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Assessment of blue-green areas to promote amphibian species diversity in the Baden-Brugg area

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Abstract

Agricultural intensification and urban sprawl lead to biodiversity loss worldwide by impacting habitats through destruction, degradation, and isolation. Blue (i.e., aquatic) and green (i.e., terrestrial) habitats in human-dominated landscapes are therefore of high importance to preserve and enhance biodiversity. Amphibians are not only among the most threatened vertebrates, they also rely on a wide range of these blue-green areas and are good indicators for biodiversity. The Baden-Brugg region is a key area for amphibian conservation due to the conjunction of three major Swiss rivers (Aare, Reuss, Limmat). In this study area, I assessed important areas for amphibian conservation based on an existing species distribution model and government data about protected sites and conservation measures. First, to compare and evaluate blue-green areas, I used landscape and patch metrics (such as aggregation and perimeter-patch ratio), environmental variables used in the species distribution models, and land-use data. Second, species diversity and habitat connectivity were also assessed in the study area. The results showed that (1) environmental variables are better suited than patch metrics to explain species diversity, (2) amphibian species diversity depends mostly on distance to closest waterbody and traffic intensity, (3) more natural land-covers like forests, waterbodies, and extensively managed meadows also correlated with a higher amphibian diversity, and (4) rare species not only were found to have a smaller suitable habitat area, but also to use their suitable habitat the least. In the study area, the smooth newt *Lissotriton vulgaris* got locally extinct, while the endangered European tree frog (*Hyla arborea*) persisted. The findings show that the breeding sites of national importance in the area still have a potential to host more species, thus a better monitoring of their quality and (re)colonization measures are recommended. In particular, rivers, streams, and forest edges function as important corridors for amphibian movement but are all affected by various degrees of traffic and other human infrastructures that hinder amphibian movement across the landscape. Thus, restoring corridors with additional stepping-stone habitat elements and safe road crossings would be a suitable conservation measure to increase connectivity for amphibians in the Baden-Brugg region.

Keywords

amphibian breeding sites of national importance, biodiversity, blue-green infrastructure, case study, connectivity, ecological corridors, ecological infrastructure, human dominated landscapes, model-based approach, patch ecology

Table of contents

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1 Introduction

1.1 Sustaining biodiversity in human-dominated landscapes

Human land-use changes, namely agricultural intensification and urban sprawl to accommodate the growing human population, are important drivers of biodiversity loss worldwide (e.g., Cordier et al., 2021; Park et al., 2021). Habitat loss, degradation, fragmentation, and isolation impact key biological processes of wildlife, such as breeding, migration, and dispersal (e.g., Hamer & McDonnell, 2008; Horváth et al., 2019). Biodiversity does not only have an inherent value but also sustains a wide variety of ecosystem services, including climate change mitigation and human well-being (Taylor & Hochuli, 2015; Weiskopf et al., 2020). Protection and improvement of biodiversity in human-dominated landscapes is therefore a major challenge for conservation, especially as many urban areas are predicted to grow further (United Nations, 2018).

1.1.1 Amphibians as indicators for biodiversity in blue-green areas

Globally, amphibians are among the most threatened vertebrate group (Hamer & McDonnell, 2008; Cordier et al., 2021). As animals with a relatively low mobility and diverse, yet specific habitat requirements, amphibians are also among the most vulnerable to demographic and environmental stochasticity due to the isolation of breeding populations (Churko et al., 2020).

One requirement of all amphibian species observed in Switzerland is that they need blue (i.e., aquatic) and green (i.e., terrestrial) habitats. These blue-green areas (BGA) comprise a wide range of habitat types, including streams, ponds, parks, forests, meadows, and also green infrastructure (GI) and blue-green infrastructure (BGI). According to Ghofrani et al. (2017, p. 15), BGI is "an interconnected network of natural and designed landscape components, including water bodies and green and open spaces, which provide multiple functions such as: (i) water storage for irrigation and industry use, (ii) flood control, (iii) wetland areas for wildlife habitat or water purification, and many others". Taguchi et al. (2020, p. 1) define GI as "the integration of ecological systems, both natural and engineered, within the built environment to maximize infrastructure, ecosystem, and community services". Since the terms GI and BGI are not consistently used in literature, I use the term BGA here to include all varieties of blue-green spaces.

1.1.2 Ecological infrastructure

To protect the amphibians and other wildlife, there are several types of ecological infrastructures that vary in size, protection, and management – for example national, cantonal, and local protection areas on private or public land, areas protected by non-government organizations (NGOs) such as Pro Natura or BirdLife and agricultural areas protected through contracts with farmers. Since biodiversity exhibits public good characteristics, there is no incentive for private landowners aside from NGOs to engage in conservation strategies that provide no benefits to them, something that traditionally led to government involvement (Kamal & Grodzinska-Jurczak, 2014). Generally, amphibians and their breeding sites are protected under the Federal Act on the Protection of Nature and Cultural Heritage (Bundesgesetz über den Natur- und Heimatschutz, NHG) Art. 18 and the Ordinance on the Protection of Nature and Cultural Heritage (Verordnung über den Natur- und Heimatschutz, NHV) Art. 20.

Of the ecological infrastructures, the amphibian breeding sites of national importance[1] are the most strictly protected and biggest specifically designed for amphibians. There are two types: permanent sites with a specified extent and non-permanent sites in gravel pits. The amphibian breeding sites of national importance are protected since 2001 under the Federal Act on the Protection of Nature and Cultural Heritage (NHG) Art. 18a and the ordinance on the protection of amphibian breeding sites of national importance (Verordnung über den Schutz der Amphibienlaichgebiete von nationaler Bedeutung, AlgV). The biotopes of national importance are designated by the Federal Council, but the management is under the responsibility of the cantonal authorities. The biotopes of national

[1] Federal Office for the Environment FOEN: Amphibienlaichgebiete. https://www.bafu.admin.ch/bafu/de/home/themen/biodiversitaet/fachinformationen/massnahmen-zur-erhaltung-und-foerderung-der-biodiversitaet/oekologische-infrastruktur/biotope-von-nationaler-bedeutung/amphibienlaichgebiete.html.

importance are to be preserved in their quality and suitability to guarantee the long-term survival as well as the reintroduction of endangered amphibian species.

However, even for this kind of protected sites, there are legal exemptions to the protection for (1) location-bound projects of national interest, (2) measures for flood prevention, (3) existing fish farms, (4) measures according to the Federal Act on the Protection of Waters or to the Ordinance on the Remediation of Polluted Sites, and (5) the preservation of crop rotation areas. One performance evaluation completed in 2010 to assess the success of the amphibian breeding sites of national importance found that in one third of all protected sites, the conditions were not in accordance with the goals and that there were conflicts of interest in 26% of all protected sites (BAFU, 2010). The authors concluded that there were substantial deficits in the design and management of the sites (BAFU, 2010, p. 13). Overall, the population trends were found to be negative, especially for pioneer species (-31%) and rare species (-25%) (BAFU, 2010, p. 33). A follow-up report conducted by the Federal Office of the Environment (FOEN) and the WSL in 2019 found that the negative population trends in amphibian breeding sites of national importance were finally stabilizing or even turning around for many species (Bergamini et al., 2019). Besides the many already lost populations, there was still an ongoing decline of *Alytes obstetricans* and *Epidalea calamita* though (Bergamini et al., 2019, p. 94).

1.2 Aims and research questions

This thesis aims to characterize and compare areas relevant to amphibians in the Baden-Brugg region (canton Aargau), namely on the basis of (1) modelled amphibian occurrence areas and diversity hotspots, (2) amphibian breeding sites of national importance, and (3) modelled inter-breeding site corridors. Through the assessment of these areas' ecological and legal characteristics, key challenges and opportunities for the protection of BGA will be identified for the study area. Criteria for ecological characteristics include quality, structural complexity, and land composition; legal characteristics are here defined as protection status and allowed usages of the land.

The Baden-Brugg region is a case study area of the project BlueGreenNet[2] within the WSL-Eawag initiative on blue-green biodiversity (BGB). BlueGreenNet assesses (1) the potential distribution of amphibian species, multispecies amphibian hotspots and movement corridors across human-dominated landscapes using spatially explicit modelling approaches (Donati et al., 2022), and (2) aims to develop social-ecological networks to support of effective environmental governance. The focus on a case study such as the Baden-Brugg area contributes detailed analysis on the use and limitation of large-scale spatial distribution models at a local level.

The research questions are:

1. How widespread are amphibian species in the study area according to a spatial distribution model? Where are occurrence hot- and coldspots? What is the 2D land use and 3D vegetation structure, ecological conditions, and composition of the occurrence areas?
2. Where are the amphibian breeding sites of national importance in the study area and what are their 2D land use and 3D vegetation structure, ecological conditions, and composition? Which amphibian species occur in these protected areas? In addition to the existing measures of protection, which habitat patches need to be secured, or increased in their quality?
3. Where are the amphibian inter-breeding site corridors in the study area and how are they characterized concerning 2D land use and 3D vegetation structure, ecological conditions, and composition? Are there barriers for amphibian movement? How could habitat connectivity be enhanced in the study area?

[2] BlueGreenNet: https://www.eawag.ch/de/abteilung/ess/projekte/bluegreennet/.

