis tests the robustness of the results by slightly changing the input data (Ishizaka & Labib, 2009). All pairwise comparisons were perturbed by $\pm 10\%$ and $\pm 20\%$, simulating possible variations in expert opinion. For each criterion set (high-level and sub-criteria) the priority weights are recalculated after increasing and decreasing the input values. This allows us to assess how sensitive the resulting weights are to small changes in the input data.

4.2.4 Species Richness & Diversity Assessment

A hexagonal grid was generated to cover Switzerland for the spatial analysis. Hexagonal grids minimize edge effects and create a more uniform spatial representation compared to square grids (Jurasinski & Beierkuhnlein, 2006). The Swiss national boundary dataset was loaded and reprojected to the LV95 coordinate system (EPSG:2056) for spatial consistency. The grid's extent was defined by Switzerland's bounding box. Each hexagon is created using a function that calculates its six vertices based on a specified side length of 7'500 m. The hexagons are staggered to ensure a seamless tiling across the study area. This resolution is used to mitigate visible "stripes" in the biodiversity data caused by the 5x5 km, respectively 10x10 km grids of some input datasets (see Appendix C). Hexagons that intersect the Swiss boundary are retained, each assigned a unique identifier and saved as a GeoDataFrame for subsequent analyses.

Data on the occurrence of mammals, amphibians, reptiles, and breeding birds were compiled, retaining attributes such as species name, taxonomic class, geographic coordinates, and year of observation. These data were converted into a GeoDataFrame, with coordinates reprojected to LV95 (EPSG:2056) for spatial accuracy. To avoid duplicate records with overlapping coordinates, a jittering function was applied that added minimal random noise to each point without compromising spatial integrity. This step could not fully eliminate the "stripes" observed in the data.

Species richness was calculated by making a spatial join between the species occurrence GeoDataFrame and the hexagonal grid. Each species record was assigned to its corresponding hexagon. Lists of species, taxonomic classes, and observation years per hexagon were generated for additional context. Species diversity was assessed using the Shannon Index, which accounts for both species richness and evenness (Duelli & Obrist, 2003; Peet, 1974).

The Shannon Index is computed for each hexagon by analysing the species composition within each hexagon. The formula for the Shannon Index is based on the proportion of each species in a hexagon, considering both the number of species and their relative abundances. The Shannon Index analyses how evenly their populations are distributed. The Shannon Index (H') is calculated for each hexagon using the formula:

$$H' = - \sum(p_i \cdot \ln(p_i))$$

where p_i is the proportion of individuals of species i relative to the total. The natural logarithm \ln weights these proportions, and the negative sign ensures H' is positive. For hexagons with one or no species, H' was set to zero, indicating no diversity. The resulting maps (see Figures 6 and 7 in Section 5.1) illustrate spatial patterns of species richness and diversity across Switzerland.

To integrate biodiversity indicators, species richness and diversity data were exported as GeoJSON for analysis in QGIS. Following the calculation of species richness and diversity, habitat connectivity was integrated by combining REN locations (ecologically significant areas) and *Interregional Wildlife*

Corridors into a single layer. These features were buffered by 50 m to create a gradient, with core zones assigned a value of 1 (highest connectivity) and outer areas a value of 0. All data were converted to raster format at a 25 m resolution, matching Külling et al. (2024), and standardized to a 0 to 1 scale for comparability.

AHP weights were applied through a weighted raster overlay, where each standardized raster was multiplied by its weight and summed to produce a composite biodiversity value map, shown in Figures 11 and 12 in Section 5.3.

5 Results

This chapter presents the findings of the spatial analyses carried out with the extended decision-support tool developed in this thesis. It describes the prioritization of biodiversity indicators by the Analytic Hierarchy Process (AHP) and shows the resulting biodiversity suitability map for PV site selection. The chapter also includes three case studies that examine specific regions in Switzerland and identify areas of potential conflict and synergy between PV development and biodiversity conservation. These results highlight significant overlaps between high-priority PV installation sites and biodiversity hotspots, particularly in (sub)alpine regions. This provides valuable insights for sustainable spatial planning.

5.1 Species Richness and Shannon Index Mapping

Species richness and diversity were assessed using four biodiversity datasets (mammals, amphibians, reptiles, breeding birds) aggregated to a 7'500 m hexagonal grid (355 hexagons total). Figure 6 shows the result of the species richness assessment. Yellow hexagons indicate high species richness; dark blue hexagons indicate low species richness. Species richness ranges from 0 to 214 species per hexagon, with a mean of 137 species. Hexagons with a count of 0 species per hexagon are mostly border hexagons where not the whole area lies within the Swiss boundary. Still, this figure indicates that the lowlands and alpine valleys in Valais, Ticino, and Grisons have higher species richness than high alpine regions.

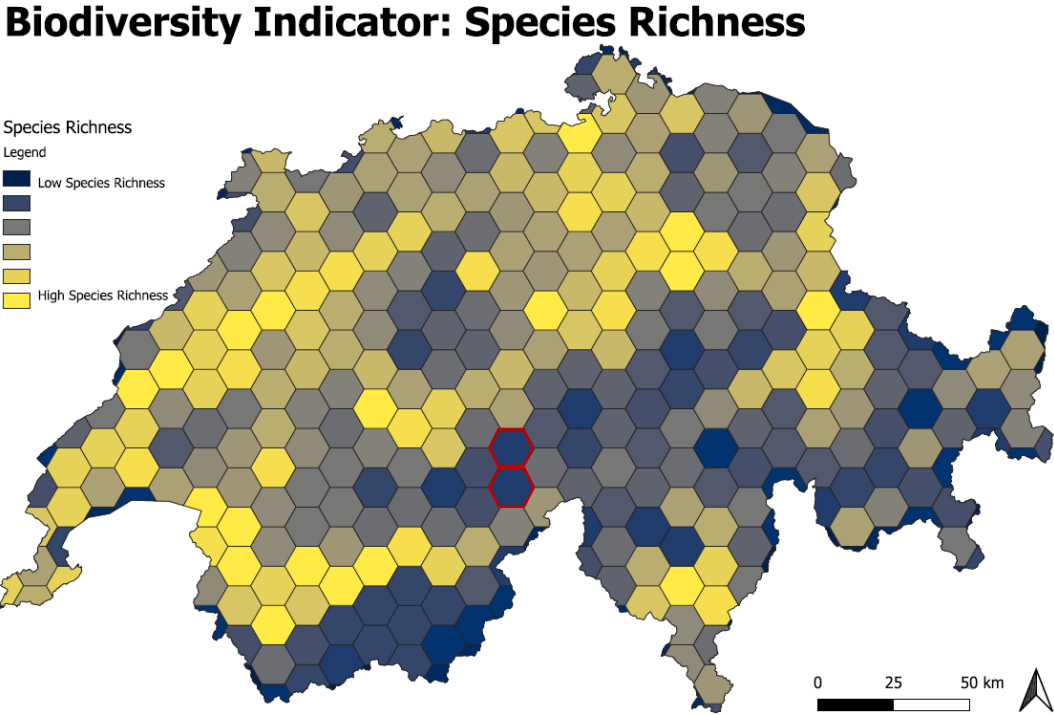


Figure 6: Species Richness Switzerland (Mammals, Reptiles, Amphibians, Birds), in a 7'500 m hexagon grid. Dark blue indicates low species richness, yellow indicates high species richness using equal count (quantile)

Figure 7 shows the result for the species diversity assessment. Yellow hexagons indicate higher species diversity; dark blue hexagons indicate lower diversity. Species diversity ranged from 0 to 4.4 species per hexagon, with a mean of 3.3 species. Low species diversity counts are mostly found in border hexagons. This figure indicates that lowlands have lower species diversity compared to alpine regions, especially in Valais and Ticino.

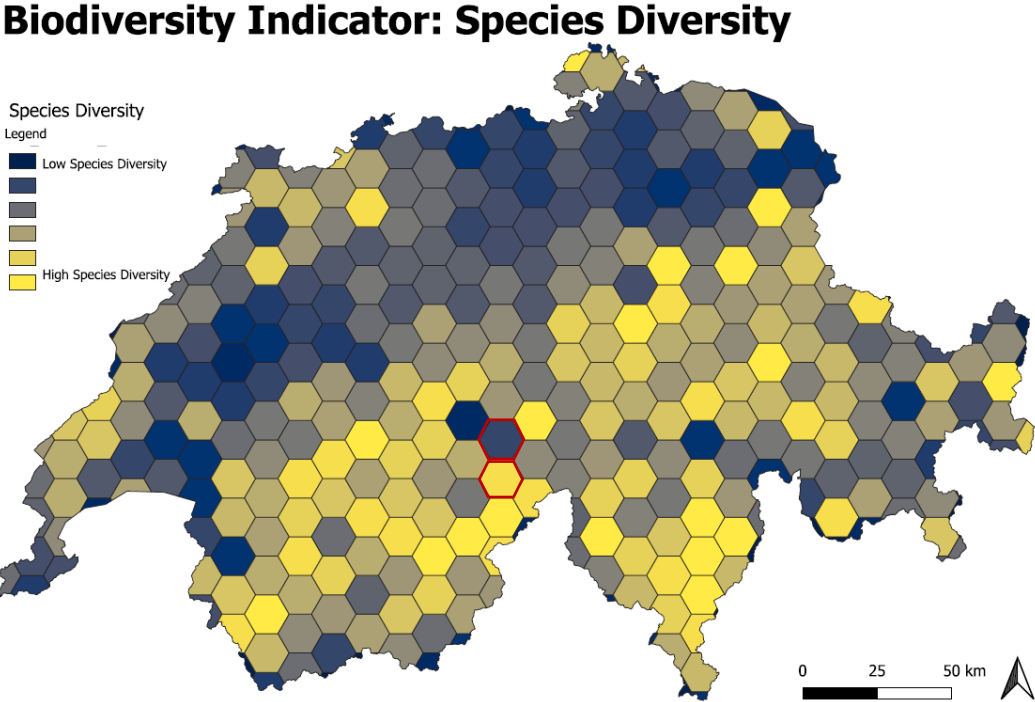


Figure 7: Species Diversity (Shannon Index) in Switzerland in a 7500m hexagonal grid cell

Figures 6 and 7 show red markings around hexagon IDs 166 and 167. Both hexagons have the same species richness value, as they both count 101 unique species, but differ significantly in their Shannon Index values.

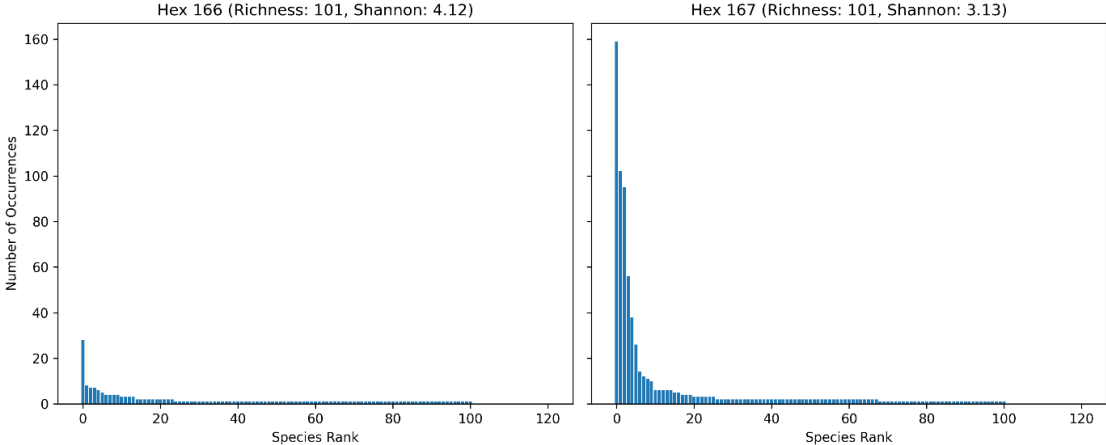


Figure 8: Comparison of hexagon ID 166 & 167 for analysing Shannon Index

ID 166 has a Shannon Index of 4.12, while ID 167 is valued at 3.13. In ID 166, the 101 species occurrences are more evenly distributed (resulting in a flatter curve). This evenness results in a higher Shannon Index, which signals a diverse ecosystem. In ID 167, a few species dominate the occurrences (resulting in a steeper curve). This unevenness results in a lower Shannon Index.

5.2 Analytic Hierarchy Process Analysis

This section presents the resulting expert weights, including the pairwise comparison matrices (PCMs) for the high-level and sub-criteria and the results for the sensitivity analysis.

Expert weights

The AHP evaluation determines the relative importance of ecological indicators for biodiversity. As described in Section 4.2.3, nine expert questionnaires are combined into PCMs using geometric means. Three PCMs are constructed: a 2x2 matrix for BC versus EF (Table 9), a 3x3 matrix for BC sub-criteria (Table 10), and a 5x5 matrix for EF sub-criteria (Table 11). The final column in the following three tables displays the local priority weights that were determined using the eigenvalue method (Saaty, 1987, 2008). The local weights for sub-criteria are multiplied by their respective higher-level criteria weights (BC: 0.427, EF: 0.573) to calculate global weights, as shown in Table 12.

Table 9: Pairwise Comparison Matrix (PCM) for Biotic Composition (BC) and Ecosystem Function (EF), showing local weights derived from expert preferences

	BC	EF	Local Priority Weight
BC	1	0.746	0.427
EF	1.341	1	0.573

Experts assigned slightly higher importance to ecosystem function (EF, 0.573) than biotic composition (BC, 0.427). This reflects a preference for ecological processes over species metrics.

Table 10: Pairwise Comparison Matrix (PCM) for Biotic Composition (BC) sub-criteria, showing local weights derived from expert preferences using the eigenvalue method

	BC1	BC2	BC3	Local Priority Weight
BC1	1	0.258	0.940	0.175
BC2	3.876	1	2.757	0.620
BC3	1.064	0.363	1	0.205

In Table 10, *Species Diversity* (BC2, 0.620) dominates. For example, the value 3.876 (row BC2, column BC1) indicates that experts rated *Species Diversity* (BC2) as moderately more important than *Species Richness* (BC1) on Saaty’s 1-9 AHP scale (see 4.2.2). This suggests that *Species Diversity* is considered roughly four times more important than *Species Richness*. The high weight assigned to *Species Diversity* (BC2, 0.620) reflects experts’ emphasis on the balance and evenness of species populations over sheer *Species Richness* (BC1, 0.175) or the presence of *Red List Species* (BC3, 0.205). This prioritization suggests that maintaining diverse, stable ecosystems is critical for biodiversity conservation, particularly in areas targeted for PV development.

Table 11: Pairwise Comparison Matrix (PCM) for Ecosystem Function (EF) sub-criteria, showing local weights derived from expert preferences

	EF1	EF2	EF3	EF4	EF5	Local Priority Weight
EF1	1	2.256	5.981	3.253	7.987	0.468
EF2	0.443	1	2.717	2.111	4.754	0.235
EF3	0.167	0.368	1	0.745	6.722	0.120
EF4	0.307	0.474	1.343	1	5.139	0.141
EF5	0.125	0.210	0.149	0.195	1	0.036

Similarly, the dominance of *Habitat Quality* (EF1, 0.468) and *Habitat Connectivity* (EF2, 0.235) underscores their role in supporting ecological integrity, which may influence site selection for PV installations to minimize habitat fragmentation. The other three criteria are less important, particularly *Human Recreation Potential* (EF5), which was given the lowest priority (0.036), suggesting that it makes a negligible contribution to the assessment of biodiversity in this context.

Table 12: Final Global Weights for Biotic Composition and Ecosystem Function Sub-Criteria

Sub-Criterion	Global Weight	Percentage
Species Richness (BC1)	0.075	7.5 %
Species Diversity (BC2)	0.265	26.5 %
Red List Species (BC3)	0.088	8.8 %
Habitat Quality (EF1)	0.268	26.8 %
Habitat Connectivity (EF2)	0.135	13.5 %
Pollinator Abundance (EF3)	0.069	6.9 %
Soil Quality (EF4)	0.081	8.1 %
Human Recreation Potential (EF5)	0.021	2.1 %

The global weights are shown in Table 12. The global weights highlight the prominence of *Habitat Quality* (EF1, 26.8%) and *Species Diversity* (BC2, 26.5%), followed by *Habitat Connectivity* (EF2, 13.5%). Other indicators such as *Red List Species* (BC3), *Pollinator Abundance* (EF3), and *Human Recreation Potential* (EF5) are given much less importance.

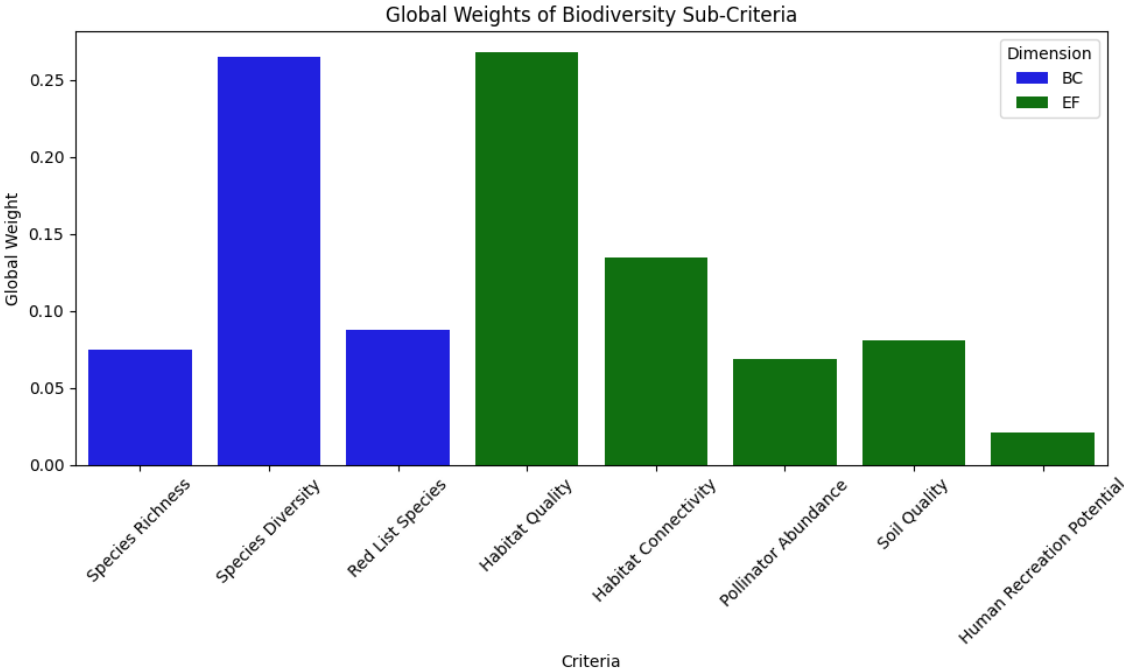


Figure 9: Bar chart illustrating the global weights of Biotic Composition (BC) and Ecosystem Function (EF) sub-criteria

This chart visually represents the global weights and makes it easier to compare the relative importance of each sub-criterion. The high weights assigned to *Habitat Quality* and *Species Diversity* suggest that PV projects should prioritize sites with minimal impact on diverse ecosystems and connectivity.

Consistency Analysis

Consistency analysis in the AHP evaluates the reliability of expert judgments by calculating consistency ratios (CR) for pairwise comparison matrices (PCMs). A CR below 0.1, as recommended by Saaty (1987), indicates consistent preferences. The CR for the PCMs confirms reliable expert judgments: CR = 0 for the 2x2 BC vs. EF matrix (Table 9), CR = 0.0074 for the 3x3 BC sub-criteria matrix (Table 10), and CR = 0.0586 for the 5x5 EF sub-criteria matrix (Table 11). All fall below the 0.1 threshold recommended by Saaty. A slight preference for *Ecosystem Function* (weight: 0.573) over *Biotic Composition* (0.427) is supported by the high-level matrix’s perfect consistency, which is typical for 2x2 comparisons. The high-level BC vs. EF matrix (Table 9) has perfect consistency (CR = 0), as 2x2 matrices require only one independent judgment; thus, 2x2 matrices always have CR = 0. The low CR

values indicate that the derived weights, such as 26.8% for *Habitat Quality* (EF1) and 26.5% for *Species Diversity* (BC2), reflect consistent expert preferences across the PCMs.

Sensitivity Analysis

The sensitivity analysis evaluates the robustness of the AHP results by testing how variations in expert judgements affect the global weights. Expert inputs for high-level criteria (*Biotic Composition*, BC, and *Ecosystem Function*, EF) and their sub-criteria were perturbed by $\pm 10\%$ and $\pm 20\%$ to assess the stability of the weights in prioritizing biodiversity indicators for PV development in Switzerland.

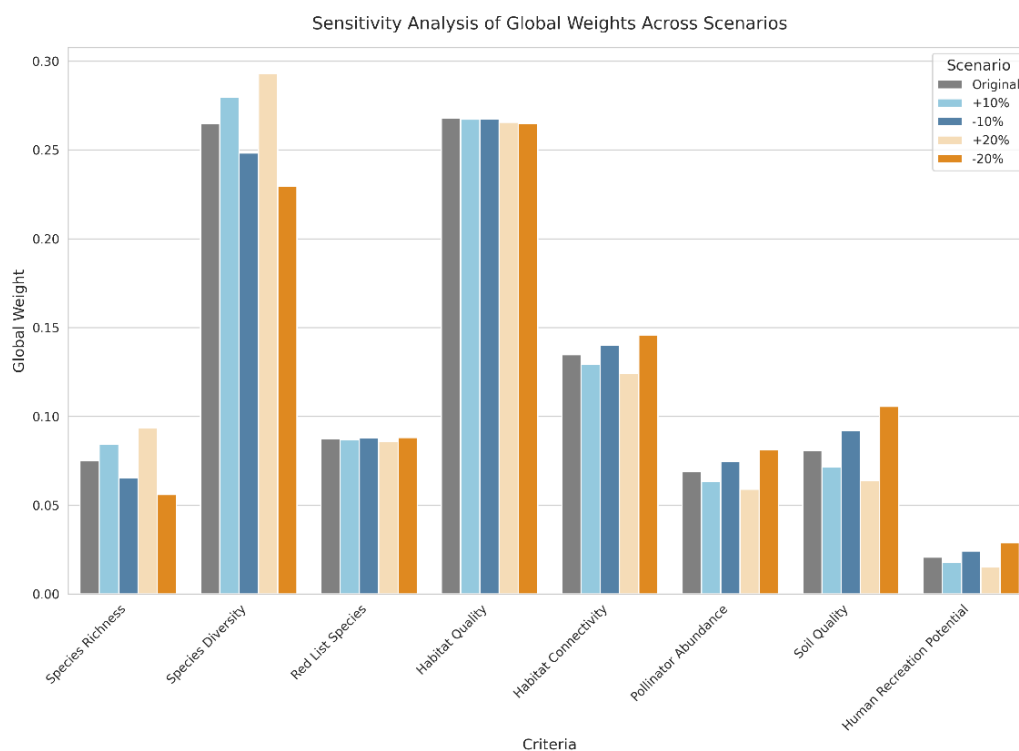


Figure 10: Grouped Bar Chart illustrating the global weights for BC and EF sub-criteria across five scenarios: original (grey), +10% (light blue), -10% (dark blue), +20% (light orange), and -20% (dark orange)

Results from the sensitivity analysis are shown as a grouped bar chart displaying global weights for each sub-criterion across five distinct scenarios: original global weights (grey), +10% (light blue), -10% (dark blue), +20% (light orange), and -20% (dark orange) (Figure 10). Overall, the figure shows that the relative ranking of the criteria are stable across all five scenarios.

Habitat quality (EF1) and *Species Diversity* (BC2) rank in the top two positions and are stable under the extend and direction of disturbance, indicating these criteria have high stability. Stability in this context refers to the ability of the criterion to remain in priority in the decision process rather than being unchanged in the context of weighting. *Habitat Quality* shows greater stability, with closely clustered bars, while *Species Diversity* shows slightly greater weight variations (e.g., $\pm 20\%$). Mid- and lower-

weighted criteria, such as *Habitat Connectivity* (EF2) and *Pollinator Abundance* (EF3), also tend to be more sensitive and show larger percentage changes associated with relatively low original weight. *Soil Quality* (EF4) and *Human Recreation Potential* (EF5) both show slight upward shifts under negative perturbation (−20%), indicating that the lower relative importance of other criteria increases the relative weighing of these criteria the most.

5.3 Biodiversity Map Switzerland based on AHP weights

Figures 11 and 12 present the biodiversity values across Switzerland as a result of the AHP analysis. Areas with low biodiversity values are displayed in yellow-green, intermediate values in light green, and high values in dark green. This distribution reflects the AHP's high weighting of *Habitat Quality* (26.8 % of total weight), which assesses ecosystem integrity, followed by *Species Diversity* (26.5 %), which highlights areas with rich fauna. Other indicators, such as *Pollinator Abundance* or *Red List Species*, contribute minimally.

Figure 11 displays biodiversity values continuously across a range from low to high. It shows nuanced variation in the results without grouping them into categories. This map shows subtle spatial patterns in biodiversity values. Figure 12 classifies biodiversity values into five classes (very low to very high) using the Jenks natural breaks method. This classification is consistent with the Sankey diagram in Figure 14 and provides a uniform visualization of biodiversity categories across all analyses. This map simplifies the complexity of the visualization and makes it easier to interpret. However, there is a loss of detail and the choice of class breaks can bias interpretation. Small changes in data can shift values across category boundaries, potentially misinterpreting reality.

These maps serve as a baseline for identifying biodiversity hotspots and evaluating their overlap with potential PV installation sites proposed by the ARE. Both maps show that lowlands and alpine valleys, with their denser urban centres and higher population density, have lower biodiversity values compared to the alpine and Jura regions, where more natural habitats dominate.

Areas of High Biodiversity Value in Switzerland

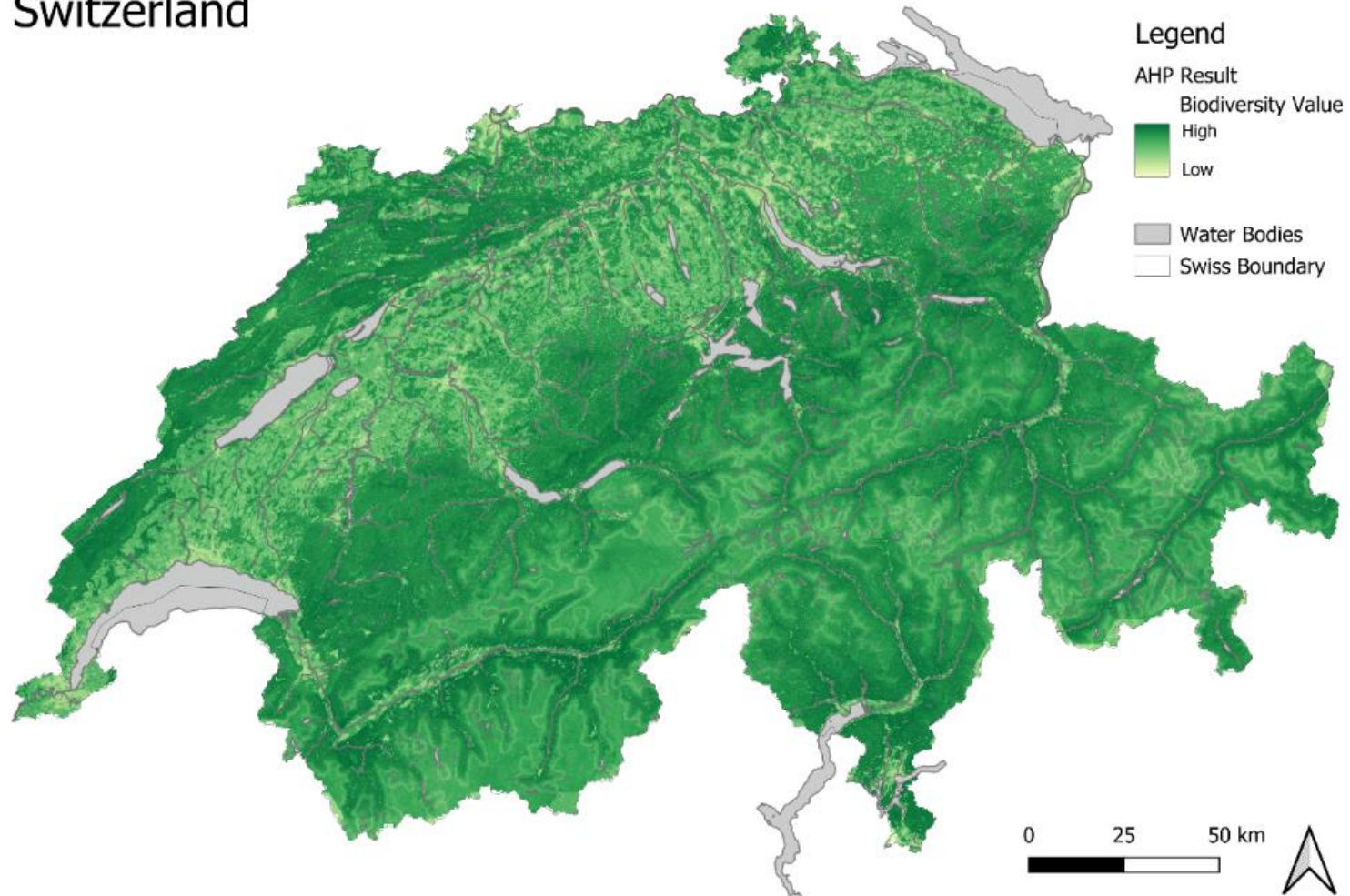


Figure 11: Continuous biodiversity value map of Switzerland based on AHP weights, with low values in yellow-green, intermediate values in light green, and high values in dark green