2 Materials and methods

2.1 Study area

The study area for this project comprises 16 administrative municipalities in the Baden-Brugg region in the canton of Aargau, Switzerland (Figure 1). The study area is situated between 326 m a.s.l. and 859 m a.s.l. and measures about 96 km^2. The municipalities have an urban to peri-urban character with 103’702 people living in the study area (Kanton Aargau, 2022). According to the Swiss Statistical Office (Schuler et al., 2005), Baden-Brugg is considered part of the Zurich metropolitan area, but also as an agglomeration area of itself.

Forests make up the majority of land use with 39% of the total Baden-Brugg area, followed by agricultural areas with 28%, impervious urban areas with 16%, and urban green spaces with 13%. Water covers about 3% of the study area while the remaining 1% is covered by rocky or gravelly areas (natural and artificial).

The Baden-Brugg region is a case study area for the WSL-Eawag joint project BlueGreenNet. Baden-Brugg was selected as a case study because the area hosts a high amphibian species diversity and was found to include predicted corridors for amphibian species movement, in particular along three major Swiss rivers, namely the Aare, the Reuss and the Limmat. It is a priority region for the protection of amphibians according to the Coordination Center for the Protection of Amphibians and Reptiles of Switzerland (karch) (2018). The study area also shows potential for further biodiversity enhancement, amphibian protection measures, and additional ecological infrastructure (Donati et al., 2022). The area includes the so-called Wasserschloss, an important landmark where the three rivers Aare, Reuss and Limmat merge. These factors make the study area a key region for amphibian conservation and enhancement of BGA. The Baden-Brugg study area includes 16 municipalities: Baden, Birmenstorf, Birrhard, Brugg, Ennetbaden, Gebenstorf, Habsburg, Hausen, Lupfig, Muelligen, Obersiggenthal, Turgi, Untersiggenthal, Villnachern, Wettingen, and Windisch.

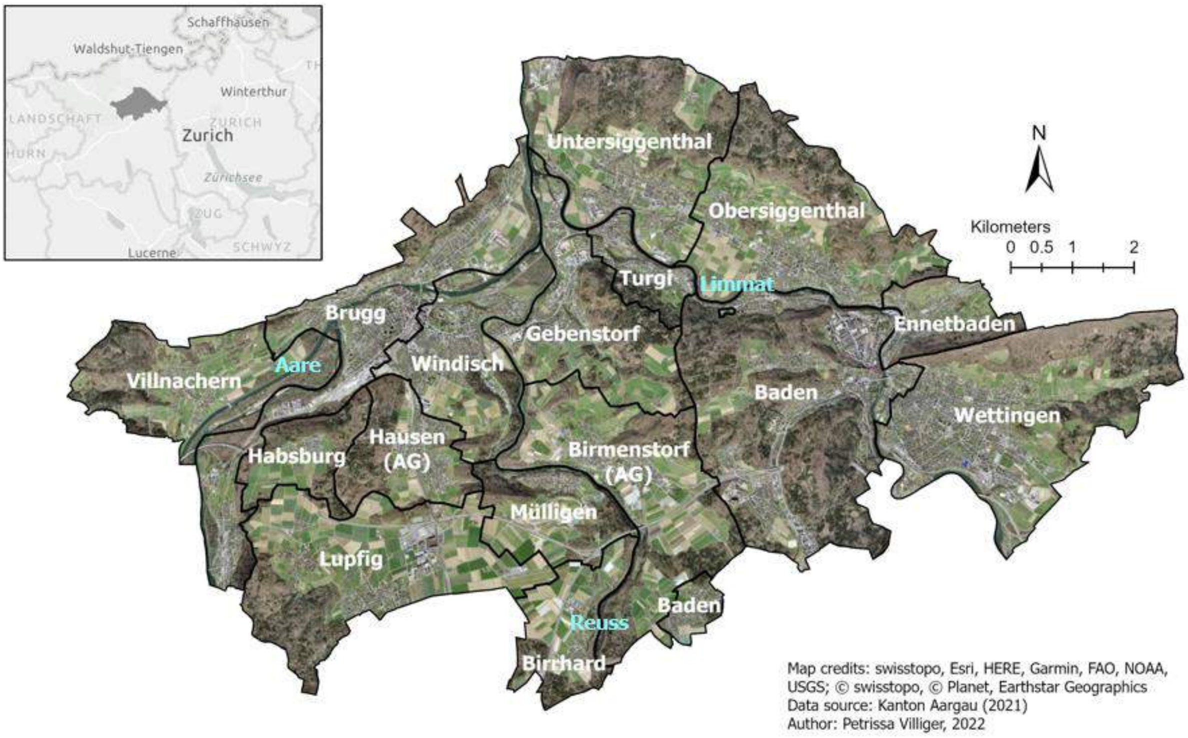

Figure 1: Map and remote imagery of the study area Baden-Brugg with the 16 municipalities included in this analysis. In blue the names of the three major rivers in the study area.

2.2 Amphibian species distribution and connectivity models

2.2.1 Species selection

For the BlueGreenNet projects, 10 out of 19 co-occurring amphibian species in the cantons of Aargau and Zurich were chosen to represent the variety of amphibian ecology and life-history diversity using a multidimensional trait analysis (Donati et al., 2022). The multidimensional trait analysis considered adult body size, metamorphosis size, parental care, egg/offspring number, juvenile diet composition, and displacement mode, in addition to representation of phylogenetic diversity (Donati et al., 2022). The species were *Alytes obstetricans* (Alytidae), *Bombina variegata* (Bombinatoridae), *Bufo bufo* (Bufonidae), *Hyla arborea* (Ranidae), *Ichtyosaura alpestris* (Salamandridae), *Lissotriton helveticus* (Salamandridae), *Lissotriton vulgaris* (Salamandridae), *Rana temporaria* (Salamandridae), *Salamandra salamandra* (Salamandridae), and *Triturus cristatus* (Salamandridae). Eight out of the ten species that were surveyed for the underlying models are on the Swiss Red List of endangered amphibian species; three are classified as vulnerable (VU) and five as endangered (EN) (Schmidt & Zumbach, 2005).

2.2.2 Spatial and connectivity assessment of amphibians

Donati et al. (2022) calibrated species-specific amphibian distribution models (SDMs). The SDMs are based on amphibian monitoring data (presence only) for the years 2017 to 2019 of the cantons Aargau and Zürich. The data was derived from karch [3]. The SDMs rely on ensemble modelling and encompass 108 records of *Alytes obstetricans* (Alytidae), 284 of *Bombina variegata* (Bombinatoridae), 548 of *Bufo bufo* (Bufonidae), 258 of *Hyla arborea* (Ranidae), 813 of *Ichtyosaura alpestris* (Salamandridae), 285 of *Lissotriton helveticus* (Salamandridae), 118 of *Lissotriton vulgaris* (Salamandridae), 698 of *Rana temporaria* (Salamandridae), 317 of *Salamandra salamandra* (Salamandridae), and 108 of *Triturus cristatus* (Salamandridae).

Donati et al. (2022) modelled the species distributions based on all the presence data in Aargau and Zurich. 13 environmental predictors were considered in the SDM to encompass the whole life-cycle of all amphibian species: (1) slope, (2) distance to water, (3) soil moisture variability, (4) Normalized Difference Vegetation Index (NDVI), (5) Normalized Difference Vegetation Index standard deviation (NDVI sd), (6) vegetation height, (7) runoff, (8) grassland density, (9) urbanization proxy, (10) traffic intensity, (11) distance to forest, (12) distance to rock-gravel and sandy areas, and (13) distance to road. To reduce uncertainty, Donati et al. (2022) generated five random pseudo-absences datasets per species and used ensemble modelling. The SDMs of individual species and the multispecies maps have a 10x10 m resolution (Donati et al., 2022).

The SDM was the basis for Donati et al. (2022) to develop habitat resistance maps for a connectivity analysis that was performed using the "Circuitscape" model with the Julia software. These species specific and multispecies connectivity models show the interconnection between breeding sites of national importance that serve as focal nodes.

The SDM from Donati et al. (2022) served in this analysis to identify biodiversity hotspots and the potential occupied and unoccupied suitable habitats in the study area Baden-Brugg and their multispecies connectivity model is used here to analyze important ecological corridors.

2.3 Characterizing key areas for amphibian dispersal and conservation

2.3.1 Patch metrics, landscape metrics, and environmental variables

Landscape metrics are tools used to assess and monitor the biodiversity and ecological conditions of landscapes (e.g. Bailey et al., 2007; Kim & Pauleit, 2007). While different metrics vary in their complexity, appropriate scale application, and explanatory power, this work mainly focuses on two metrics of landscape composition: patch shape influence on local amphibian species diversity and landscape connectivity for amphibian movement in the study area. Therefore, the set of landscape and patch metrics shown in Table 1 was selected for this analysis. These metrics were applied to both, occurrence areas of amphibians and protected breeding sites, while keeping in mind that these areas are very different

[3] info fauna karch: http://www.karch.ch/karch/de/home.html.

in their nature and the results need to be interpreted accordingly. The R package *landscapemetrics* (Hesselbarth et al., 2019) that builds upon the software program *FRAGSTATS* (McGarigal et al., 2012) was used to calculate the metrics.

Table 1: Patch and landscape metrics used to characterize important areas for amphibian dispersal and conservation based on Hesselbarth et al. (2019) and McGarigal et al. (2012).