Areas of High Biodiversity Value in Switzerland

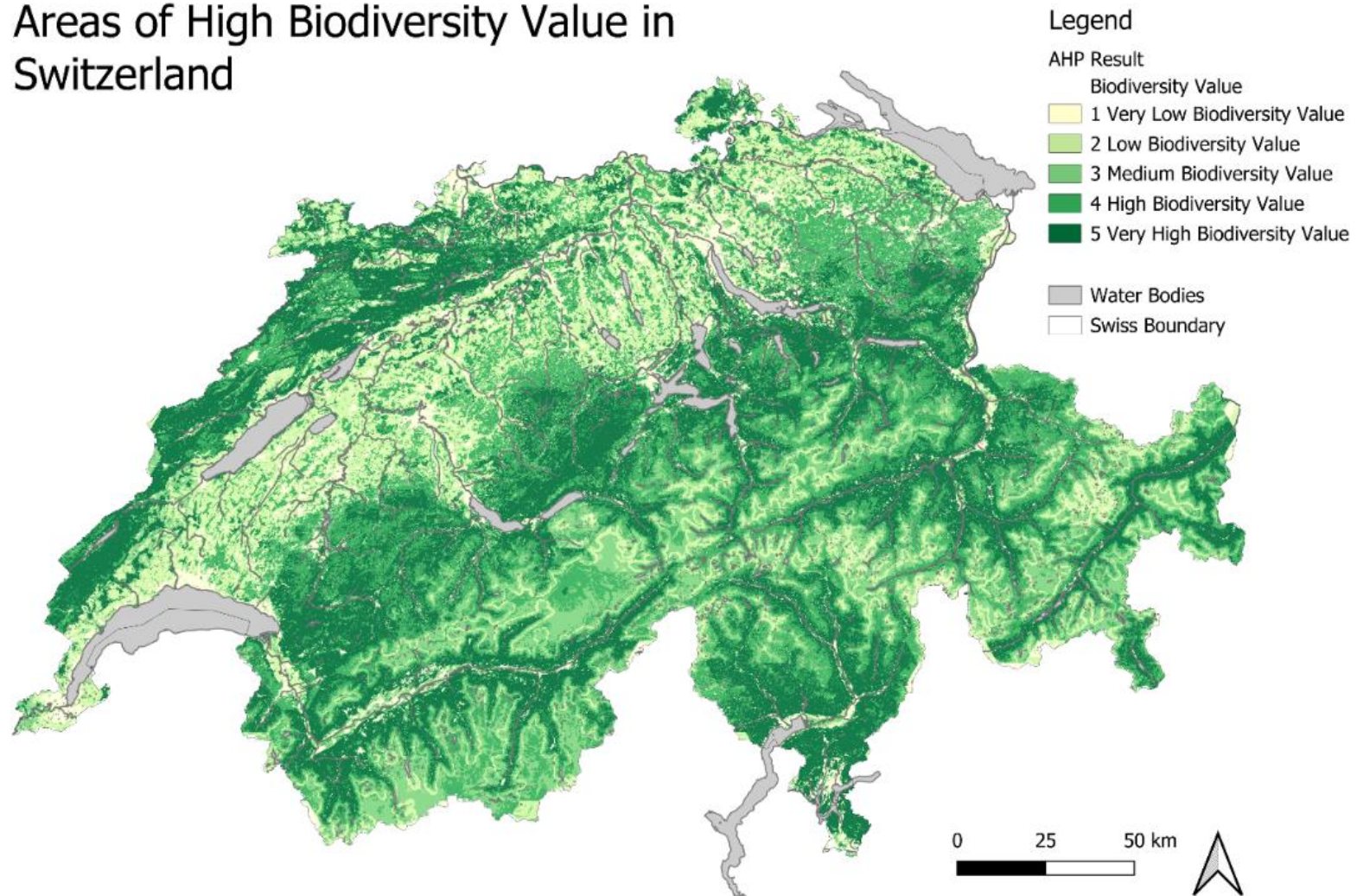


Figure 12: Classified biodiversity value map of Switzerland using AHP weights, categorized into five classes (very low to very high) with the Jenks natural breaks method, consistent with the Sankey diagram (Figure 14)

The outcome of this analysis is summarized in a Sankey diagram (Figure 14). It illustrates the relationship between PV installation priorities and biodiversity value classes. For that, biodiversity values are categorised into five classes from very high to very low, using the Jenks natural breaks method, as shown in Figure 13. This is a statistical method for clustering data by minimising variance within classes and thereby optimising class boundaries based on data distribution.

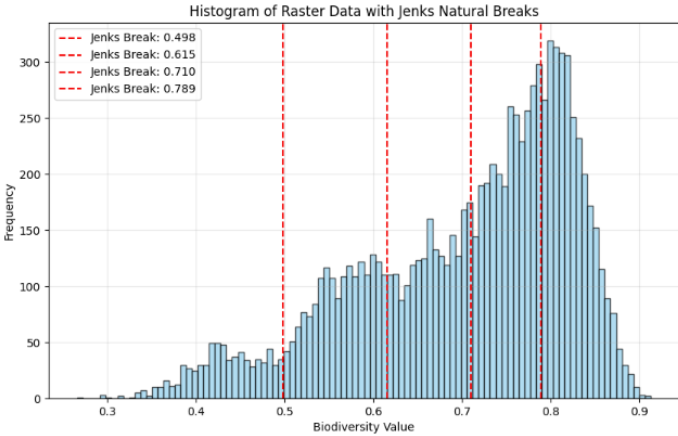


Figure 13: Jenks Natural Breaks to identify biodiversity classes

The Sankey diagram illustrates how different PV priority classes correspond to biodiversity value classes. The diagram features four PV priority classes: *Priority 1* in purple, *Priority 2* in turquoise, *Priority 3* in orange, and *Priority 4* in grey. These categories connect to five biodiversity value classes: *very low*, *low*, *medium*, *high*, and *very high*, displayed vertically on the right. The width of each band represents the proportional area of overlap between priority classes and biodiversity value classes.

This diagram highlights that there are generally more areas evaluated as *Priority 4*, and *Priority 1* has the fewest locations for potential PV installation. Furthermore, there are only a few areas considered to be of *Low Biodiversity Value*. The prominence of wider bands from *Priority 4* suggests a significant proportion of areas fall into this category which indicates a large number of areas deemed less immediately critical for further investigation. In contrast, the narrower bands from *Priority 1* indicate that this class encompasses the fewest locations. The thicker bands demonstrate the dominance of *High Biodiversity Value* and *Very High Biodiversity Value* classes. This suggests that the majority of the region in Switzerland maintains substantial ecological richness. The thin bands for *Low Biodiversity Value* and *Very Low Biodiversity Value* indicate that areas with minimal biodiversity are rare.

The most substantial flows from each priority class lead toward *High* and *Very High Biodiversity Value* classes. This pattern suggests that even areas with lower planning priority (e.g., *Priority 4*) are ecologically significant, which could imply a need to reassess prioritization criteria to better align with biodiversity conservation goals.

PV Priority Classes per Biodiversity Classes in Switzerland

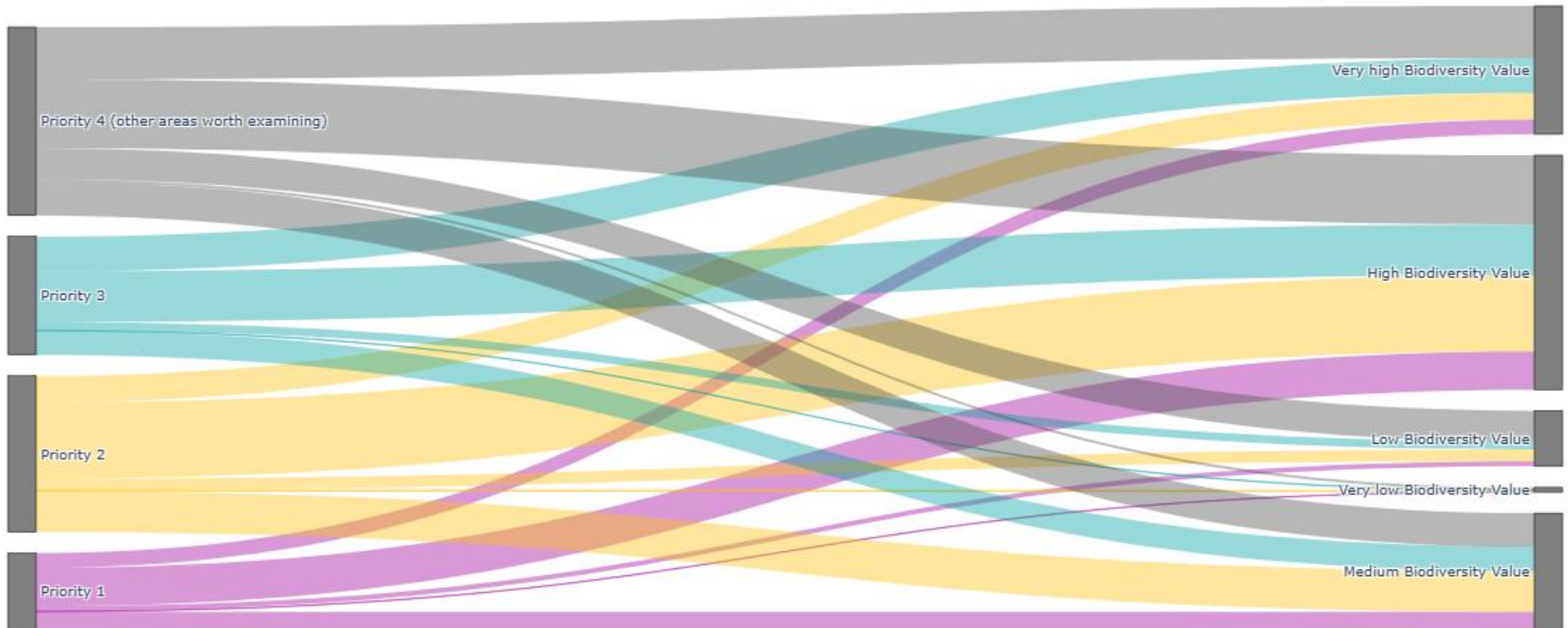


Figure 14: Sankey Diagram illustrating the relationship between PV installation priorities and biodiversity value classes in Switzerland, with band widths proportional to the percentage of total area. Biodiversity value classes are defined using Jenks Natural Breaks, priority classes are used according to AREs definition from low priority to high priority

5.3.1 Comparison with ARE Results & Case Studies

The Federal Office for Spatial Development (ARE) produced a map identifying areas suitable for PV installations across Switzerland. The map delineates polygons, each with a minimum side length of 50 m, that represent potential sites for PV development from a federal perspective. The definition of suitability, again, is a first estimation and does not consider other factors such as economic efficiency, natural hazards, or electrical connections (see 4.1). The map (Figure 15) uses distinct colours: purple for Priority 1 (highly suitable), turquoise for Priority 2 (suitable), orange for Priority 3 (moderately suitable), and grey for Priority 4 (least suitable areas).

Resulting PV suitability categorized according to Priority Classes by the ARE

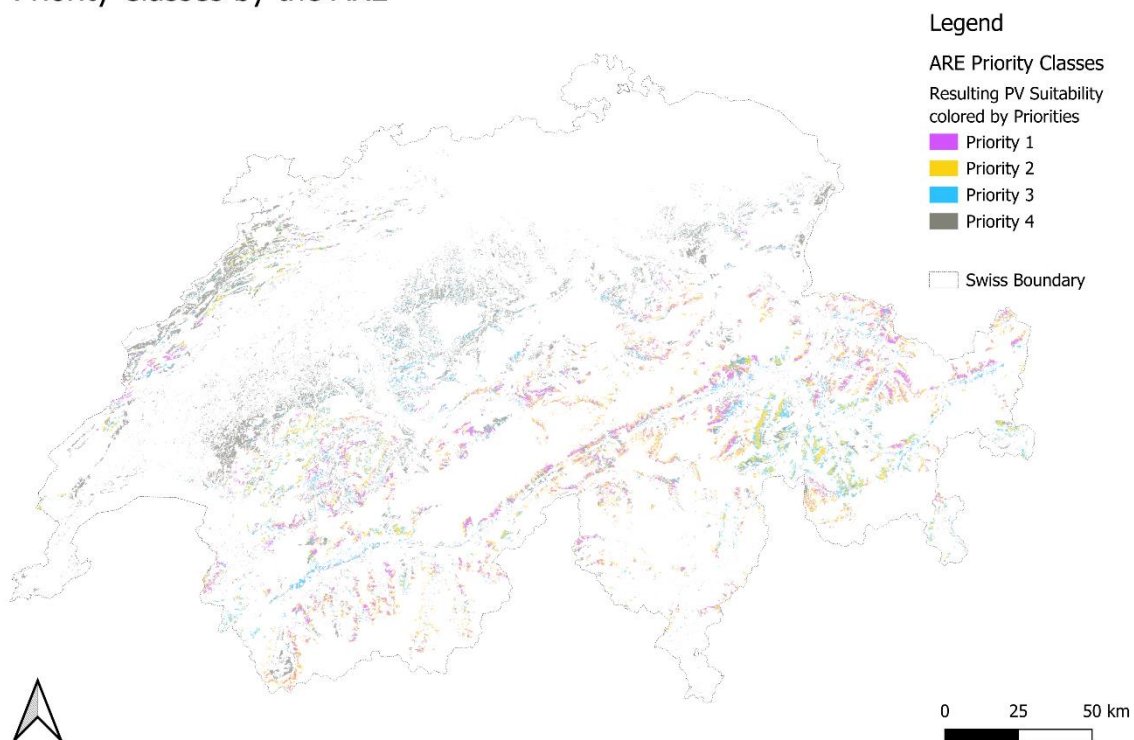


Figure 15: PV Installation coloured by priority developed by ARE

This map illustrates that the “areas worthy of consideration from a federal perspective” are not evenly distributed across Switzerland. There are especially interesting locations in the Jura, the foothills of the Alps and south-facing valleys. In the Central Plateau stretching from Geneva to northern Switzerland, there are very few or no areas worthy of consideration from a federal perspective. This map also highlights that the majority of the areas are considered to be of Priority 4, and only a few areas have a high priority.

Based on these insights, the following part examines three case studies to illustrate key scenarios of conflict, identify areas for further detailed local investigation in low-biodiversity, high-suitability areas, and real-world application for PV development in Switzerland. The cases are selected using the Sankey Diagram (Figure 14) and are visually supported by Figure 15. The cases represent potential conflicts and opportunities comparing the application to planned large-scale PV installations in Switzerland.

Case A: Potential Conflicts (showcasing the Jura Mountains)

This case highlights potential conflict between very high suitability PV areas (Priority 1) and high-biodiversity zones. This case is located in the Jura Mountains in the west of Switzerland. This area is generally evaluated as having a high biodiversity value; this excerpt in particular ranges from high to very high biodiversity value, except for the residential area coloured in bright yellow. In this area, the potential for PV installations is also estimated to be high (Priorities 1 & 2). This highlights a potential conflict between promoting biodiversity and the planning of GMPP, thereby underscoring the challenge of developing PV in ecologically sensitive areas. Mitigation strategies, such as biodiversity-friendly PV designs could be essential to balance renewable energy and conservation goals.

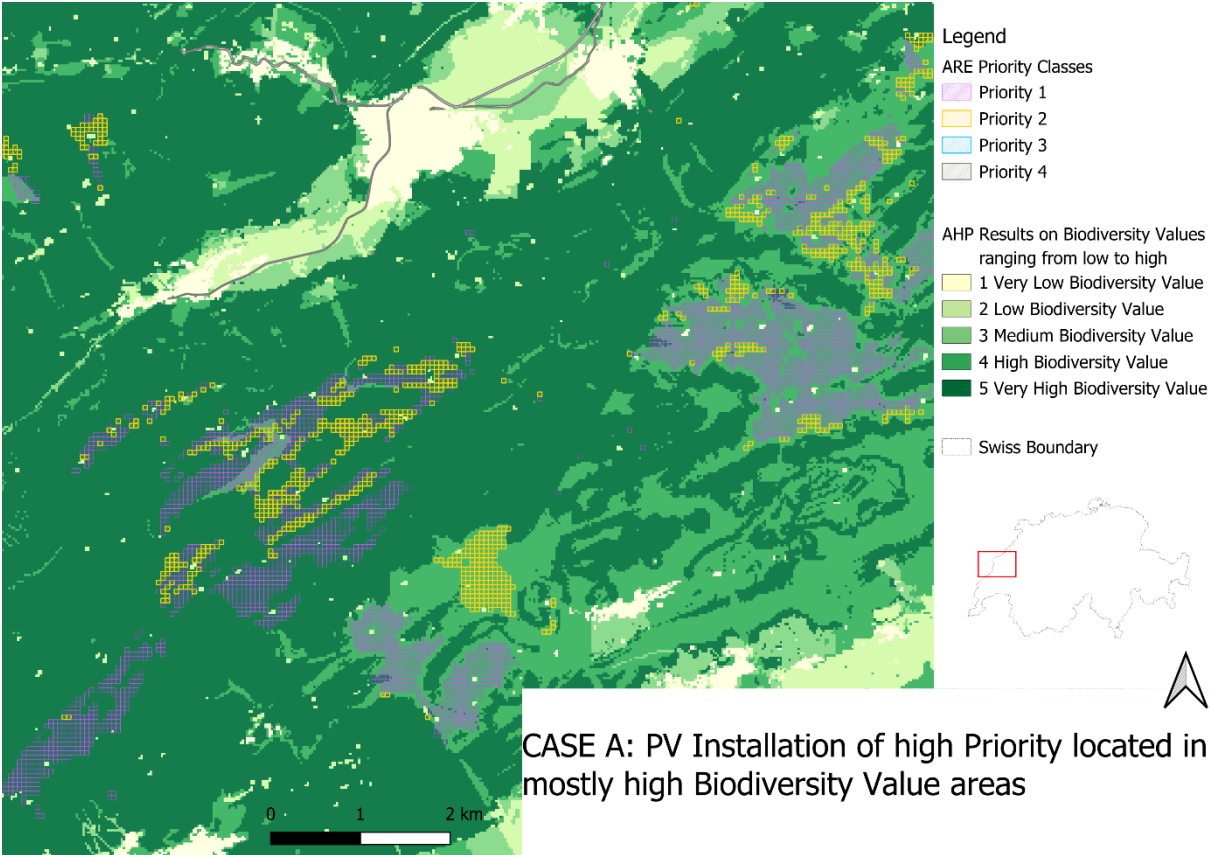


Figure 16: Case A showcases Jura mountains; highly suitable locations for PV development are marked in purple and turquoise (Priority 1 and 2) and biodiversity values ranked from low (light green) to high (dark green), illustrating potential conflict for PV development

Case B: Potential Opportunities (Central Plateau)

An “ideal scenario” for PV development aims to identify regions with low biodiversity values and high PV priority classes. Case B highlights such a scenario in the Central Plateau near Fribourg, located at the ecological transition from lowlands to subalpine regions. The map in Figure 17 illustrates this case and displays AREs priority classes (only from Priority 1 to 3) and the AHP results for biodiversity values (from very low to very high). In this region there are very few areas of Priority 1 & 2 that overlap with very low or low biodiversity values. This pattern is widespread across the Central Plateau in Switzerland. A national comparison shows that most low biodiversity areas typically correspond to lower PV priority classes, usually not exceeding Priority 3. High-priority PV zones (Priorities 1 & 2) are often found in or near regions with higher biodiversity values, which complicates land-use decisions and raises ecological trade-offs.

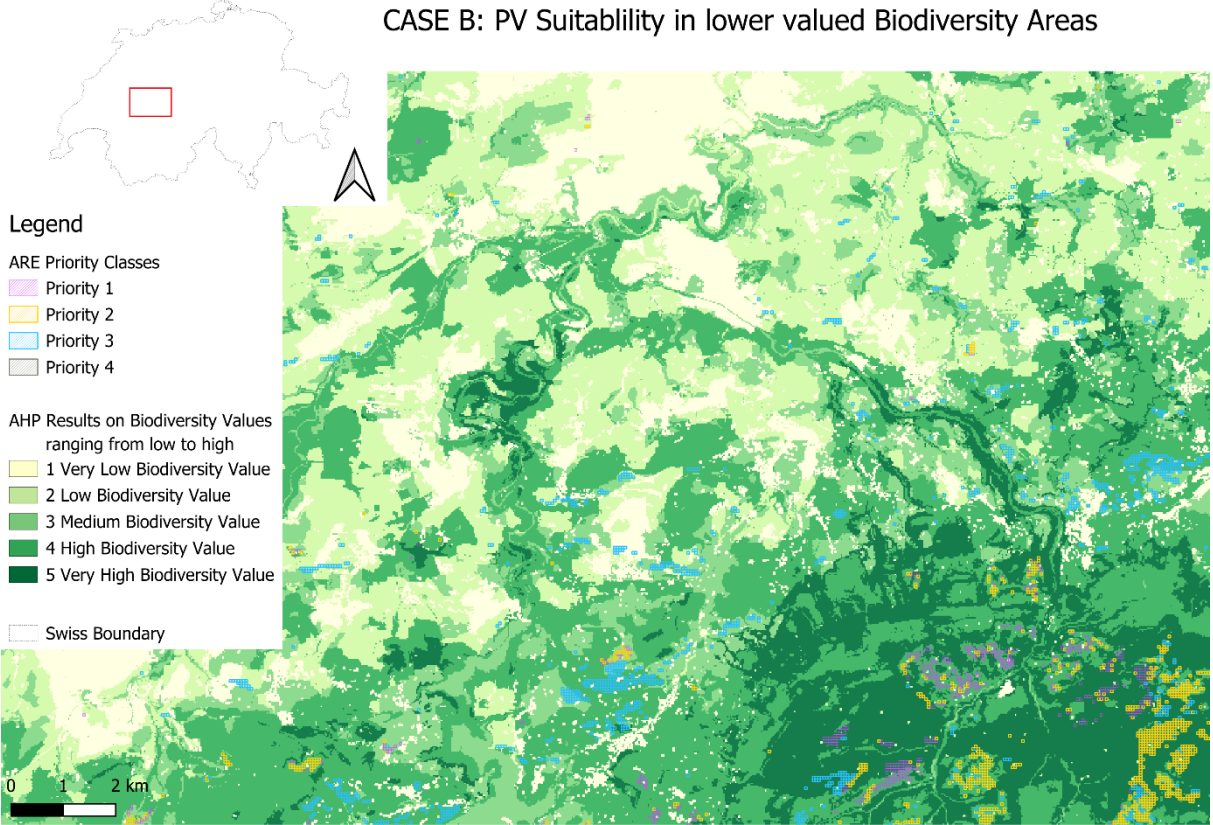
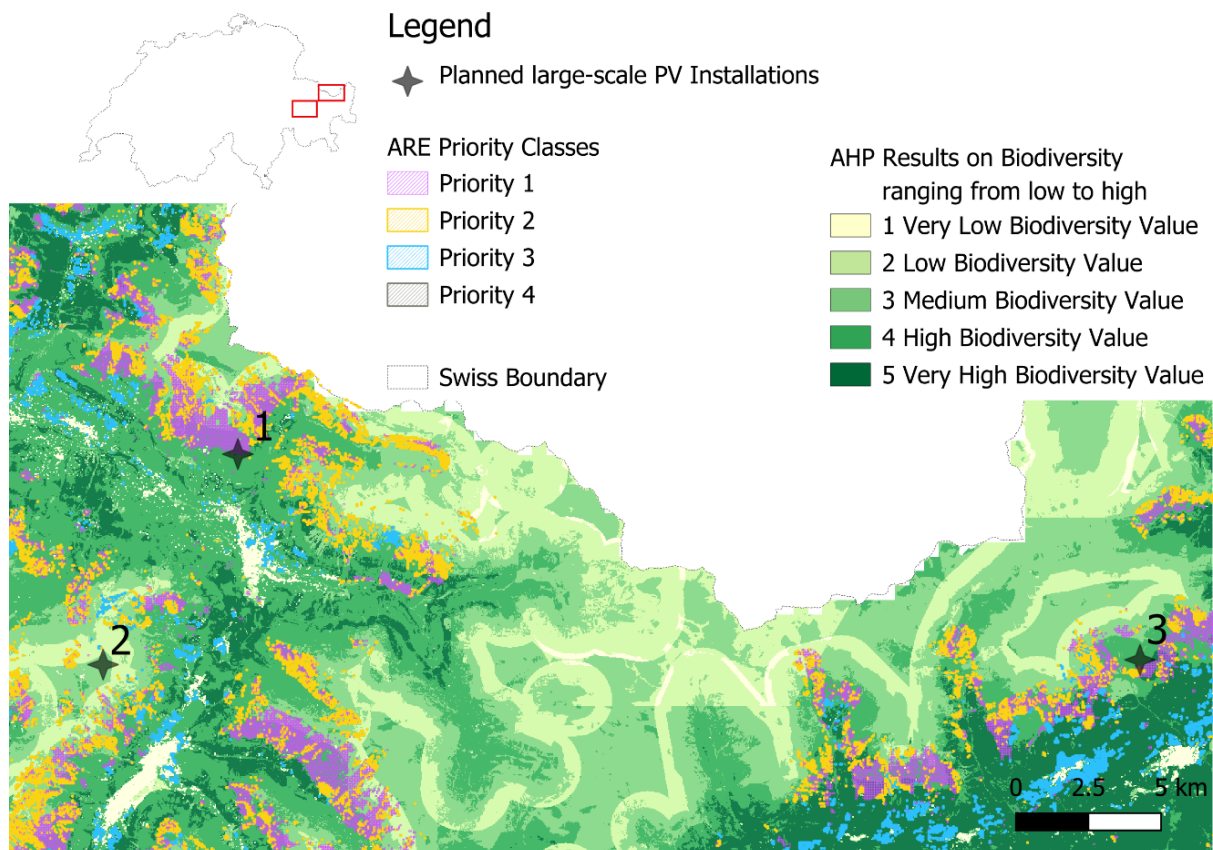


Figure 17: Case B is representative of the Central Plateau; this case shows high priority PV areas (Category 1 and 2) and biodiversity values ranked from low (light green) to high (dark green), illustrating an ideal scenario for PV development.

Case C: Application on planned large-scale PV Plants in Switzerland (showcasing Eastern Alps)

As of August 2025, Switzerland has authorized five of its 23 planned large-scale PV plants (see Section 2.1). They are predominantly located in high-alpine regions above 1'200 m.a.sl. (Bundesamt für Energie BFE, 2023a). Case C is situated in the *Eastern Alps* and identifies six of these plants across two distinct regions in Grisons. This case shows their alignment with biodiversity values (light green to dark green). Most plants fall in medium to high biodiversity values and align with high priority classes 1 and 2. Number 2 is the only planned PV plant in this example that does not align with the priority classes set by ARE and is located in an area of low to medium biodiversity values. This reflects a general gap in planning under article 71a of the EnG, which prioritizes solar radiation and terrain over biodiversity value (Energiegesetz (EnG), 2016). The AHP analysis highlights the importance of ecological indicators such as *Habitat Quality* and *Species Diversity*, which are probably overlooked in traditional PV suitability assessments. Integrating these criteria could reduce ecological impacts through mitigation strategies, such as site-specific environmental assessments.



CASE C: Biodiversity Values compared with planned PV Installations in the Eastern Alps

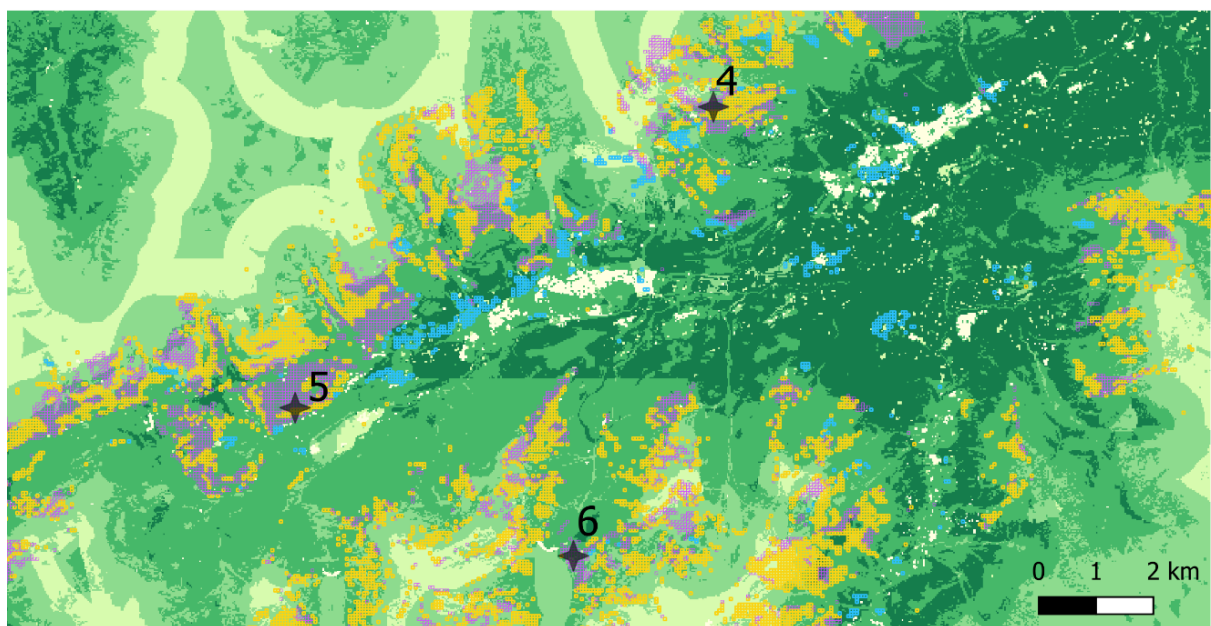


Figure 18: Map of planned large-scale PV plants in Switzerland (Case C), showing their locations and biodiversity values ranked from low (light green) to high (dark green)

These three case studies highlight diverse PV development scenarios in Switzerland. The Jura Mountains (Case A) demonstrate the importance of mitigation strategies in high-biodiversity areas. Case B is representative of opportunities in low-biodiversity zones that align with high priority PV installations. Case C examines planned PV plants and their associated biodiversity values, revealing gaps in current planning regarding the incorporation of biodiversity criteria.

6 Discussion

The results of this thesis highlight the complex trade-offs between the expansion of ground-mounted photovoltaic (PV) systems and the conservation of biodiversity in Switzerland. This chapter reflects critically on the conclusions of the spatial analysis and case studies, their implications for sustainable spatial planning and policy, the challenge of mapping biodiversity criteria into the ARE's geodata model, and the utility of the proposed decision-support tool in balancing renewable energy development with ecological integrity. The limitations based on the restricted data availability and the static nature of its analysis are mentioned, as well as possible ways to improve the approach.

6.1 Introduction: Linking to the Research Question

The Federal Office for Spatial Development (ARE) developed a geodata model to identify suitable locations for PV installations, considering both protection (e.g., ecological sensitivity) and utilization (e.g., solar potential) criteria (see Chapter 4.1). This *Utilization-Protection-Matrix* categorizes land into priority classes for PV development, primarily focusing on large-scale ground-mounted PV plants (GMPP). Since this thesis is concerned with identifying areas related to biodiversity protection, the latter (utilization) is not important. Protection Criteria (see Appendix A) excluded some ecologically sensitive areas, but their methodology did not prioritize biodiversity conservation, thus potentially overlooking critical areas.