Variable code	**Variable**	**Specifications**	**Biological relevance**
circle	related circumscribing circle	Ratio between the patch area and the smallest circumscribing circle of the patch, used to characterize the compactness of the patch and comparable among patches with different area. Circle=0 for a circular patch and approaching circle=1 for a linear patch, no unit.	Since disturbances are higher along the borders of protected areas, it is proposed that compact conservation areas and areas with a buffer are better suited to protect populations (e.g. Woodroffe & Ginsberg, 1998; Crawford & Semlitsch, 2007).
enn	Euclidean nearest neighbor in m	Distance to the nearest neighboring patch of the same class in meters, measured from edge to edge.	The distance to the nearest neighbor is a straight-forward way to describe habitat patch isolation and structural connectivity (e.g. Kim & Pauleit, 2007).
para	perimeter-area ratio	Shape metric to describe the patch complexity, not standardized and therefore dependent on patch size. Para>0, no unit.	Since disturbances are higher along the borders of protected areas, it is proposed that compact conservation areas and areas with a buffer are better suited to protect populations (e.g. Woodroffe & Ginsberg, 1998; Crawford & Semlitsch, 2007).
ai	aggregation in %	Aggregation metric in % that equals the number of like adjacencies divided by the theoretical maximum possible number of like adjacencies for that class summed over each class for the entire landscape. The metric is based on the adjacency matrix and the single-count method. 100% for maximally aggregated.	Aggregation gives information about the configuration of the landscape and reveals if patches are located aggregated or isolated. Depending on the nature of the patch it can be used to assess landscape heterogeneity or connectivity and the occurrence of certain species in aggregated/isolated patches (e.g. Crist et al., 2005; Bailey et al., 2007).
cohesion	cohesion in %	Aggregation metric in % that characterizes the connectedness of patches. Approaching cohesion=0 if patches are more isolated; increases if patches are more aggregated (max. 100%).	Cohesion gives information about the configuration of the landscape and reveals if patches are located aggregated or isolated. Depending on the nature of the patch it can be used to assess landscape heterogeneity or connectivity and the occurrence of certain species in aggregated/isolated patches (e.g. Crist et al., 2005; Bailey et al., 2007).

To characterize key areas for amphibian occurrence, dispersal and conservation, ten environmental variables that describe environmental factors relevant for amphibians during their whole life cycle and that proofed to have a high predictive power in the SDMs (Donati et al., 2022) were considered in this analysis. Table 2 shows the ten variables which are related to vegetation, water, and urbanization.

Table 2: Environmental variables to characterize areas important for amphibian dispersal and conservation.

Variable code	Variable	Biological relevance	Source
VHM	median of the vegetation height model (VHM) in meters	Woody areas are important terrestrial habitats for amphibians (e.g. Hamer & McDonnell, 2008; Baldwin & deMaynadier, 2009).	Ginzler and Hobi, 2015
VHMsd	standard deviation of the VHM in meters	Vegetation height variability serves as a proxy for structural and habitat complexity, which are important factors for niche diversity and amphibian species richness (e.g. Gardner, Barlow, & Peres, 2007).	Ginzler and Hobi, 2015
NDVI	median of the Normalized Difference Vegetation Index (NDVI) from April to October 2016-2019	NDVI measures photosynthetic activity and serves as a proxy for primary production as amphibian species diversity and occurrence correlate with plant resources (e.g. Clauzel & Godet, 2020).	swisstopo, NPOC, 2019
NDVIsd	standard deviation of the NDVI from April to October 2016-2019	NDVI variability serves as a proxy for structural and habitat complexity, which are important factors for niche diversity and amphibian species richness (e.g. Gardner et al., 2007; Clauzel & Godet, 2020).	swisstopo, NPOC, 2019
distforest	nearest distance to forest in meters	Forests and woody areas are important terrestrial habitats for amphibians (e.g. Hamer & McDonnell, 2008; Baldwin & deMaynadier, 2009).	Cantonal cadaster map, 2020; Donati et al., 2022
distwater	nearest distance to waterbody in meters	Streams, ponds, and lakes are important aquatic habitats for amphibians, and most amphibian species are dependent on waterbodies for reproduction (e.g. Hamer & McDonnell, 2008; Hillmann et al., 2008).	Cantonal cadaster map, 2020; Donati et al., 2022
distroad	nearest distance to any road type in meters	Road surfaces and traffic negatively affect amphibian presence because of increased mortality and disturbances such as noise and pollutants (e.g. Jochimsen, Peterson, Andrews, Gibbons, & Service, 2004; Park, Park, & Borzée, 2021).	Cantonal cadaster map, 2020; Donati et al., 2022
traffic	daily averaged traffic intensity (cars per day)	Traffic intensity negatively affect amphibian presence because of increased mortality and disturbances such as noise and pollutants (e.g. Jochimsen et al., 2004; Pellet, Guisan, & Perrin, 2004).	Verkehrsmodellierung im UVEK, 2017; Donati et al., 2022
urban	urbanization grade proxy by using number of buildings per area	Habitat loss, degradation and fragmentation due to urbanization negatively affect amphibian presence (e.g. Pellet et al., 2004; Hamer & McDonnell, 2008).	Cantonal cadaster map, 2020; Donati et al., 2022
soilmoist	intraannual soil moisture variability from the spatial modelling of Ecological Indicator Values (EIV) in Switzerland (gradient from low (1) to high (3) variability in soil moisture)	Wetlands and seasonally wet areas are important habitats for amphibians, and amphibians prefer moist habitats to minimize desiccation risk (e.g. Hamer & McDonnell, 2008; Youngquist & Boone, 2014).	Descombes et al., 2020; Donati et al., 2022

Figure A1 in the Appendix shows the ten environmental variables mapped out for the whole study area. In the Baden-Brugg area, the average vegetation height is 7.9 m (mean sd: 1.9 m). The average NDVI is 5454.0 (mean sd: 1252.0). The mean distance to the closest forest measures 46 m, the mean distance to the closest waterbody 302 m, and the mean distance to the closest road 122 m.

2.3.2 Land-use and zoning

In addition to the environmental variables, the blue-green areas relevant for amphibian conservation were also analyzed concerning land-use and assigned utilization zones. Land-use is essential to explain the suitability and quality of an area as a habitat (e.g. Houlahan & Findlay, 2003; Baldwin & deMaynadier, 2009).

Land-use was analyzed on the basis of the cantonal cadastral map[4]. For this characterization of areas relevant for amphibian conservation, the values attributed to the objects of the cadaster map were summarized as shown in Table A1 in the Appendix.

Every parcel of land in the study area is also assigned to a specific utilization zone[5]. These zones are mandated by the municipality in accordance with cantonal and national regulations and indicate the allowed usages and constructions at a site. The administration distinguishes between the agricultural and the residual zonal plans that complement each other to cover every parcel. In Table A2 in the Appendix all zones that appear in the important areas for amphibian conservation in the study area were described. The cantonal agricultural and residual zonal plans are publicly available, here the ones from February 2022 were used.

The zonal plan will sometimes overlap with land-use, but it is a planning instrument and not based on an actual landscape image. Moreover, as a planning instrument it might not yet be implemented or can be violated and will therefore not match the current land-use. Still, the assigned zonal uses can give more insight into actual land management since it gives information about allowed practices. Therefore, the analysis of the zonal plans gives valuable information about the protection status of amphibian occurrence areas and how well nationally protected sites are implemented, and even about possible future usages of blue-green areas. Figure A2 in the Appendix shows the land-use and zonal uses in the study area in comparison.

2.4 Assessment of blue-green areas based on amphibian species distribution models

Three types of areas in the study area are of special interest for amphibian conservation and protection of blue-green areas: (1) occurrence areas of modelled amphibian species, especially diversity hotspots, (2) amphibian breeding sites of national importance, and (3) modelled connectivity between the amphibian breeding sites (corridors). These areas were identified, quantified, and compared.

2.4.1 Amphibian species occurrence areas

The hotspots of amphibian species diversity were identified by stacking the modelled species occurrence maps (Donati et al., 2022). This way, multispecies occurrence maps of four to nine species co-occurring according to the model were established.

These multispecies occurrence areas were then described by environmental variables (Table 2) in order to assess habitat structure and quality. Since a complex array of interacting biotic and abiotic factors impact amphibians in human-dominated landscapes (Hamer & McDonnell, 2008), this also helped to reveal patterns between area characteristics and number of species occurring. I computed mean, standard deviation, minimum and maximum values with the R package *raster* (Hijmans et al., 2015) and showed the results as violin plots. A Pearson correlation analysis was conducted to identify linear relationships between the environmental conditions and the number of species co-occurring. The cantonal cadastral maps were clipped to the edited species occurrence areas with ArcGIS Pro (Ver 2.7.0,

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[4] Kanton Aargau: Bauzonen- und Kulturlandplan. Geoportal: https://www.ag.ch/de/verwaltung/dfr/geoportal/geodaten.

[5] Kanton Aargau: Allgemeine Nutzungsplanung. https://www.ag.ch/de/verwaltung/bvu/raumentwicklung/orts-siedlungs-und-regionalplanung/ortsplanung/allgemeine-nutzungsplanung.

Esri Inc. 2020), so that the attributed land-use categories for all six stacked species occurrence areas could be extracted and summarized. The same method was used for the cantonal zonal planning maps.