This study was guided by two questions: What are the key challenges and ecological impacts associated with GMPP on biodiversity in Switzerland? How can biodiversity considerations be integrated into the planning and decision-making process for GMPP using methods such as Multi-Criteria Decision Making (MCDM) and the Analytic Hierarchy Process (AHP)? The approach presented in this thesis refines the ARE model by highlighting areas important for biodiversity conservation and ensuring that PV development can consider ecologically sensitive areas. However, focusing only on the exclusion of protected areas is not sufficient to effectively protect biodiversity. Many species depend on habitat quality, ecological connectivity, and landscape structures that extend beyond protected boundaries, especially in human-influenced environments (Purvis & Hector, 2000; Regan et al., 2007). Furthermore, factors such as climate change and land use change are already changing species distributions, making static protection alone inadequate (Hogue & Breon, 2022; Nordberg & Schwarzkopf, 2023). Therefore, this thesis takes a broader perspective identifying ecologically valuable areas beyond strictly protected zones, thereby contributing to a more comprehensive approach to biodiversity conservation.

Literature shows that GMPP pose several key ecological challenges. These include land use change, soil degradation, and negative impact on flora and fauna, such as habitat fragmentation. However, they may also offer positive impacts, for instance, by serving as refuge areas for biodiversity if they are managed

correctly (e.g., Armstrong et al., 2016; Dvořáčková et al., 2024; Evans et al., 2023; Gómez-Catasús et al., 2024; Levin et al., 2023; Montag et al., 2016; Moscatelli et al., 2022; Sánchez-Zapata et al., 2016; Schlegel, 2021; Taylor et al., 2019; Vervloesem et al., 2022). To systematically integrate biodiversity into the planning process, indicators were weighted using the AHP as part of a MCDM framework. The resulting biodiversity maps (see Figures 11 and 12) identify areas of ecological importance and analyses the spatial distribution of PV priority classes across biodiversity value classes. Based on this analysis, three case studies are examined that highlight both potential conflict and opportunities regarding PV development and biodiversity conservation. The results indicate that many high-priority areas for PV expansion are located in (sub)alpine regions, which frequently overlap with areas of high biodiversity value.

6.2 Biodiversity Assessment Application

The application of the biodiversity assessment framework gives an overview of the trade-offs and opportunities for freestanding photovoltaic (PV) development in Switzerland. This section evaluates the performance of the assessment through key findings and case studies.

Figures 11 and 12 illustrate the results of the AHP analysis. The classification for biodiversity values ranges from “very low biodiversity” (lightest green) to “very high biodiversity” (darkest green). The maps show that areas with high and very high biodiversity values are located predominantly in sub(alpine) and mountainous areas. Some biodiversity hotspots are visible in the Central Alps, Jura Mountains and Ticino region. The spatial pattern of biodiversity values seen here likely has a strong ecological basis related to factors such as topography and land use. Mountainous regions support biodiversity as these regions have topographic heterogeneity and habitat diversity (Bundesamt für Umwelt BAFU, 2023a; Körner, 2021). The Central Plateau and lowland agricultural areas generally have lower biodiversity values, likely due to increased urbanization, intensive agriculture and fragmentation (Bundesamt für Umwelt BAFU, 2023a). Therefore, maintaining and re-establishing ecological corridors between regions should be an important focus of conservation, especially in fragmented landscapes (Berthoud et al., 2004).

These results are then analysed with the PV priority classes by the ARE. The outcome is highlighted in the Sankey diagram (Figure 14). This figure illustrates how different PV priority classes correspond to biodiversity values. This analysis reveals potential tension between PV development and biodiversity conservation goals in Switzerland. The Jura Mountains and Eastern and Central Alps are primarily home to Priority 1 and 2 areas, which are located in regions with very high and high biodiversity value regions. This situation presents a potential conflict between sustainable energy development and biodiversity conservation: areas that are most favourable for solar energy production are often the same areas that are most ecologically valuable.

Priority 1 and 2 have considerable overlap with high and medium biodiversity values, as seen in Figure 14. Priority 3 and 4 areas have more association with medium to low biodiversity areas and may offer lower impact options for PV expansion. These areas may offer more sustainable options for PV expansion with reduced environmental impact. There is little transition from Priority 1 to low or very low biodiversity values. This highlights the few available high-priority PV areas that do not conflict with ecological priorities.

These findings also correspond with current research. Gómez-Catasús et al. (2024) criticize in their paper that PV installations often prioritize low cost over biodiversity conservation. According to them, there are overlaps of PV facilities with important conservation areas, which could lead to conflicts between PV development and conservation goals (p. 2). Also, they criticize that research is often strongly focused on specific contexts, which is also evident for this research, as only very few papers highlight this issue specifically in Switzerland. The results also point to the importance for spatially explicit planning that considers both ecological and renewable energy priorities. There has been recent work on the need for appropriate site selection and avoiding ecologically sensitive sites to minimize impacts on biodiversity while still ensuring that the energy transition is supported (Hernandez et al., 2014). The AHP-based assessment completed in this study provides a reasonable basis for this kind of planning, as it shows where there are likely trade-offs between biodiversity and solar development (e.g., Giamalaki & Tsoutsos, 2019; Marques-Perez et al., 2020; Villacreses et al., 2022).

6.2.1 Findings from Case Studies

The AHP results show that *Habitat Quality* and *Species Diversity* are the most critical indicators. These findings highlight conflicts between PV installations and biodiversity conservation but also identify areas for further detailed local investigation in low-biodiversity, high-suitability areas. Three case studies demonstrate these dynamics and offer helpful information about trade-offs and mitigation strategies. This subsection interprets these findings and evaluates their implications.

The results of the AHP analysis and case studies have several important implications for energy policy and spatial planning in Switzerland. Case C showcases planned PV plants in *Eastern Alps* and demonstrates the current planning process, which highlights the minimal prioritization of ecologically sensitive areas. The planning process places most of the PV plants in areas deemed to have higher biodiversity values. Case C highlights that, in practice, current frameworks largely continue to prioritize technical criteria, such as solar radiation and slope, over considerations for biodiversity. When this is the case, there is a risk that PV development will be pushed into ecologically-sensitive areas (Bundesamt für Energie BFE, 2023a). However, their alignment with ARE-detected areas suggests that both approaches employ comparable criteria.

To avoid these overlaps, the considerations of biodiversity would need to be systematically better integrated into the planning process for PV. Case A from the Jura Mountains exemplifies this issue:

important priority classes for PV areas overlap with biodiversity hotspots. This indicates a need for careful site selection as well as mitigation measures to reduce the ecological effects. Solutions may include designing PV systems with consider for biodiverse values; such as elevated solar panels to allow vegetation growth and movement of species, or pollinator-friendly ground cover to encourage ecosystem services (e.g., Blaydes et al., 2021; Gómez-Catasús et al., 2024; Hernandez et al., 2014). Recent studies also show that some species could positively contribute to GMPP, as these could provide the species with refuge or their undisturbed habitat (Blaydes et al., 2021; Carvalho et al., 2024). Furthermore, the choice of fencing bordering a GMPP can influence the biodiversity-friendliness of a PV plant. A fence that allows for species movement (especially for smaller animals) does not contribute to habitat fragmentation and could even act as “ecological islands” that connect habitats across the landscape. The influence of the type of fencing and PV design is species-dependent (Schlegel, 2021). There is not one solution for a biodiversity-friendly design that fits the requirements of all species affected. An adjustment could be made in revising article 71a of the EnG (Energiegesetz (EnG), 2016) to create explicit requirements for biodiversity protection. Alternatively, requiring ecological impact assessments for all large-scale PV projects could also be viewed as an approach to ensure that environmental trade-offs are considered. In addition, spatial planning methods (e.g., selecting exclusion zones to avoid areas of high ecological value) could also help to target development in less sensitive areas, as seen in Case B.

Case B (Central Plateau) is the clear outlier where low-biodiversity and anthropogenically modified land use, such as industrial areas, leads to the best opportunities and pathways for PV development due to flat topography and low ecological sensitivity. Case B highlights an “ideal scenario”, that is interesting for further detailed local investigation. However, these scenarios are quite rare, as the Sankey Diagram showed.

While the case studies help illustrate the trade-off within the environmental space that exists between constructing renewable energy infrastructure and protecting biodiversity, there are technological improvements (i.e., consideration of biodiversity-friendly designs of PV) that primarily lessen the environmental impact but will not remove all conflict between renewable energy and biodiversity. This underlies the need for a more nuanced, MCDM approach that goes beyond energy yield optimization and that considers ecological, social, and technical aspects (Gómez-Catasús et al., 2024). The AHP method applied in this study is one such framework; however, future refinement is possible by incorporating additional socio-economic indicators, including land-use conflicts with tourism, or cultural heritage (Giamalaki & Tsoutsos, 2019; Marques-Perez et al., 2020). The current analysis provides a snapshot based on existing biodiversity patterns and land-use data. However, climate change is expected to alter species distributions, habitat suitability, and ecosystem dynamics (Hoban et al., 2020; Swingland, 2001). This creates real uncertainty for long-term PV strategies. For example, areas like the Central Plateau, which seem less biodiverse now, might become ecologically significant as the climate shifts. Meanwhile, some high-biodiversity spots could face habitat decline, forcing us to rethink

conservation priorities. To make PV planning more resilient, we could work with dynamic biodiversity models and climate forecasts. PV suitability modelling with dynamic biodiversity models adds resilience in planning for the future (Hoban et al., 2020; Lafitte et al., 2023; Swingland, 2001).

The results of this study are influenced by several factors: the selection of biodiversity indicators, the quality and availability of data for each indicator, and the composition of the expert pool responsible for assessing weights. Collectively, these elements shape the identification and prioritization of biodiversity-sensitive areas. Thus, the findings should be understood as a representation of important biodiversity areas based on current data, values, processing and land-use patterns. They do not predict how biodiversity patterns might change in response to factors such as climate change or future land use changes.

6.3 Conceptual Framework for Biodiversity Assessment

Competing ecological and energy development priorities can complicate biodiversity assessment in the context of GMPP. This study has shown that often areas suitable for PV development overlap with ecologically sensitive areas, creating challenges for planning GMPP and considering biodiversity. Among other challenges, data gaps, spatial resolution limitations, and the dynamic nature of ecosystems complicate the assessment. However, the conceptual framework involves simplifications and limitations that are critically discussed below.

6.3.1 Selection of Biodiversity Indicators

Eight biodiversity indicators were selected to analyse the impacts of GMPP on biodiversity. These include biotic composition (*Species Richness, Species Diversity, Red List Species*) and ecosystem function (*Habitat Quality, Habitat Connectivity, Pollinator Abundance, Soil Quality, Human Recreation Potential*). This is in agreement with ecological models, for instance, those proposed by Regan et al. (2007) and Feest et al. (2010). Both emphasize the importance of both biological and ecological dimensions, which the selected set of indicators achieves.

Both species richness and species diversity (via the Shannon Index) are well-established measures used in biodiversity research (e.g., Duelli & Obrist, 2003; Peet, 1974; Purvis & Hector, 2000). These indices provide a standardized scheme for comparing biodiversity between sites, which is necessary to identify areas with high biodiversity, or hotspots. Indicators of ecosystem function capture functional aspects of ecosystems not usually addressed by surveys of biodiversity (DeLong, 1996). *Soil Quality*, for instance, is a key aspect of ecosystem function. Healthy soils support plant growth, microbial diversity, and nutrient cycling which are all essential for above-ground biodiversity. This indicator ensures that PV development does not disproportionately affect these underlying processes, which indirectly contribute

to species richness and habitat quality (Armstrong et al., 2016; Barron-Gafford et al., 2016; Blaydes et al., 2021; Gasparatos et al., 2017; Zhang et al., 2023).

Habitat Quality encompasses the structural and ecological conditions that enable species to persist (DeLong, 1996). Even though it does not directly measure the presence of species, it supports species-based indicators by providing a landscape-scale prediction of areas likely to sustain biodiversity in the future (DeLong, 1996). High-quality habitats often provide essential resources such as shelter, food, and breeding sites, which directly influence species richness and population stability (Van Der Plas, 2019). In addition, *Habitat Quality* reflects more broad-scale ecological processes, such as soil condition, vegetation structure, and habitat heterogeneity, that are all key to ecosystem function (Regan et al., 2007). In comparison to species-specific indicators, *Habitat Quality* can indicate ecological integrity even in areas of low species presence which makes it highly valuable for large-scale spatial planning such as PV site selection.

A key indicator is *Habitat Connectivity*. Its inclusion is particularly critical, as landscape fragmentation can disrupt species movement and gene flow, which is also a major concern for the Federal Office for the Environment (Berthoud et al., 2004). However, defining criteria for *Habitat Connectivity* was challenging. ARE had already taken into account some aspects (e.g., moorlands; see Appendix A), but it did not consider others. In this study, *Habitat Connectivity* consists of *Réseau Écologique National* (REN) locations and *Interregional Wildlife Corridors* (see 4.2.2). Some areas might be included in both the ARE model and in this biodiversity framework, which could unintentionally assign them more importance than intended. For example, ARE classified floodplains as non-interest areas, while REN also considers floodplains, which were buffered and treated as high biodiversity value. This double exclusion from PV development elevates their weight beyond what expert input alone would suggest. To assess the extent of this issue, the relevant spatial layers were overlaid manually and checked for potential overlaps. Although these overlaps were minor and likely did not skew the results, it is important to keep this limitation in mind.

Nevertheless, despite this holistic assessment, they represent a simplification of the complex interplay of ecological processes and likely overlook local variations such as microhabitats or species-specific responses to PV infrastructure (Blaydes et al., 2021; Boscarino-Gaetano et al., 2024; Gómez-Catasús et al., 2024; Lafitte et al., 2023; Vervloesem et al., 2022). The selected indicators are broadly defined and not explicitly tailored to the specific impacts of ground-mounted PV systems, such as shading, microclimate changes, or the “Lake Effect” on birds (as noted in Chapter 3.1.4). For example, although *Pollinator Abundance* is included, the methodology does not discuss how PV panels might alter floral resources or nesting sites. This gap could limit the methodology’s ability to address the research question about the ecological impacts of PV systems.

We must critically question the decision to include indicators of ecosystem functions in biodiversity assessments, despite their controversial status (DeLong, 1996). The functional differences between

lowland and Alpine regions justify this inclusion, but it risks confusing biodiversity with broader ecological processes. For instance, the relationship between *Human Recreation Potential* and ecosystem health is socio-ecological, not purely biological. Nevertheless, it can still be considered an important factor for several reasons. First, areas with high recreation potential often overlap with accessible natural spaces, which can promote public support for biodiversity conservation (Siikamäki et al., 2015). Thus, while recreation potential is not a direct measure of biodiversity, it reflects socio-ecological dynamics that can indirectly support biodiversity outcomes by increasing social value of natural areas (Burger, 2000). Second, recreation potential can serve as a proxy for ecosystem accessibility and landscape attractiveness, both of which influence patterns of human pressure and land use change (Burger, 2000; Siikamäki et al., 2015). Areas with high recreational value may face competing interests between conservation and development, making them critical zones for integrated planning (Burger, 2000; Qiu et al., 2013). In this sense, the inclusion of this criterion, despite its low global weight, helps to capture the human dimensions that influence the persistence of biodiversity. Finally, consideration of recreation potential takes into account the fact that conservation does not occur in isolation from human use. Especially in densely populated regions such as Switzerland, socio-ecological indicators can provide a more realistic assessment framework by taking into account potential trade-offs between biodiversity protection and human well-being (Qiu et al., 2013).

Drawing on the insights of experts and a literature review (e.g., Regan et al., 2007) strengthens the methodology as it is based on both practical and academic knowledge. Input from scientific experts ensures that the selected indicators align with Swiss conservation priorities, such as the “Aktionsplan Biodiversität” (Aktionsplan des Bundesrates, 2017). However, the focus on only four species groups (mammals, amphibians, reptiles and breeding birds) for species richness and diversity further limits the representation of Switzerland’s biodiversity. This limitation risks underrepresenting biodiversity in regions with unique flora or insect communities. However, these species groups were selected because they include some of Switzerland’s most threatened and publicly recognizable species and are not already considered in other indicators. For instance, insects are represented in the indicator *Pollinator Abundance* which includes a representative range of insect species and estimates habitat suitability through nesting and floral resources (Cordillot & Klaus, 2011; Külling et al., 2024).

This study selected relevant indicators based on the literature review and expert input. However, there are many indicators that were not considered in this research. Duelli & Obrist (2003) mention for instance indicators to evaluate “biological control of potential pest organisms” (p. 92) to be important in the European industrialised context. Their Figure 1 (p. 88) provides an overview of potential biodiversity indicators to consider. Regan et al. (2007) divides criteria into “current biological value, fully restored biological value, and threat” (p. 2718) to fully capture criteria relevant for biodiversity. These criteria were then divided into sub-criteria to evaluate the weights in an AHP analysis. Both papers discuss biodiversity indicators, but from different perspectives. While Regan et al. (2007) discuss it in the context of conservation planning, Duelli & Obrist (2003) discuss biodiversity indicators from a more

general perspective. None of them discuss it from a PV planning perspective, although the motivation for dealing with biodiversity influences the choice of biodiversity indicators (Duelli & Obrist, 2003). The availability of open access (*libre*) data limited the selection of biodiversity indicators used in this study. Thus, this research focuses on general biodiversity indicators that may not fully represent biodiversity in the context of PV site selection adequately. For instance, high-altitude PV installations, which are a priority in Switzerland to close the “winter energy gap” (see Chapter 2.1), are located in Alpine ecosystems that are particularly sensitive to disturbance. The lack of studies on the impacts of PV installations in these regions limits the ability to provide targeted recommendations (Bundesamt für Energie BFE, 2023a; Rupf & Rohrer, 2024; Schlegel, 2021).

Biodiversity is inherently complex. Several studies try to explain and define this complexity with simple measures (Duelli & Obrist, 2003). However, simple measures can never fully capture all relevant aspects, such as genetic diversity or indirect effects like trophic cascades (Van Der Plas, 2019). Still, the selected indicators arguably represent biodiversity for the Swiss context and the scope of this research.

6.3.2 Biodiversity Data Resolution and Accuracy

The spatial modelling approach in this study enables the assessment of biodiversity hotspots across Switzerland. A hexagonal grid was used to map species richness and diversity (using the Shannon Index), with a weighted grid overlay derived from AHP weights. This approach allows for a spatial assessment of important biodiversity areas and enables comparison with PV priorities defined by the ARE. The choice of a coarse grid resolution was driven by data limitation and requires critical evaluation due to its impact on accuracy and the risk of overlooking local conflicts or opportunities.

Hexagonal Grid

The hexagonal grid was selected because it minimizes edge effects and provides a more uniform spatial representation in terms of distance and adjacency compared to square grids (Juraskinski & Beierkuhnlein, 2006). A hexagonal grid with 7'500 m sides was chosen due to smooth patterns in the coarse GBIF occurrence data for reptiles and breeding birds, which are provided in 5x5 km or 10x10 km grids to ensure data protection, which resulted in artificial spatial patterns in the data, likely reflecting observation alignments within these grids. The coarser hexagonal grid helped smooth these patterns. However, this resolution may obscure small-scale variation critical for species, such as amphibians or endemic alpine flora, potentially misclassifying local biodiversity hotspots as less sensitive areas. Isolated alpine habitats, for example, may not be captured, which has implications for site selection (Gómez-Catasús et al., 2024; Mentges et al., 2020). Consequently, while broad patterns such as overlaps between high-priority PV classes and biodiversity hotspots can be detected, important fine-scale habitats might be masked. Similarly, in the Eastern Alps (Case C), the underrepresentation of small areas with

lower biodiversity value could lead to incorrect site selection. This shows the importance of cautious interpretation of results at the local level. Moreover, the use of GBIF data leads to uncertainties due to inconsistent sampling efforts (Brown et al., 2015; Mentges et al., 2020). Urban lowlands are probably better represented than remote alpine areas, potentially biasing assessments towards more populated regions and underestimating conservation values in others.

Hexagons were clipped at the national border to correspond to the Swiss territory. As a result, boundary cells contained less area and fewer species occurrences, which artificially lowered species richness. This edge effect can distort spatial ecological patterns and lead to an underrepresentation of biodiversity near the borders. One possible correction is to adjust species counts based on the proportion of each clipped cell remaining within Switzerland, assuming that species are evenly distributed within the cell. However, a trial using this method in this study resulted in unrealistic overestimation of biodiversity in these cells, likely due to ecological heterogeneity and the non-random distribution of species. Therefore, no area-based adjustment was applied, and this limitation should be considered when interpreting results.

A grid size of 7'500 m is an appropriate compromise in terms of data availability and analytical feasibility but it limits the model in terms of capturing the full potential of Switzerland's diverse landscapes. Finer grid sizes could help identify local conflicts or planning opportunities (e.g., infrastructure-adjacent sites) and make for more informed decisions. However, this resolution is adequate for a first overview. Additionally, there are limitations regarding the use of the Külling et al. (2024) data. Külling et al. (2024) model species-level habitat suitability using ensemble (Species Distribution Models) SDMs, combine these into a multi-species biodiversity indicator via Zonation, and then explore spatial patterns and drivers of biodiversity–NCP (“nature’s contribution to people”) bundles using clustering and classification tools. Their methodology is comprehensive and data-rich, specifically designed to inform spatial planning in Switzerland. There are spatial and resolution inconsistencies to consider. While Külling et al. (2024) provided high-resolution (25 m) raster maps, other input datasets used in this study have coarser spatial resolution, which may constrain the ability of the model to accurately represent local ecological variability. Furthermore, biodiversity data and model outputs from Külling et al. (2024) were adopted in their original form. Any potential inaccuracies in their datasets are inevitably present in this study.

All considered, the above data are thought to have been appropriately detailed and of acceptable quality. The use of secondary datasets and expert input provides a reasonably robust foundation for analysing biodiversity patterns. However, one should consider uncertainties in data quality and coverage when interpreting the results.

Mapping and Visualization of Results

A further challenge occurred after generating the results, particularly in effectively visualizing and interpreting the spatial data. One significant issue was the integration of different map scales within a single map. Biodiversity data consists of fine-scale data provided by Külling et al. (2024) and broad assessments (such as *Species Diversity*), which is only evaluated in a 7'500 m hexagonal grid. Thus, the biodiversity maps show trends in patterns on a national scale. PV installation priority classes are stored in coarse polygons determined by the ARE. The challenge of combining these scales, the overall biodiversity patterns versus localized polygons, required careful consideration to ensure that results are both broadly applicable and locally relevant. Presenting results from the ARE model and the AHP-based biodiversity assessment in a single, nationwide map was not possible due to differences in scale and data resolution. Instead a two-step approach was applied: first, an overview was provided using the coarse hexagonal grid to identify general patterns and areas of potential conflict between PV development and biodiversity. Subsequently, selected case study areas were examined in greater detail through zoomed-in maps to highlight specific areas of interest and better capture small-scale ecological dynamics that might be underestimated at the national scale. This approach follows the information-seeking mantra by Shneiderman (1996): “overview first, zoom and filter, then details-on-demand” (p. 337). To solve this issue, case studies were selected to highlight some areas of interest in particular. For instance, the coarse hexagonal grid risked oversimplifying complex ecological dynamics, potentially underestimating the conservation value of small, high-biodiversity patches. At the same time, it might classify areas of low biodiversity as high-biodiversity areas, thereby overlooking potential opportunities.

6.3.3 AHP Design, Distribution and Processing & Result

The AHP process in this study weighted biodiversity indicators based on input from nine experts, resulting in the following global weights: *Habitat Quality* (26.8%), *Species Diversity* (26.5%), *Habitat Connectivity* (13.5%), *Red List Species* (8.8%), *Soil Quality* (8.1%), *Species Richness* (7.5%), *Pollinator Abundance* (6.9%), and *Human Recreation Potential* (2.1%) (see Table 12). This section critically evaluates the AHP indicator weighting process and focuses on constraints in the survey design, expert response patterns and the resulting indicator priorities.

Resulted Expert Weights

According to the AHP analysis *Ecosystem Function* (EF; 0.573) is weighted as more important than *Biotic Composition* (BC; 0.427). This suggests that experts prioritized functional ecological characteristics over compositional biodiversity indicators. In other words, maintaining ecological processes such as *Habitat Quality* and *Habitat Connectivity* is considered more significant than species count alone.

At the sub-criteria level, *Species Diversity* (BC2) and *Habitat Quality* (EF1) are the most influential indicators, with almost equal global weights (26.5% and 26.8%, respectively). This emphasis reflects a consensus among experts that biodiversity depends on both species-level variety and the underlying physical conditions that support it.

The third most important sub-criterion is *Habitat Connectivity* (EF2) (13.5%). This highlights how important spatial continuity is to ecological flows and the migration of species. Sub-criteria with moderate weights, such as *Red List Species* (BC3) and *Soil Quality* (EF4) (8.8% and 8.1%), indicate that they are important but not the main drivers of biodiversity in this framework. *Human Recreation Potential* (EF5) received the lowest global weight (2.1%). The low global weight reflects expert consensus that, in the context of strictly biological biodiversity assessments, recreation potential is not a direct ecological indicator, such as *Species Diversity* or *Habitat Quality*. However, its inclusion ensures that broader socio-ecological factors are at least considered, which is important for ensuring that conservation outcomes are viable and supported in practice.

These weights show a preference for evaluating biodiversity not just by species count or legal conservation status, but also by ecosystem function and structural diversity. This has practical implications for renewable energy development: PV projects should aim to avoid areas of high habitat quality and species diversity, since these are the ones that most strongly influence ecological connectivity.

Limitations in AHP Survey Design & Distribution

The AHP survey encountered challenges in both design and participation. In the introduction to the questionnaire, each indicator was introduced with a brief definition; however, in retrospect, some definitions may have lacked sufficient detail, which led to misinterpretations about definitions and thus weight distribution. For instance, *Habitat Connectivity* was broadly described as the ability of species to move between habitats, but lacked concrete examples (e.g., wildlife corridors), which may have resulted in varied interpretations among respondents.

The response rate was also limited. Initially, the survey was distributed to a diverse pool of experts working in different fields and organisations. From this initial pool, only three responses were received. In a second round, experts were collected based on personal contacts at the University of Zurich. This yielded 9 responses. Notably, only one response came from a non-academic participant. This predominantly academic view may have emphasized broader ecological concerns over region-specific biodiversity issues. A larger and more diverse expert pool would have enhanced the robustness of the AHP results and the reliability of indicator weights. Furthermore, the subjective nature of AHP responses presents a challenge, as experts' judgments are influenced by their professional backgrounds. With a homogeneous group (largely academic), the responses tended to converge, which is visible in the weighting results. The absence of participants directly involved in applied biodiversity assessment may

have resulted in weighting the indicators towards more theoretical priorities. If the pool of experts had been expanded to include local land managers, conservation NGOs, or practitioners, it might have better balanced academic and applied perspectives, and could have resulted in a different weight distribution (Ball, 2002; Brown, 2015; Brown et al., 2015).

Geometric Mean Aggregation in AHP

In this study, a geometric mean was used to aggregate pairwise comparison judgments from nine experts. This resulted in three pairwise comparison matrices (PCMs). This method synthesizes diverse expert inputs while mitigating the influence of extreme judgements. The geometric mean is less sensitive to outliers, and thereby prevents any single expert from disproportionately affecting the result. This property is particularly valuable due to the small sample size of experts and the predominantly academic expert pool (Escobar et al., 2004; Grošelj & Zadnik Stirn, 2012; Ishizaka & Labib, 2009). For example, in the 5x5 ecosystem function PCM, complex indicators such as *Habitat Connectivity* and *Pollinator Abundance* were compared. The geometric mean helps reduce outlier impact which results in a low consistency ratio (CR = 0.0586). This supports the robustness of highly weighted indicators. The geometric mean also preserves the ratio scale structure of AHP (1–9 scale) and ensures mathematical consistency, as it sums the ratios into a single product, and extracts the n^{th} root (Saaty, 1987).

Nonetheless, this method has limitations. By averaging judgements, the geometric mean may suppress dissenting expert views that capture ecological nuance. This concern is particularly relevant for the complex 5x5 ecosystem function PCM, where minor variability in preferences could be meaningful. The limited diversity in the expert pool enhances this issue, potentially reinforcing academic biases. For instance, theoretical metrics such as *Species Diversity* may have been prioritized over practical concerns such as *Habitat Connectivity*, which could affect how the results are translated into real-world planning contexts. An alternative approach would have been to calculate AHP results separately for each expert and compare the variation between individual priority structures. While this process was beyond the scope of the current study, such an analysis could provide valuable insights into the degree of consensus or divergence among experts and highlight areas of uncertainty or disagreement in indicator weighting (Saaty, 1987).

Sensitivity Analysis: AHP Robustness

The sensitivity analysis was conducted to assess the robustness of the AHP results by perturbing expert inputs by $\pm 10\%$ and $\pm 20\%$ for high-level criteria (biotic composition BC and ecosystem function EF) and their sub-criteria. This tested the effect of variations in expert judgments on global indicator weights.

The sensitivity analysis highlights key limitations. First, it does not account for synergies between indicators, such as complex ecological interactions (e.g., how *Habitat Connectivity* influences *Species*

Diversity). Second, the uniform perturbations assumed throughout the analysis ($\pm 10\%$, $\pm 20\%$) may not quite reflect expert opinion shaped through disciplinary focus or regional ecological knowledge. Additionally, tipping points were not exhibited at all. Even despite these adjustments, high-priority indicators remained stable in their relative importance. *Habitat Quality*, as well as *Species Diversity*, for example, did not change. In the sensitivity analysis, no criterion experienced a reversal in its relative ranking compared to others. This stability showed decision-making results are solid, that these results are not sensitive to differences in experts' inputs, which increases confidence in the reliability of the prioritization framework.

Overall, the conceptual framework was robust for the core indicators. Despite perturbing the indicator weights, the results consistently indicated the same biodiversity hotspot. This indicates that the model is robust and that there are no tipping points, which allows the model to be adapted to different contexts or planning goals while still prioritizing biodiversity. However, the results can still be greatly affected by how biodiversity is defined, which indicators are chosen, and how they are weighted. This variability is not inherently a problem but rather an expected part of the process. One goal of this study was to determine important areas for biodiversity in Switzerland, and this goal can be achieved in various ways. Each decision should have transparent reasoning, reflecting the values and priorities of those involved in the planning process.