2.4.2 Amphibian breeding sites of national importance

The data for the breeding sites of national importance are publicly available, I downloaded the data in February 2022. To describe the habitat of the five permanent amphibian breeding sites of national importance in the study area, I used ten environmental variables (Table 2). A Pearson correlation test was conducted to identify linear relationships between the variables and the number of species per breeding site. Land-use and zonal planning was analyzed for the stationary amphibian breeding sites of national importance in the same fashion as the species occurrence areas.

The occupation and suitability as a habitat were analyzed for the breeding sites. Additionally, I did a species co-occurrence analysis for all seven amphibian breeding sites of national importance in the study area (permanent and temporary).

2.4.3 Connectivity and corridors of amphibian movement

The connectivity as modelled by Donati et al. (2022) was analyzed in detail in the study area by identifying and assessing main corridors. Corridors were defined as areas in the top 70% of the cumulative current in the multispecies connectivity model and above an area size of 20'000 m^2. Most corridors are at least 20 m in width, so this corresponds to a corridor length of about 1 km which is a typical dispersal distance for many amphibians (Smith & Green, 2005; Churko et al., 2020).

The corridors were then described with the 10 environmental variables (Table 2) in the same way as for the other areas of interest. The same applies to the land-use and zonal analysis. The connectivity analysis was overlaid with the cantonal map of amphibian road crossings that covers important routes for annual amphibian migration patterns. I checked the degree of overlap between these maps and which conflicts with roads were identified by the canton, and which conflicts might have been missed.

In addition, the connectivity analysis for amphibians was compared to the national and regional wildlife corridors as defined by the FOEN[6]. These wildlife corridors cover important routes for all wildlife species and have a high influence on policy decisions concerning landscape connectivity. It is therefore of interest to know how much these national and regional wildlife corridors overlap with local blue-green corridors important for amphibian movement.

[6] Federal Office for the Environment FOEN: Wildtierkorridore. https://www.bafu.admin.ch/bafu/de/home/themen/biodiversitaet/fachinformationen/massnahmen-zur-erhaltung-und-foerderung-der-biodiversitaet/oekologische-infrastruktur/wildtierpassagen.html.

3 Results

3.1 Characterization of amphibian species occurrence areas

3.1.1 Amphibian species occurrence

Except for *Lissotriton vulgaris*, all amphibian species selected for the underlying models occur in the study area. The modelled areas with a moderate to high amphibian species diversity are mostly situated along rivers and streams as well as in gravel pits and forested areas (Figure 2). While the co-occurrence of at least four species is relatively common (in 21% of the study area), a minimum of eight species only co-occurs in 1.15% and nine species in 0.36% of the study area (Table A3 in the Appendix). This is due to the relative rarity of certain species in the area – like *Hyla arborea* and *Triturus cristatus* whose occurrence areas cover only 1.45% and 0.55% of the study area respectively according to the model (Table A4 and Figure A4 in the Appendix). The most common species, regarding occurrence area modelled, are *Bufo bufo* (present in 50.51% of the study area) and *Ichthyosaura alpestris* (present in 30.05% of the study area).

According to the model, a high amphibian diversity (at least seven species) can be found along the rivers Aare and Reuss with a hotspot (nine species) around their junction. Six different species are mostly present along smaller streams that flow into the Aare or the Reuss and in gravel pits close to these rivers. Four to five species are present along the Limmat and along smaller streams further away from the rivers as well as along some forest edges (Figure 2).

The most widespread ubiquist species include *Bufo bufo* which occupies 94%, and *Ichthyosaura alpestris* which occupies 77% of its suitable habitat, respectively. The share of occupied suitable habitat is especially relevant with regard to connectivity measures. According to the model, *Triturus cristatus* is only present in 12% of its suitable habitat, and *Hyla arborea* in 19%. One of the modelled species, *Lissotriton vulgaris*, is not present in the study area at all, despite a potentially suitable habitat of 385 ha (4% of study area). The least common species according to the model are also the species with the smallest suitable habitat in the study area and the species that can occupy the smallest share of that potential habitat (Table A4 in the Appendix).

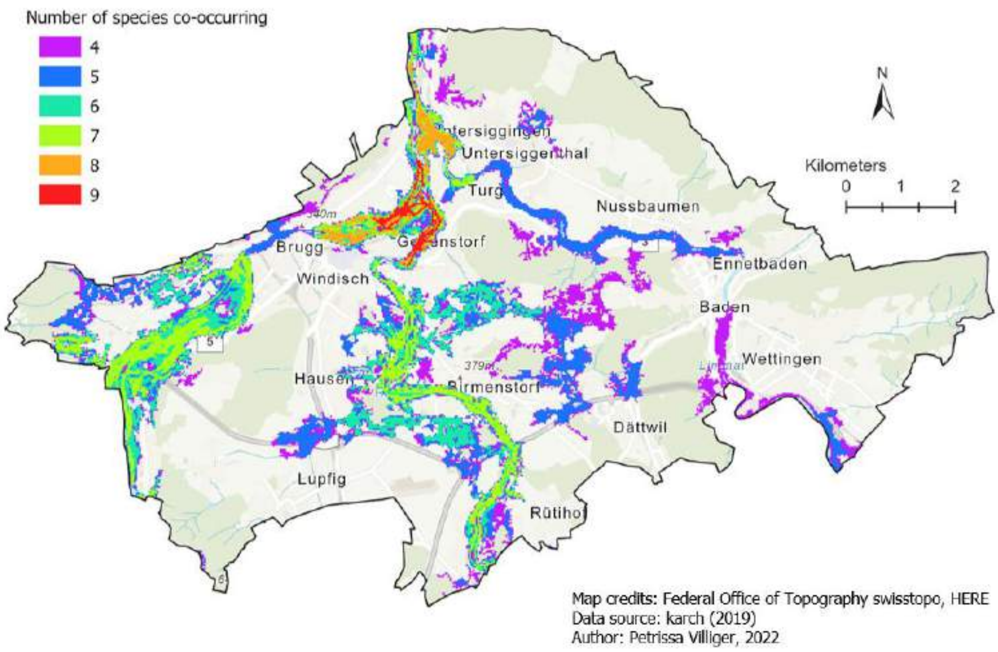

Figure 2: Map of the study area Baden-Brugg with modelled areas where four to nine amphibian species co-occur.

About half of the amphibian species diversity hotspot area with nine co-occurring species is protected by several amphibian breeding sites of national importance (Figure A3 in the Appendix).

3.1.2 Patch metrics and environmental variables

The landscape metrics calculated for the modelled multispecies occurrence areas show high aggregation (97.1-99.9) and cohesion indices (99.8-100), indicating that the occupied habitats are highly connected and aggregated in the landscape. However, there are still some unconnected, possibly isolated populations in the study area (Figure 2).

Areas where amphibians occur are characterized by a higher vegetation variation, lower distances to the nearest forest and the nearest waterbody, a lower urbanization index, and higher soil moisture variability compared to the averages in the study area (Table 3). However, there are also variables without a clear pattern in this regard: vegetation height, NDVI, variation in NDVI, and distance to closest road.

The distribution of the environmental variables shows mostly similar patterns for areas of moderate to high species diversity (Figure A5 in the Appendix). However, distance to forest, urbanization index, and traffic show a spike for some areas. For example, where a moderate number of species occurs (four to six), there are some streets with high traffic intensity, but not in areas with a high species diversity (Figure A5 in the Appendix).

The Pearson correlation between the number of species co-occurring and the landscape metrics and environmental variables is shown in Figure A6 in the Appendix, $\alpha=0.05$ is used as a guiding threshold for significance. The number of species co-occurring correlates most significantly with mean of distance to water (-0.97, $p=0.001$), distance to forest (-0.93, $p=0.008$), soil moisture variability (0.96, $p=0.002$), traffic intensity (-0.96, $p=0.002$), and NDVI (-0.96, $p=0.003$) (Figure A6 in the Appendix).

The negative correlation with distance to waterbodies and forests (Figure A6 in the Appendix) highlights the importance of these features for a high amphibian species diversity. The mean distance to the nearest waterbody declines from 162 m in areas where at least four species co-occur to 13 m in areas where nine species co-occur (Table 3). The mean distance to forest is generally low with 10 m for areas where at least four or five species co-occur and 4 m where nine species co-occur. Soil moisture variability is highest in areas where nine species co-occur, indicating that variability in wet habitats favors a high species diversity.

The negative correlation of amphibian diversity with mean traffic intensity on streets is apparent: In areas where a minimum of four species co-occur mean traffic intensity mounts up to 231 cars per day, while it is only 8 cars per day in areas where at least eight species co-occur and 11 cars per day in areas where nine species co-occur (Table 3). A negative correlation of amphibian diversity with distance to roads is also apparent (0.90) even if less significant ($p=0.014$) than traffic ($p=0.002$), indicating that the direct negative effects of traffic like death and disturbances weight heavier than the simple presence of a road.

The significant negative correlation between mean NDVI and amphibian species diversity (Figure A6 in the Appendix) can be explained by the high proportion of open water surfaces in those areas (Figure 3). There is also a slight negative correlation (-0.80, $p=0.054$) with vegetation height due to the same reason as there is no vegetation on open water. The slight positive, however not significant correlation between the number of species co-occurring and the variation in NDVI (0.73, $p=0.099$) which is less influenced by the shares of different landcovers, might point to the importance of habitat variability for a higher species diversity. The mean urbanization index shows no relation to the number of co-occurring species in an area.