6.3.4 Equifinality & AHP

Equifinality refers to the principle that multiple pathways, or different combinations of inputs, can lead to the same outcome (Fitzgerald, 2019; Odoni, 2007). In the context of this study, the inputs are the selected biodiversity indicators, their associated datasets, and the weights assigned to each indicator through the AHP analysis. The output is a map highlighting biodiversity hotspots across Switzerland. Eight indicators were selected based on literature and expert input, with weights determined through AHP to reflect their relative importance. This supports the equifinality principle: different sets of indicators and weighting combinations can still lead to valid, meaningful identification of biodiversity-sensitive areas (Fitzgerald, 2019).

While equifinality is an advantage in that it acknowledges the complexity of ecological systems and allows for multiple valid perspectives, it can also be a disadvantage, as it may obscure the understanding of which specific inputs led to a given outcome. However, the transparent structure of the AHP methodology in this study addresses this limitation. Since each biodiversity-sensitive area can be traced back to the specific combination of indicators and weights that contributed to its classification, it is possible to provide policymakers with clear, area-specific information on the factors driving sensitivity. This not only helps overcome the potential disadvantage of equifinality but also enhances the practical utility of the results for targeted conservation action.

The AHP methodology systematically ranks and weight these indicators based on expert input. This MCDM process allows for the integration of potentially diverse perspectives and the explicit quantification of trade-offs between indicators. To explicitly record a variety of expert priorities, weights can be adjusted, resulting in another, potentially different, but still valid, priority rating. This demonstrates that there is no single set of “correct” inputs for biodiversity hotspots prioritization. Instead, a combination of indicators can lead to similar outputs. In this way, AHP is a key tool that enables transparent and consistent decision-making that also prioritizes the realities of complex ecological systems and the broad scope of MCDM. Communicating this understanding to those using the resulting maps is equally important. One should be aware that there are no single, definitive pathways leading to the identification of biodiversity-sensitive areas. Rather, different combinations of indicators and expert priorities can result in similar classifications. By making these underlying factors transparent and accessible, the map becomes not only a visual tool but also a means of informing more nuanced, evidence-based conservation decisions (Fitzgerald, 2019).

6.4 Recommendation for Future Research

Future research could potentially overcome the limitations raised in this chapter. For instance, future studies could extend the taxonomic scope of biodiversity in Switzerland to better reflect species diversity in general, including some underrepresented taxonomic groups such as plants, insects, and molluscs. Additionally, the use of finer-scale data would be useful for identifying small scale changes in biodiversity patterns, especially in heterogeneous alpine and subalpine landscapes.

Also, future studies should avoid considering criteria twice. A broader evaluation of the protection-relevant criteria, which could ideally bring in all criteria from the outset rather than as a "final step", may improve the credibility of biodiversity considerations in spatial planning. Future studies could explore the possibility of adding additional indicators to expand the facets of biodiversity; maximizing the data at hand to improve quality or precision; or utilizing a larger or different group of experts to re-evaluate the AHP outcomes. Future studies could also consider inverting the perspective: instead of trying to identify areas abundant with biodiversity, they could think about where the biodiversity is lacking or degraded (e.g., Regan et al., 2007). This analysis could provide valuable insights into identifying areas that are ecologically underrepresented, indicating significant losses in conservation planning, or suggesting locations for potential PV development. This understanding of “biodiversity coldspots” may complement conservation planning efforts while providing insight into the impact of urban growth and land use change.

A further relatively less explored topic is the role of microhabitat structures within PV parks, particularly for alpine and subalpine ecosystems. Empirical studies are needed to assess the real-world biodiversity impacts of different PV designs, fencing types, and management practices (Gómez-Catasús et al., 2024; Schlegel, 2021), including in Swiss landscapes. Furthermore, the incorporation of dynamic temporally

defined data (e.g., seasonal biodiversity patterns, migration routes) within the AHP method would significantly contribute to the accuracy of PV suitability analyses. Social acceptance, public perception, and stakeholder engagement should also be investigated as part of future research regarding GMPP project location. Local communities, conservation organizations, and renewable energy developers should all take part in site selection, design, and monitoring in order to make balanced and informed decisions (Gómez-Catasús et al., 2024). This is particularly important in ecologically sensitive areas such as the Jura Mountains and high-alpine regions, where local ecological knowledge and stakeholder input can support more context-sensitive decisions. In addition, participatory approaches can also help build public acceptance for PV projects, especially when biodiversity co-benefits are demonstrated (Brown, 2015; Qiu et al., 2013).

Furthermore, incorporating climate change scenarios into biodiversity and PV suitability analyses could improve the long-term resilience of GMPP planning, accounting for shifting species distributions and habitat conditions under future climatic conditions.

In this regard, the methodology remains flexible and adaptable, capable of addressing a range of conservation purposes, whether it be to highlight ecological richness or regions of concern. This highlights the more general observation that the value of conservation planning can profit from different analytical perspectives, all of which contribute to a more sophisticated understanding of biodiversity patterns and priorities.

7 Conclusion & Outlook

This thesis addressed the ecological impact of ground-mounted photovoltaic plants (GMPP) on biodiversity in Switzerland and developed a framework to integrate biodiversity considerations into their planning. This study refined the Federal Office for Spatial Development (ARE)'s protection-utilization matrix to prioritize biodiversity conservation. It developed a biodiversity-focused Multi-Criteria Decision Analysis (MCDA) framework in which indicators were weighted through expert-based Analytic Hierarchy Process (AHP). Indicators were then ranked to derive a spatially explicit map of biodiversity values. Combined with case studies in the Jura Mountains, Central Plateau, and Eastern Alps, the analysis determined significant overlaps between areas suitable for PV installations and biodiversity hotspots, particularly in (sub)alpine regions. For example, the Eastern Alps case study (Case C) showed that five out of six (shown) planned large-scale PV plants in Grisons are located in medium to high biodiversity values, highlighting need to incorporate ecological indicators to mitigate impacts in these sensitive regions.

These results highlight the tension between two urgent global challenges: the rapid expansion of renewable energy to meet climate goals (e.g., Swiss Energy Strategy 2050) and conserving biodiversity in the face of accelerating habitat loss driven by climate change. The trade-off between climate change mitigation and biodiversity conservation is central to this study. While developing GMPP will be critical for reducing greenhouse gas emissions, it can lead to habitat fragmentation and loss of species, particularly in ecologically sensitive areas. Conversely, degraded or anthropogenically modified and locally low biodiversity areas can be used for PV with a relatively limited ecological trade-off.

There is evidence in the literature that GMPP installations can provide local ecological benefits, such as providing microhabitats or refuges for threatened species, but these benefits underline the importance of careful site selection. In this context, it is crucial to avoid biodiversity hotspots as GMPP locations in the first place, in order to protect sensitive ecosystems from irreversible damage. Furthermore, GMPP projects should be planned and designed using biodiversity-friendly approaches that support local species and enhance the ecological value of the site, such as the installation of raised panels or pollinator-friendly plantings, which can help in maintaining habitat connectivity and supporting species resilience (Blaydes et al., 2021).

Therefore, this thesis shows that Switzerland can achieve its climate goals while ensuring biodiversity through context- and side-based planning. The MCDA framework and the spatial biodiversity data allow for a flexible, transparent, and repeatable decision-making process to better assist decision-making in developing GMPP. In this sense, while the study has national relevance, this approach contributes to the broader scientific discourse on how spatial planning tools can provide the right balance between the global energy transition and biodiversity conservation.

Switzerland can thus serve as a model for balancing the expansion of renewable energy and the conservation of biodiversity, to address the interlinked global challenges of climate change and ecological loss.

While this study provides an important foundation, further investigation is needed to explore certain aspects. Section 6.4 discusses these in depth and outlines recommendations for future research, including methodological improvements, expanded biodiversity assessments, and the exploration of biodiversity-friendly photovoltaic designs. Advancing research along these lines will make decision-making tools necessary and ensure that the energy transition proceeds without weakening ecological integrity.

Responsible integration of biodiversity considerations into renewable energy planning ultimately requires continuous scientific innovation, interdisciplinary collaboration, and a long-term, ecosystem-oriented perspective that is both a societal imperative and a technical challenge.

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Glossary

Table 13: Key Terms for defining Biodiversity

Component	Description	Reference
Genetic Diversity	Variability in genetic information within species, populations, and individuals	(Hughes et al., 2008; Swingland, 2001)
Species Diversity	The variety of species within a given area, including species richness (number of species) and species evenness (relative abundance)	(Swingland, 2001)
Ecosystem Diversity	The variety of ecosystems in a region, encompassing different habitats, biotic communities, and ecological processes	(Purvis & Hector, 2000)
Ecosystem Function	Processes and interactions, such as nutrient cycling, energy flows, and pollination, that sustain ecosystems.	(Redford & Richter, 1999)
Endemism	The presence of species unique to a specific geographic area	(Swingland, 2001)
Composition	The identity and abundance of biotic elements, such as genes, species, and populations.	(DeLong, 1996)
Structure	The spatial arrangement of ecosystems and their biotic components, including vertical (e.g., canopy layers) and horizontal (e.g., habitat patches) arrangements.	(DeLong, 1996)
Function	Processes and interactions that sustain ecosystems, including nutrient cycling, energy flows, and pollination.	(DeLong, 1996)
Hotspots	Areas with exceptionally high biodiversity and endemism that are often under threat	(Purvis & Hector, 2000; Swingland, 2001)
Invasive Species	Non-native species that disrupt local ecosystems and biodiversity.	(Hogue & Breon, 2022)
Indicators	Measurable factors used to assess biodiversity health or threats.	(Hoban et al., 2020)
Ecosystem Services	Benefits provided by ecosystems, such as pollination, water purification, and carbon storage.	(Van Der Plas, 2019)
Resilience	The capacity of ecosystems to recover from disturbances while maintaining biodiversity.	(Hoban et al., 2020)

Appendix

Appendix A: Utilization and Protection Criteria used by ARE

Table 14: Utilization Criteria developed by ARE (as of Oktober 2024)

Thematic Area	Geospatial Dataset	Usage Interest	Description / Details on Dataset Usage
Determining usage aspects and identifying areas to exclude (= Class 5)			
Global Radiation	Horizontal global radiation, winter semester	Not relevant for usage	Horizontal global radiation during the winter semester
Technology/Natural Hazards	Slope inclination	Not relevant for usage	Slope inclination > 40°
Technology/Natural Hazards	Swisstopo SwissTLM3D land cover	Not relevant for usage	Debris, boulders, glaciers, snowfields/dead ice
Accessibility	Synthetic dataset (created for analysis)	Not relevant for usage	Class "Very poor accessibility"
PV Production Potential	Specific yield, winter semester	Variable usage interest	Expected production per year
PV Production Potential	Production expectation, winter semester average	Variable usage interest	Expected production during the winter semester (Oct–March)
Technology/Natural Hazards	Slope inclination	Variable usage interest	Slope inclination
Technology/Natural Hazards	Permafrost	Low usage interest	Permafrost distribution
Technology/Natural Hazards	Avalanche hazard: SLF CAT (classified avalanche terrain by WSL Snow and Avalanche Research Institute)	Low usage interest	Avalanche starting and runout zones
Technology/Natural Hazards	Swisstopo SwissTLM3D land cover	Low usage interest	Loose debris, loose boulders, loose rock, wetland
Accessibility	Accessibility quality in 3 or 4 classes	Variable usage interest	Accessibility classified as "Good / Moderate / Poor"

Synergy with Other Infrastructures	Presence of important transport, tourism, or energy infrastructure (existing load)	High usage interest	Existing load present
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Table 15: Protection Criteria developed by ARE (as of Oktober 2024)

Thematic Area	Geospatial Dataset	Protection Interest	Description / Details on Dataset Usage
Not Considered Areas	Harmonized Building Zones Switzerland	Not Considered	All zones
Not Considered Areas	ARE Settlement	Not Considered	Groupings outside building zones plus traffic areas (roads / rail / aviation)
Not Considered Areas	Usage Area (not covered by building zones; cf. TLM3D)	Not Considered	Selection of recreational areas, cemetery, public park area
Not Considered Areas	Lake Surface (Swisstopo SwissTLM3D standing waters)	Not Considered	Selection of standing waters
Not Considered Areas	Forest (Swisstopo SwissTLM3D land cover)	Not Considered	Selection of forest, scrubland
Biotope Protection	Peat Bogs	No Interest Consideration	Protection area
Biotope Protection	Wetlands	No Interest Consideration	Protection area
Biotope Protection	Floodplains of national significance	No Interest Consideration	Protection area
Biotope Protection	Amphibian Breeding Areas	No Interest Consideration	Protection area
Biotope Protection	Water and Migratory Bird Reserves (WZZV)	No Interest Consideration	Protection area
Biotope Protection	National Park	No Interest Consideration	Protection area
Biotope Protection	Nature Experience Park / Core Zone	No Interest Consideration	Protection area
Landscape Protection	Moorlands	No Interest Consideration	Protection area
Water Protection	Groundwater Protection Zone 1	No Interest Consideration	Protection area
Species Protection	Regional Wildlife Corridors	Basic Exclusion Area	Protection area

Biotope Protection	Nature Experience Park / Transition Zone	Basic Exclusion Area	Protection area
Landscape Protection	BLN	Basic Exclusion Area	Nationally significant perimeter inventory
UNESCO Natural Heritage	UNESCO World Heritage Nature Sites	Basic Exclusion Area	Protection area
Forest	Forest Reserves	Basic Exclusion Area	Protection area
Forest	Forest Distance	Basic Exclusion Area	Protection area
Water Protection	Water Area (Lakes)	Basic Exclusion Area	Protection area
Water Protection	Water Area (Rivers)	Basic Exclusion Area	Protection area
Water Protection	Groundwater Protection Zone 2	Basic Exclusion Area	Protection area
Water Protection	Groundwater Protection Area	Basic Exclusion Area	Protection area
Agricultural Areas (FFF)	FFF	Basic Exclusion Area	All areas
Local Appearance Protection	ISOS (outside building zones)	Basic Exclusion Area	ISOS as area
Local Appearance Protection	ISOS (outside building zones)	Basic Exclusion Area	ISOS as point
UNESCO Cultural Heritage	Core and Buffer Zones	Basic Exclusion Area	Core zones of World Heritage Sites
Military	Weapon & Firing Ranges	Basic Exclusion Area	Weapon/Firing ranges as per SPM
Energy Use Avoidance	Avoidance of Hydroelectric Power Use	Basic Exclusion Area	VAEW Areas
Agriculture	Ecological Direct Payments - Biodiversity Contributions	Low Protection Interest	Biodiversity Promotion Areas (BFF) Quality Level II
Agriculture	Ecological Direct Payments	Low Protection Interest	BFF Connectivity Area
Agriculture	Perimeter of Agricultural Land (LN) and Summer Grazing Areas	Low Protection Interest	Summering Areas (without LN)
Agriculture	Perimeter of Agricultural Land (LN) and Summer Grazing Areas	High Protection Interest	Agricultural Land Area (LN)
Landscape Protection	Biosphere Reserve	Medium Protection Interest	

Landscape Protection	Regional Nature Park	Medium Protection Interest	
Species Protection	Hunting Ban Areas	High Protection Interest	
Species Protection	Wildlife Rest Zones	High Protection Interest	
Species Protection	Pro Natura Nature Reserves	High Protection Interest	
Biotope Protection	Floodplains outside Federal Inventory	High Protection Interest	
Biotope Protection	Wetlands outside Federal Inventory	High Protection Interest	
Biotope Protection	High and Transitional Moorlands outside Federal Inventory	High Protection Interest	
Biotope Protection	TWW outside Federal Inventory	High Protection Interest	
Water Protection	Groundwater Protection Zone Sh	High Protection Interest	
Water Protection	Groundwater Protection Zone Kt in Force	High Protection Interest	
Water Protection	Groundwater Protection Zone 3	Medium Protection Interest	
Water Protection	Groundwater Protection Zone Sm	Medium Protection Interest	
Water Protection	Groundwater Protection Zone Kt not in Force	Medium Protection Interest	
Water Protection	Groundwater Protection Zone S3Zu	Medium Protection Interest	
Local Appearance Protection	ISOS (outside building zones) with high location quality	High Protection Interest	ISOS as point
UNESCO Cultural Heritage	Buffer Zones	High Protection Interest	Buffer Zones
Theme Area	Geo Dataset	Protection Interest	Description / Details for Dataset Usage

Appendix B: AHP Survey

Analytical Hierarchy Process (AHP) Questionnaire on Biodiversity Indicators

Introduction

This questionnaire aims to identify and rank key biodiversity indicators that can be used to evaluate the ecological impacts of photovoltaic (PV) installations, particularly large, ground-mounted systems. Considering biodiversity in the use of solar energy plays a crucial role. Therefore, my research seeks to identify locations where biodiversity conservation and future PV installations are as compatible as possible. To achieve this, I will review the ecological effects of PV installations, assess important biodiversity indicators, and explore ways to integrate biodiversity considerations into planning. The study applies the Analytical Hierarchy Process (AHP) method, a structured decision-making method that helps prioritize complex issues by analysing relative priorities.