Table 3: Mean values of the ten environmental variables for the entire study area Baden-Brugg (CSA) and for the different areas where a minimum of four to nine species co-occur.

area with	area (m²)	VHM mean (m)	VHMsd mean (m)	distforest mean (m)	distwater mean (m)	distroad mean (m)	urban mean	NDVI mean	NDVIsd mean	soilmoist mean	traffic mean (vehicles/day)
total CSA	96'455'499	7.9	1.9	46.0	302.4	122.1	103.8	5454	1252	1.81	151.8
min 4 species co-occurring	19'866'954	8.5	2.5	10.3	162.2	120.4	39.1	5470	1190	1.86	231.1
min 5 species co-occurring	14'561'314	8.0	2.5	9.5	130.8	120.4	37.0	5373	1181	1.87	222.4
min 6 species co-occurring	8'861'299	8.2	2.6	9.1	90.8	123.7	31.9	5291	1180	1.89	110.6
min 7 species co-occurring	4'710'036	7.9	2.8	5.8	34.1	122.0	36.0	5014	1188	1.93	103.2
min 8 species co-occurring	1'111'256	6.1	2.5	7.1	18.2	126.2	42.8	4476	1196	2.00	7.8
min 9 species co-occurring	346'762	7.0	2.8	3.7	12.5	131.4	36.9	4320	1229	2.05	10.7

3.1.3 Land-use and assigned zones

The predominant landcovers in areas with a medium to high (minimum four species) modelled amphibian species diversity are forest, agricultural land, and streams (Figure 3). There is a correlation between the share of water and the number of species that co-occur: from 13% covered by waterbodies in areas with at least four species to 51% in areas with nine species. The shares of forest and agricultural land decline with an increasing number of species from 42% down to 26%, and from 21% down to 3% respectively. The share of areas classified as gardens varies between 8% in areas where at least four to seven species co-occur and 12% in areas where at least eight specie co-occur. The total impervious area is with 10% highest in areas where a minimum of four species co-occur and with 3% lowest in areas where nine species co-occur – as expected, a higher share of natural habitats supports a higher amphibian species diversity. This relationship is also apparent in the comparison of impervious surface in the entire study area (16%) to the share of impervious surface where at least four (10%) or nine (3%) species co-occur.

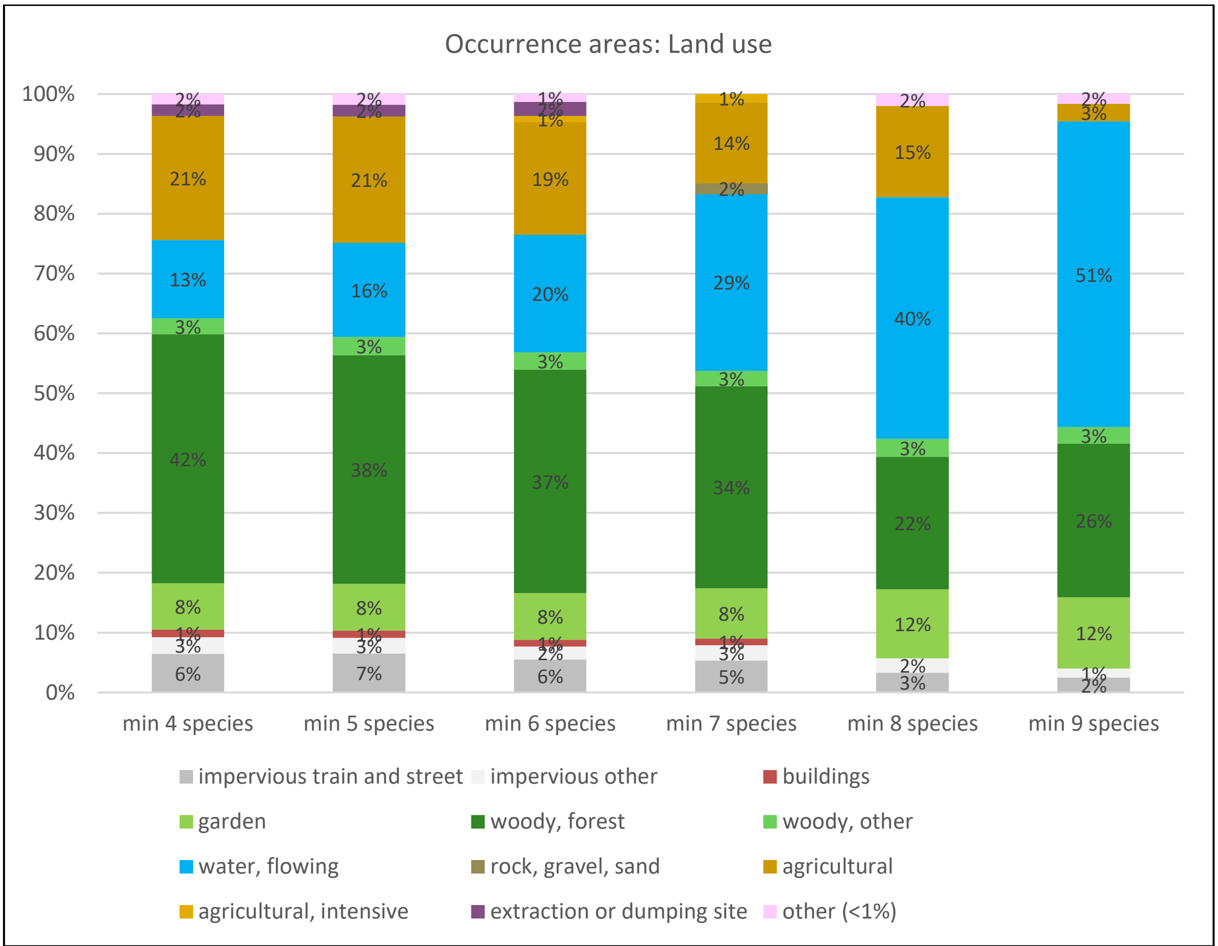

Figure 3: Shares of different land uses in modelled areas with medium to high amphibian species diversity.

The shares of different utilization zones mostly overlap with the different land-uses, whereby forests and waterbodies are the dominant assigned zones (Figure 4). However, the analysis of the utilization zones gives more insight into the agricultural land-use and about the impervious surfaces. In areas where at least four species co-occur, 19% of the agricultural area is protected and should be managed according to conservation goals, while this share is as high as 83% in areas where eight or nine species co-occur, mostly in the form of protected meadows. The shares of different impervious surfaces show that in areas where at least eight species co-occur, there are no residential or industrial zones, only zones assigned for public infrastructures.

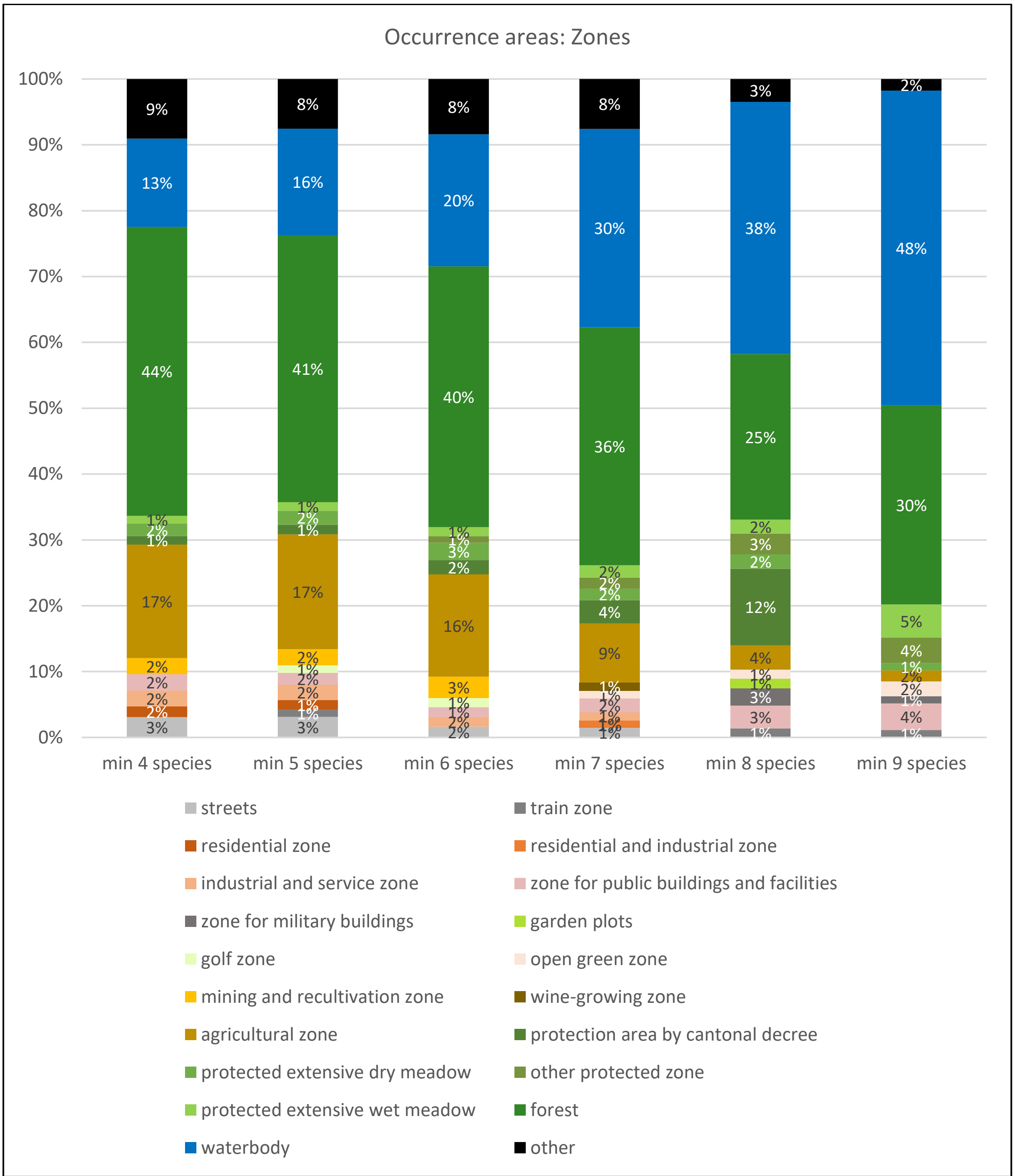

Figure 4: Shares of different zones in modelled areas with high amphibian species diversity.

3.2 Characterization of amphibian breeding sites of national importance

3.2.1 Amphibian species presence

Among the nine breeding sites of national importance in the study area, seven are permanent with a specified extent, while two are non-permanent composed of gravel pits without a specified extent (Figure 5). The permanent breeding sites are between 5.7 and 53.9 ha and most of them are situated along the Aare river. Two permanent breeding sites (AG820 and AG260) are about 600 m away from the closest stream. Of the non-permanent breeding sites, one is close to the Reuss river, the other close to the Limmat. Most species co-occur in the breeding sites at the Aare river.

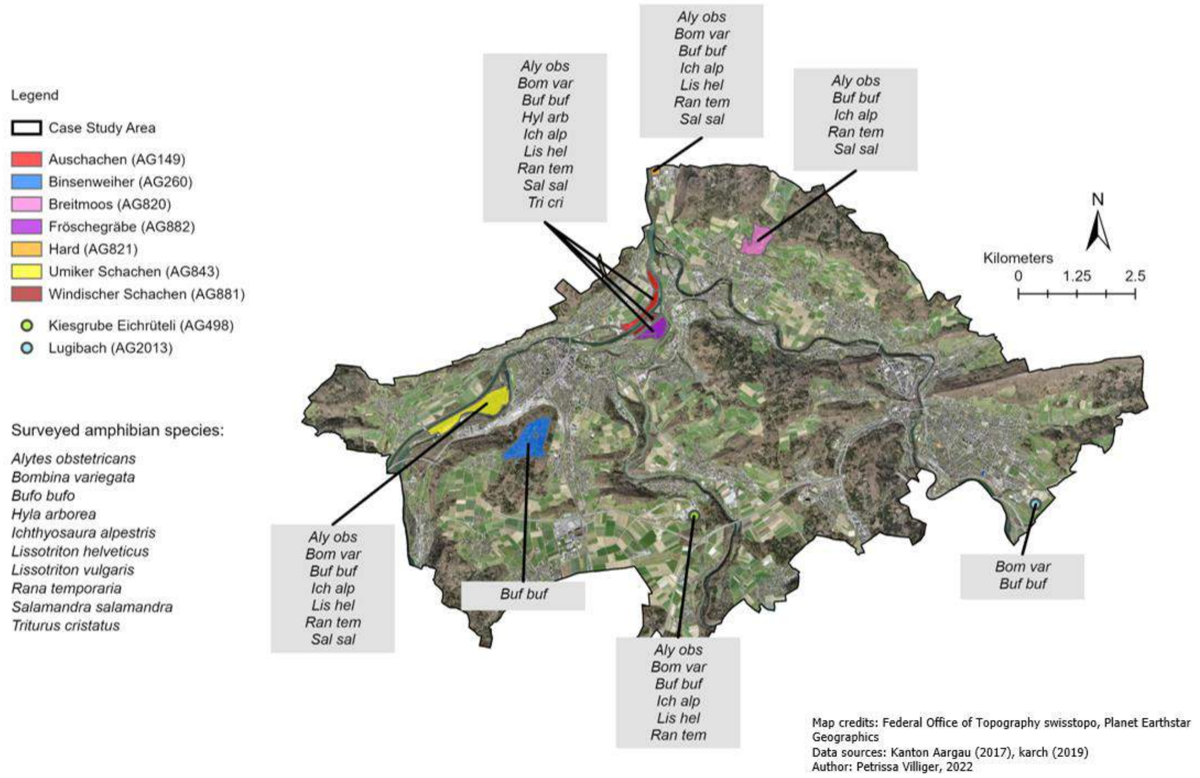

Figure 5: Map of the amphibian breeding sites of national importance in the study area Baden-Brugg with six permanent (colored areas) and two non-permanent (colored points) breeding sites. In the boxes the abbreviated names of the modelled species present at the breeding sites.

Table 4 shows the co-occurrence of the ten examined amphibian species in the breeding sites of national importance and the potential habitat suitability of the sites according to the model. All amphibian breeding sites of national importance would be a suitable habitat for one to nine additional species. For example, AG821 would also offer suitable habitat for *Hyla arobrea*. AG260 would even be suitable for all species occurring in the study area even though it only hosts *Bufo bufo* at the moment.

For the amphibian breeding sites of national importance, there exists amphibian survey data from the year when the site was established[7]. For all sites but AG821, this data is from 2001 and allows an insight into population trends over the past two decades (Table A5 in the Appendix), assuming the model depicts the current occurrence correctly. Two breeding sites (AG820 and AG843) are unchanged. Three breeding sites host more species than 2001: *Alytes obstetricans* is modelled to newly occur in AG149, AG881 and AG882; *Hyla arborea* in AG881 and AG882; *Bufo bufo* in AG881. With *Lissotriton vulgaris*, AG881 also lost a species in the same period. AG260 is the only breeding site with a net loss of species: *Ichthyosaura alpestris*, *Lissotriton helveticus*, and *Rana temporaria* all vanished.

[7] Federal Office for the Environment FOEN: Amphibienlaichgebiete-Inventar: Objektbeschreibungen. https://www.bafu.admin.ch/bafu/de/home/themen/biodiversitaet/fachinformationen/massnahmen-zur-erhaltung-und-foerderung-der-biodiversitaet/oekologische-infrastruktur/biotope-von-nationaler-bedeutung/amphibienlaichgebiete-inventar--objektbeschreibungen.html.

Table 4: Co-occurrence of the ten amphibian species in the breeding sites of national importance in the study area Baden-Brugg according to the model from Donati et al. (2022). 1=species is present, 0=species is absent even though habitat is suitable, X=species is absent and habitat is not suitable.

site no	site name	*Bufo bufo*	*Rana temporaria*	*Alytes obstetricans*	*Salamandra salamandra*	*Ichthyosaura alpestris*	*Lissotriton helveticus*	*Bombina variegata*	*Hyla arborea*	*Triturus cristatus*	*Lissotriton vulgaris*
AG260	Binsenweiher	1	0	0	0	0	0	0	0	0	0
AG820	Breitmoos	1	1	1	1	1	0	0	0	X	0
AG821	Hard	1	1	1	1	1	1	1	0	X	X
AG843	Umiker Schachen	1	1	1	1	1	1	1	0	0	0
AG881	Windischer Schachen	1	1	1	1	1	1	1	1	1	0
AG882	Fröschegräbe	1	1	1	1	1	1	1	1	1	0
AG149	Auschachen	1	1	1	1	1	1	1	1	1	0

3.2.2 Patch metrics and environmental variables

All protected amphibian breeding sites of national importance together cover 1.85% of the study area. Their aggregation and cohesion indices are high (98-99), indicating a highly aggregated patch distribution in the landscape. Interestingly, the biggest protected breeding site (AG260) contains one modelled species, while the smallest (AG881) contains nine (Table 5).

The three breeding sites AG149, AG881, and AG882 are close together (nearest-neighbor distance of 32 m, and 70 m respectively) and the same species co-occur (all nine that can be found in the study area). However, closeness alone is no guarantee for species presence: While seven species are present in AG843, the site AG260 that is closest (594 m) contains only one species (*Bufo bufo*). Most of the surveyed amphibian species have a dispersal range of 1-2 km, *Salamandra salamandra* typically one of under 1 km, and only *Hyla arborea* is a highly mobile species with a maximum dispersal range of more than 5 km (Smith & Green, 2005; Bani et al., 2015; Churko et al., 2020). Two amphibian breeding sites of national importance (AG820 and AG821) are more than 1 km away from another site (including sites outside of the study area).

AG820 has the lowest circle value, indicating a round shape and therefore less edge effects. Most different from a circle patch shape are AG881 and AG882 that have the highest number of modelled species present. The perimeter-area ratio is lowest for AG260 (0.008) where one modelled species is present and highest for AG881 (0.045) where nine modelled species are present, indicating that in the Baden-Brugg area, the patch shape of protected amphibian breeding sites does not influence the diversity of amphibian species present (Table 5).