In Switzerland, natural habitats already face significant pressure from various threats. The expansion of ground-mounted PV systems adds to these challenges, with potential impacts such as habitat disruption and loss. This research aims to address these concerns by identifying the most relevant biodiversity indicators to guide sustainable PV planning.

The questionnaire follows a structured approach, asking you to compare biodiversity indicators in pairs and rate their relative importance on a scale from 1 to 9 (from equal importance to extremely more important). Your input will help prioritize the most critical factors for assessing the ecological impact of PV installations.

Description of the Biodiversity Indicators

	Indicator	Description
Biotic Composition		
BC_1	Species Richness	Species richness refers to the number of different species present in a given area or ecosystem. It is a measure of biodiversity, focusing solely on the count of species, without considering their abundance or distribution.
BC_2	Species Diversity	Species diversity is a measure of biodiversity that accounts for both the number of different species (species richness) and the relative abundance of each species in an area or ecosystem. Metrics such as the Shannon Index is used to quantify species diversity.

BC_3	Red List Species	Red List Species are those identified as threatened and classified on the Swiss Red List, which includes species categorized as vulnerable, endangered, or critically endangered. These species face a high risk of extinction and are recognized as priorities for conservation efforts.
Ecosystem Function		
EF_1	Habitat quality	Habitat quality describes the distribution of habitats and their state of degradation, such as the extent of vegetation loss, soil erosion, or pollution. High-quality habitats support biodiversity and sustain essential ecosystem functions.
EF_2	Habitat Connectivity	Habitat connectivity refers to the degree to which different habitats are linked, allowing wildlife to move freely between them. It enables species to migrate, find food, reproduce, and adapt to environmental changes. Connectivity is crucial for maintaining biodiversity, supporting healthy ecosystems, and preventing habitat fragmentation, which can lead to isolated populations and decreased genetic diversity.
EF_3	Pollinator abundance	Pollinator abundance reflects the potential presence of wild pollinator species, such as bees and butterflies, based on habitat nesting suitability and the availability of floral resources within their flying range.
EF_4	Soil Quality	Soil quality refers to the ability of soil to perform essential functions effectively, including supporting plant growth, regulating water, cycling nutrients, and sustaining biodiversity. High-quality soil is fertile, well-structured, and resilient to degradation. Key aspects include nutrient retention, which prevents the leaching of essential nutrients, and sediment retention, which helps prevent soil erosion and maintains water quality.
EF_5	Human Recreation Potential	This indicator represents areas with minimal human disturbance, emphasizing visually undisturbed landscapes, natural water bodies, and sparse human activity. These zones are critical for recreation, mental well-being, and the preservation of peaceful natural environments, particularly on the Swiss Plateau.

Scale for Pairwise Comparisons

For each pair of indicators, you will use a scale from 1 to 9 to indicate their relative importance.

Explanation: A score of 1 means both indicators are equally important, while a higher score (e.g., 7 or 9) means one is much more important than the other.

1	3	5	7	9
Equally important	Moderately more important	Strongly more important	Very strongly more important	Extremely more important
2, 4, 6, 8 are intermediate values				

Example: How does it work?

- When assessing biodiversity, which is more important and by how much: Indicator_A (IA) or Indicator_B (IB)?
 - IA: Indicator_A
 - IB: Indicator_B
 - Equally important

Based on your selection, how much more important is the chosen factor?

1	2	3	4	5	6	7	8	9
Equally important		Moderately more important		Strongly more important		Very strongly more important		Extremely more important

AHP Questionnaire: Pairwise Comparisons

Section A: Biotic Composition Indicators

- When assessing biodiversity, which is more important and by how much: Species Richness (BC_1) or Species Diversity (BC_2)?
 - BC_1: Species Richness
 - BC_2: Species Diversity
 - Equally important

Based on your selection, how much more important is the chosen factor?

1	2	3	4	5	6	7	8	9
Equally important		Moderately more important		Strongly more important		Very strongly more important		Extremely more important

- When assessing biodiversity, which is more important and by how much: Species Richness (BC_1) or Red List Species (BC_3)?
 - BC_1: Species Richness
 - BC_3: Red List Species
 - Equally important

Based on your selection, how much more important is the chosen factor?

1	2	3	4	5	6	7	8	9
Equally important		Moderately more important		Strongly more important		Very strongly more important		Extremely more important

- When assessing biodiversity, which is more important and by how much: Species Diversity (BC_2) or Red List Species (BC_3)?
 - BC_2: Species Diversity
 - BC_3: Red List Species
 - Equally important

Based on your selection, how much more important is the chosen factor?

1	2	3	4	5	6	7	8	9

Equally important		Moderately more important		Strongly more important		Very strongly more important		Extremely more important
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Section B: Ecosystem Function Indicators

- When assessing biodiversity, which is more important and by how much: Habitat Quality (EF_1) or Habitat Connectivity (EF_2)?
 - EF_1: Habitat Quality
 - EF_2: Habitat Connectivity
 - Equally important

Based on your selection, how much more important is the chosen factor?

1	2	3	4	5	6	7	8	9
Equally important		Moderately more important		Strongly more important		Very strongly more important		Extremely more important

- When assessing biodiversity, which is more important and by how much: Habitat Quality (EF_1) or Pollinator Abundance (EF_3)?
 - EF_1: Habitat Quality
 - EF_3: Pollinator Abundance
 - Equally important

Based on your selection, how much more important is the chosen factor?

1	2	3	4	5	6	7	8	9
Equally important		Moderately more important		Strongly more important		Very strongly more important		Extremely more important

- When assessing biodiversity, which is more important and by how much: Habitat Quality (EF_1) or Soil Quality (EF_4)?

- EF_1: Habitat Quality
- EF_4: Soil Quality
- Equally important

Based on your selection, how much more important is the chosen factor?

1	2	3	4	5	6	7	8	9
Equally important		Moderately more important		Strongly more important		Very strongly more important		Extremely more important

4. When assessing biodiversity, which is more important and by how much: Habitat Quality (EF_1) or Human Recreation Potential (EF_5)?
- EF_1: Habitat Quality
 - EF_5: Human Recreation Potential
 - Equally important

Based on your selection, how much more important is the chosen factor?

1	2	3	4	5	6	7	8	9
Equally important		Moderately more important		Strongly more important		Very strongly more important		Extremely more important

5. When assessing biodiversity, which is more important and by how much: Habitat Connectivity (EF_2) or Pollinator Abundance (EF_3)?
- EF_2: Habitat Connectivity
 - EF_3: Pollinator Abundance
 - Equally important

Based on your selection, how much more important is the chosen factor?

1	2	3	4	5	6	7	8	9
Equally important		Moderately more important		Strongly more important		Very strongly more important		Extremely more important

6. When assessing biodiversity, which is more important and by how much: Habitat Connectivity (EF_2) or Soil Quality (EF_4)?

- EF_2: Habitat Connectivity
- EF_4: Soil Quality
- Equally important

Based on your selection, how much more important is the chosen factor?

1	2	3	4	5	6	7	8	9
Equally important		Moderately more important		Strongly more important		Very strongly more important		Extremely more important

7. When assessing biodiversity, which is more important and by how much: Habitat Connectivity (EF_2) or Human Recreation Potential (EF_5)?

- EF_2: Habitat Connectivity
- EF_5: Human Recreation Potential
- Equally important

Based on your selection, how much more important is the chosen factor?

1	2	3	4	5	6	7	8	9
Equally important		Moderately more important		Strongly more important		Very strongly more important		Extremely more important

8. When assessing biodiversity, which is more important and by how much: Pollinator Abundance (EF_3) or Soil Quality (EF_4)?

- EF_3: Pollinator Abundance
- EF_4: Soil Quality
- Equally important

Based on your selection, how much more important is the chosen factor?

1	2	3	4	5	6	7	8	9

Equally important		Moderately more important		Strongly more important		Very strongly more important		Extremely more important
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9. When assessing biodiversity, which is more important and by how much: Pollinator Abundance (EF_3) or Human Recreation Potential (EF_5)?
- EF_3: Pollinator Abundance
 - EF_5: Human Recreation Potential
 - Equally important

Based on your selection, how much more important is the chosen factor?

1	2	3	4	5	6	7	8	9
Equally important		Moderately more important		Strongly more important		Very strongly more important		Extremely more important

10. When assessing biodiversity, which is more important and by how much: Soil Quality (EF_4) or Human Recreation Potential (EF_5)?
- EF_4: Soil Quality
 - EF_5: Human Recreation Potential
 - Equally important

Based on your selection, how much more important is the chosen factor?

1	2	3	4	5	6	7	8	9
Equally important		Moderately more important		Strongly more important		Very strongly more important		Extremely more important

Section C: Overall Category Comparison

1. When assessing biodiversity, which is more important and by how much: Biotic Composition (BC) or Ecosystem Function (EF)?
- BC: Biotic Composition
 - EF: Ecosystem Function
 - Equally important

Based on your selection, how much more important is the chosen factor?

1	2	3	4	5	6	7	8	9
Equally important		Moderately more important		Strongly more important		Very strongly more important		Extremely more important

Section D: Additional Information

<i>Demographic Question</i>	<i>Response Option</i>
<i>Education Level</i>	<input type="radio"/> High school <input type="radio"/> Bachelor's <input type="radio"/> Master's <input type="radio"/> PhD <input type="radio"/> other
<i>Occupation/ Industry working</i>	
<i>Location (City / Region)</i>	
<i>Familiarity with Biodiversity</i> <i>(1 = not familiar, 5 = very familiar)</i>	<input type="radio"/> 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5
<i>How important is biodiversity to your work? (1= not important, 5 = extremely important)</i>	<input type="radio"/> 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5

Appendix C: Biodiversity Data Resolution Example

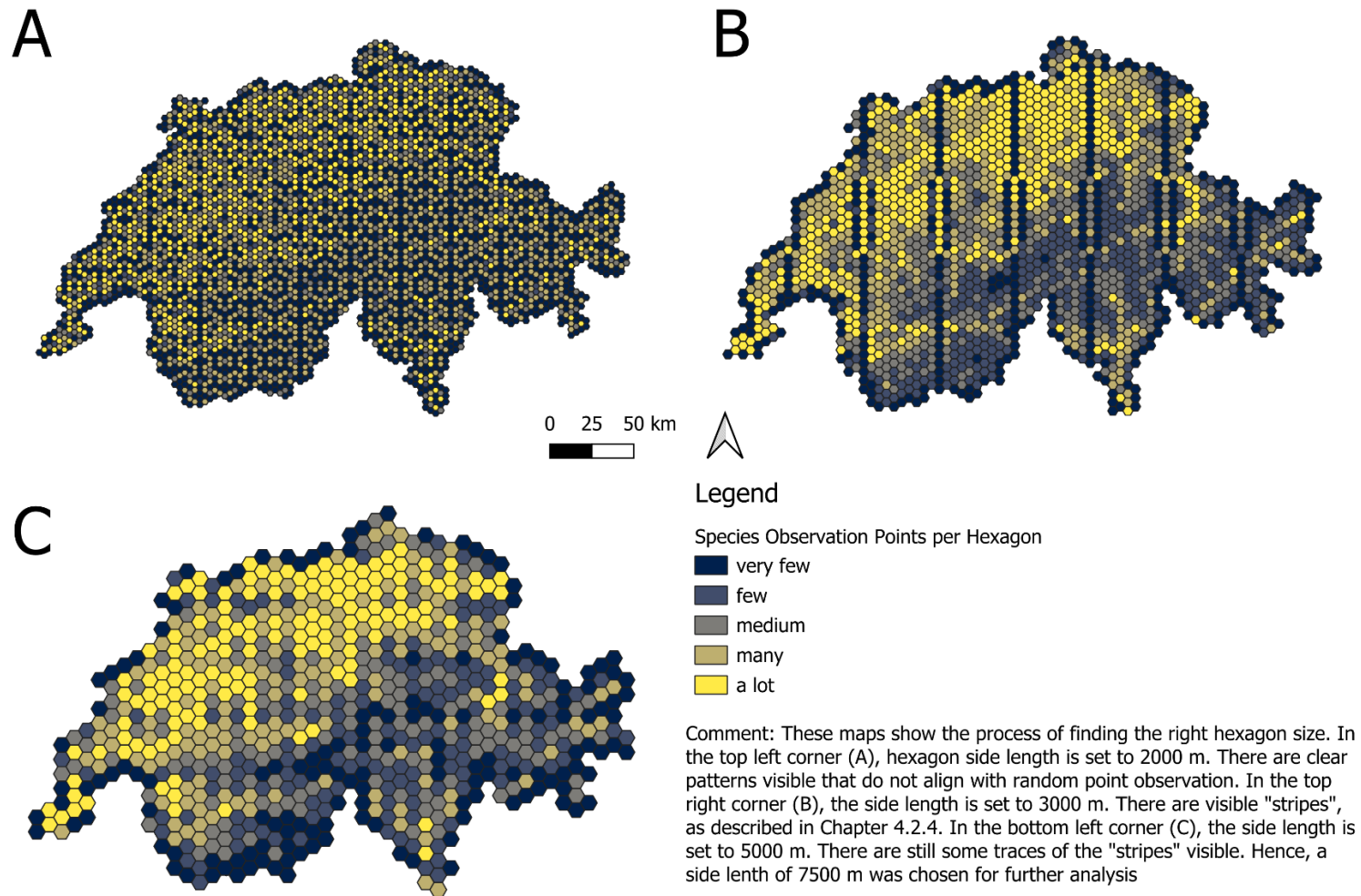


Figure 19: Process of finding an appropriate side length for hexagons. Not clipped to Swiss Boundaries. Displays Point Counts per Hexagon

Personal declaration: I hereby declare that the submitted thesis results from my own independent work. All external sources are explicitly acknowledged in the thesis.

Disclaimer: The tools DeepL Translator and ChatGPT were used for translation and rewording in some circumstances. ChatGPT was used as support in certain coding problems.

Zurich, August 15, 2025

Marie Hamm

Marie Hamm