Table 5: Landscape metrics of the seven permanent amphibian breeding sites of national importance in the study area Baden-Brugg (CSA). Shown are the area in square meters, circle (a shape metric characterizing the compactness of the patch), Euclidean nearest-neighbor distance (enn), and the perimeter-area ratio (para). Sector A encompasses the actual spawning grounds and sector B the area around it as a buffer zone. Additionally, the number of species present at the sites according to the model is shown.

site no	site name	sector	area m^2	share CSA	circle	enn (m)	para	no of species
AG149	Auschachen	A	186'579	0.19%	0.853	70	0.030	9
AG260	Binsenweiher	B	530'533	0.55%	0.604	594	0.008	1
AG260	Binsenweiher	A	8'841	0.01%				
AG820	Breitmoos	B	282'908	0.29%	0.474	1825	0.012	5
AG820	Breitmoos	A	5'825	0.01%				
AG821	Hard	A	37'782	0.04%	0.745	1541	0.029	7
AG821	Hard	B	18'879	0.02%				
AG843	Umiker Schachen	A	482'631	0.50%	0.848	594	0.013	7
AG881	Windischer Schachen	A	9'712	0.01%	0.895	32	0.045	9
AG881	Windischer Schachen	B	55'378	0.06%				
AG882	Fröschegräbe	A	27'455	0.03%	0.685	32	0.015	9
AG882	Fröschegräbe	B	140'975	0.15%				
	Sum:			**1.85%**				
		sector A:		0.79%				
		sector B:		1.07%				

The means of the ten examined environmental variables are shown in Table 6. Violin plots of the resulting value distribution of the environmental variables (Figure A7 in the Appendix) show differences between the breeding sites of national importance. For example, the breeding site AG821 has lower vegetation height values and the values for distance to forest vary more. The site AG149 has the highest spike in traffic intensity. Urbanization is most unevenly distributed in AG821 and AG881.

For the correlation analysis, α=0.05 is used as a guiding threshold for significance (Figure A8 in the Appendix). The number of modelled species present at a breeding site of national importance correlates most significantly with traffic intensity (-0.87, p=0.018), while there is no correlation visible with distance to the nearest road (Figure A8 in the Appendix).

Relevant is the correlation between the number of modelled species present and the distance to the closest waterbody (-0.86, p=0.014), highlighting the importance of those landscape features for amphibians. There is no correlation visible with distance to forest, this landscape feature being close in most sites (0-6 m), only AG821 being a bit further away (40 m). While the correlation between number of modelled species present and soil moisture variability is slightly positive, the relation is not significant (p=0.373) (Figure A8 in the Appendix).

The mean vegetation height varies between 5.18 m in AG821 and 18.95 m in AG882. There is no correlation visible between vegetation height, vegetation height variation, or NDVI and the number of species present at a site. There is a slight positive correlation between number of species modelled and variation in NDVI though (0.68, p=0.096) (Figure A8 in the Appendix).

Table 6: Area and mean of ten environmental variables at the seven amphibian breeding sites of national importance in the study area Baden-Brugg. Additionally, the number of species present at the sites according to the model is shown.

site no	site name	area (m²)	VHM mean (m)	VHMsd mean (m)	distforest mean (m)	distwater mean (m)	distroad mean (m)	NDVI mean	NDVIsd mean	traffic mean (vehicles/day)	urban mean	soilmoist mean	number of species
AG149	Auschachen	186'579	12.1	3.4	6.2	29.3	68.2	6156	1239	5	8.10	2.07	6
AG260	Binsenweiher	539'374	12.6	3.5	1.5	194.7	108.4	7253	1179	17	0.63	1.90	1
AG820	Breitmoos	288'733	15.7	3.5	1.4	147.8	125.0	7125	1122	5	16.71	1.86	5
AG821	Hard	56'661	5.2	1.7	40.4	101.4	102.3	5481	1233	7	29.65	1.71	7
AG843	Umiker Schachen	482'631	17.0	3.1	0.5	45.5	303.6	6880	1174	0	1.81	2.16	7
AG881	Windischer Schachen	65'090	17.7	3.7	0.0	33.5	157.5	6603	1308	0	24.55	2.07	6
AG882	Fröschegräbe	168'429	19.0	3.3	0.0	105.3	227.2	7067	1271	0	6.42	2.0	6

3.2.3 Land-use and assigned zones

Forest is the dominant landcover in all amphibian breeding sites of national importance but AG821, where open fields and shrubs are prevalent (Figure 6). AG149 and AG843 have a relatively high share (15% and 9% respectively) of area covered by the river, riverine gravel banks also accounting for the 7% covered by gravel and sand in AG843.

All protected sites have at least some impervious human infrastructures; with up to 5% of the total area found for AG149 and AG260. Most impervious surfaces include streets and railway tracks. However, in AG881, there are buildings in the protected site because of the expansion of a sewage treatment plant that the cantonal council allowed without compensation despite the loss of alluvial forest.[8]

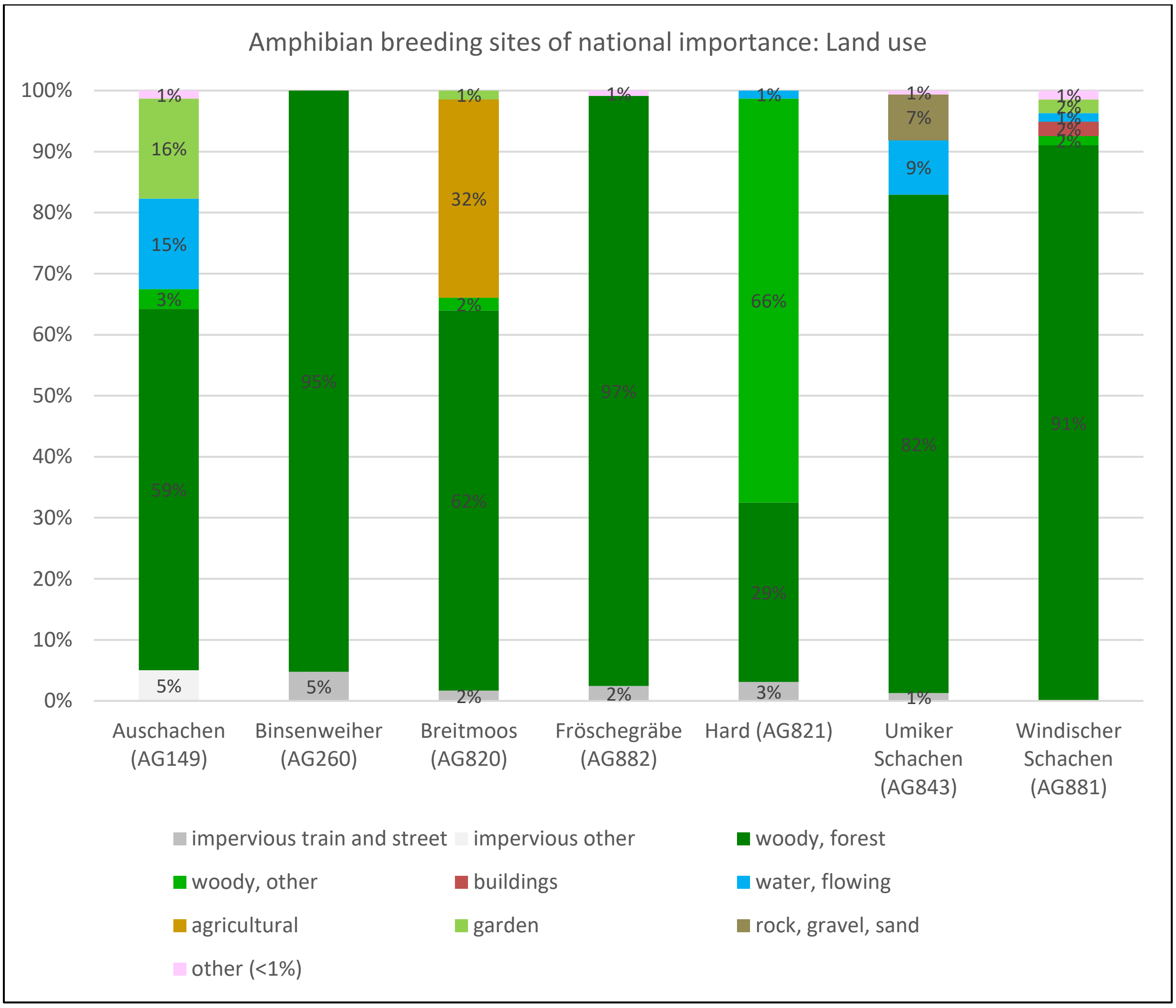

Figure 6: Shares of different land uses in the protected amphibian breeding sites of national importance in the study area Baden-Brugg.

AG820 is the only amphibian breeding site of national importance in the study area with a high share of agricultural land (32%). The assigned zonal uses reveal that most of this agricultural land as well as of the land covered by some type of garden in AG149 is actually classified as a protected extensive wet meadow (Figure 7).

[8] Hunziker, Michael: Wegen ARA-Ausbau wird Auenwaldgebiet 25 Aren kleiner. *Aargauer Zeitung*, 27.02.2013, https://www.aargauerzeitung.ch/aargau/brugg/wegen-ara-ausbau-wird-auenwaldgebiet-25-aren-kleiner-ld.1749693.

Zones in amphibian breeding sites of national importance are mostly assigned to natural habitats. However, the land use analysis reveals that some of this area is actually covered by roads and other human infrastructure (Figure 6).

No strong difference was found between the number of modelled species in an area and the landcover. For example, the site with only one species (AG260) and one of the sites with nine species (AG882) have very similar assigned zonal uses (Figure 7).

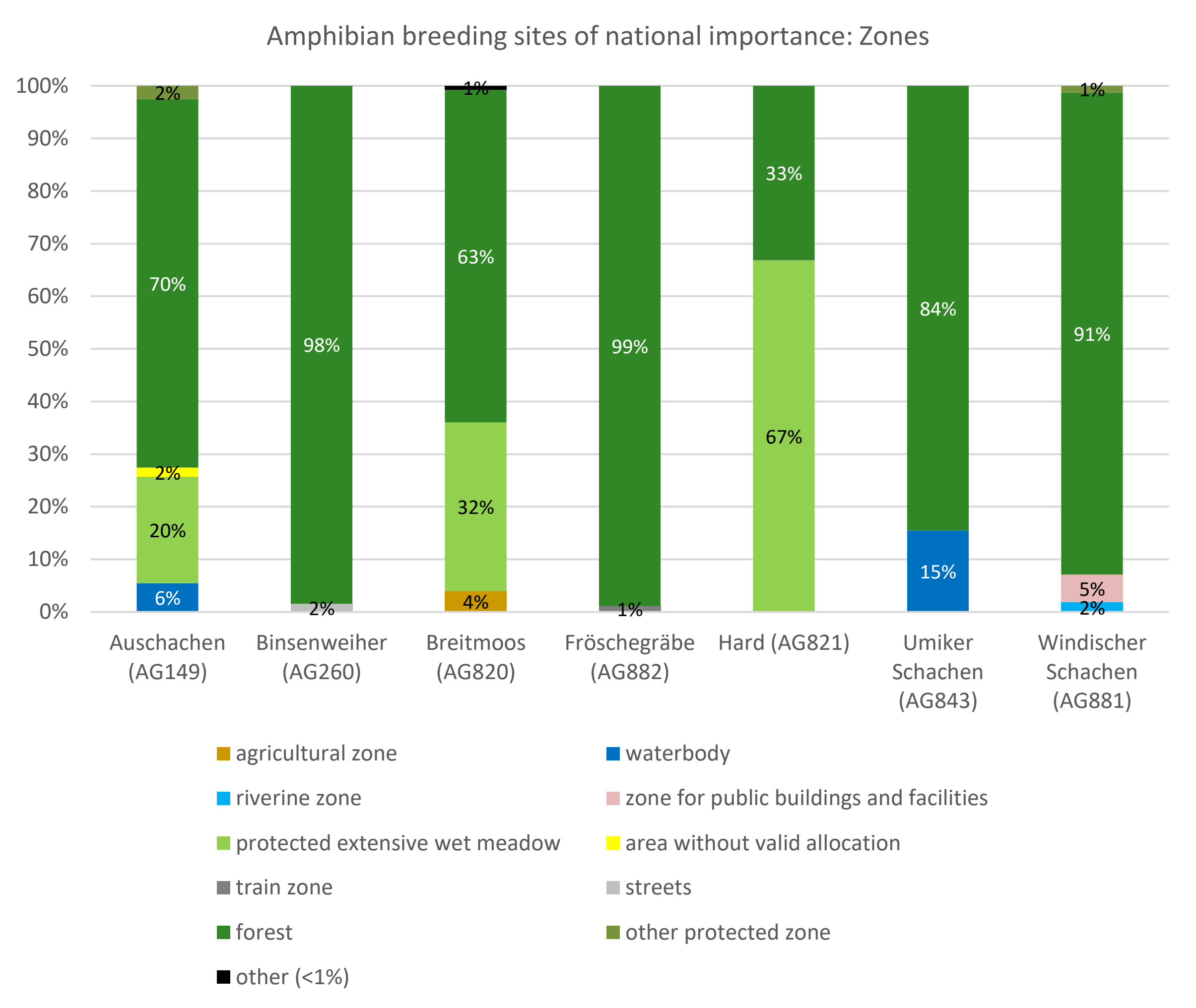

Figure 7: Shares of different zones in the protected amphibian breeding sites of national importance in the study area Baden-Brugg.

3.3 Characterization of inter-breeding sites corridors

3.3.1 Connectivity and road crossings

17 main corridors of amphibian movement were identified; they differ widely in their size and shape (Figure 8). It is however noticeable how all major rivers act as main corridors. Very important are also smaller streams (e.g. corridors 5, 6, 11) and forest edges (e.g. corridors 4, 8, 9, 15). It is evident that two permanent breeding sites (AG820 and AG260) and one non-permanent breeding site (AG2013) are not connected to a main corridor – these are also the three protected sites that accommodate the fewest species (AG820: 5 species, AG260: 1 species, AG2013: 2 species).

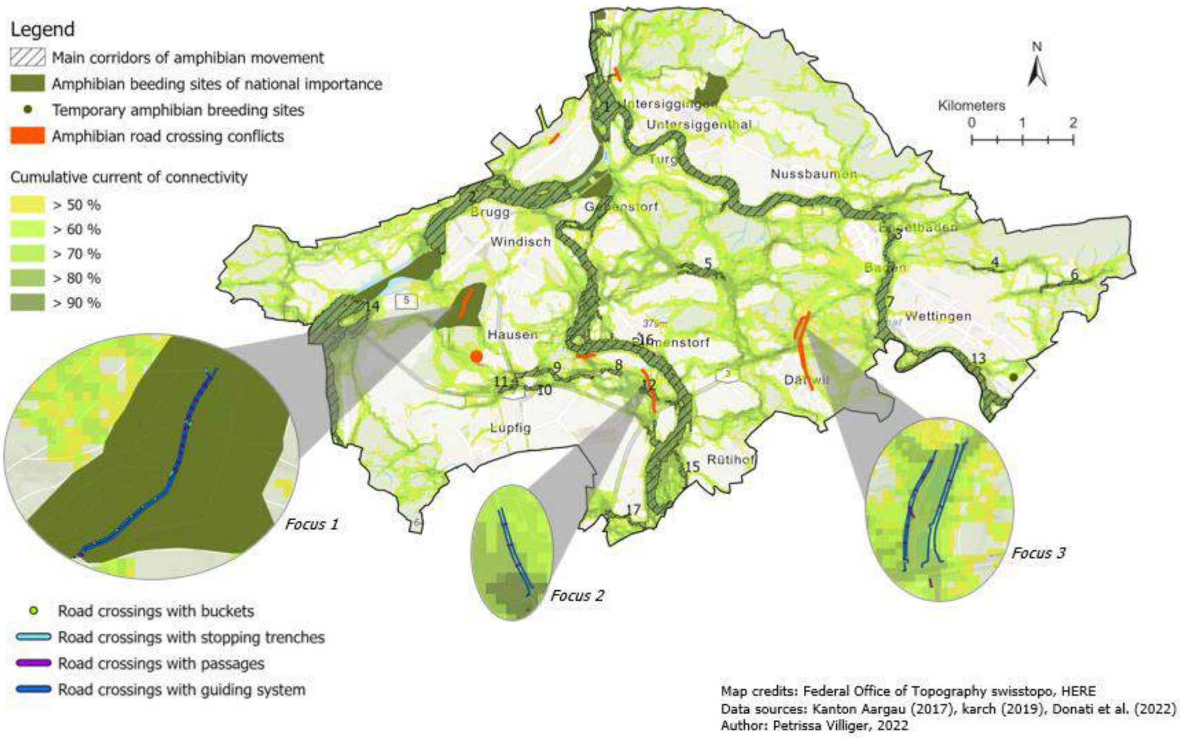

Figure 8: Connectivity between Amphibian breeding sites of national importance in the study area Baden-Brugg according to the model of Donati et al. (2022). The main corridors of amphibian movement are numbered from 1-17. In orange the amphibian road crossings registered by the canton with detailed views of three areas where measures are applied to facilitate the crossing for amphibians.

The overlap with major road crossings as identified by the canton show that one of the most important upgrades was made in several steps since 2010 at Habsburgerstrasse, in the amphibian breeding site of national importance AG260, where the amphibian protection measures were upgraded with a new guiding system and under-street passages[9,10]. Such passages were also installed at three other streets: at Hauptstrasse Mülligen, Mellingerstrasse, and Dättwilerstrasse. For smaller road crossings in the study area there is no technical solution planned and some road crossings were not identified as a conflict zone even though they interfere with crucial corridors according to the model (Figure 8).

Two wildlife corridors of regional importance as defined by the FOEN cross the study area. For these regional wildlife corridors, the canton identified five crucial passage points over natural or artificial barriers: AG-R05 that overlaps with corridor 1, AG-R06 that overlaps with corridor 4, and AG-R16 that overlaps with corridor 17, as well as AG-R07 that crosses the highway A1 and the Badenerstrasse at Grosszelg and AG-R08 that crosses the Mellingerstrasse and the Dättwilerstrasse and overlaps with Focus 3 in Figure 8. For the passage point AG-R05, the canton identified the need for wildlife tunnels under the nearby streets, however these have not yet been realized. For AG-R06 a passage is planned. AG-R07 was restored in 2004 with an under-street passage and a wildlife bridge. AG-R08 was also restored in 2004 with the amphibian guiding system and passages (Focus 3, Figure 8). AG-R16 is not yet restored[11].

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[9] Hunziker, Michael: Kostenpunkt 4,8 Millionen: Die Habsburgstrasse erhält einen neuen Belag. *Aargauer Zeitung*, 01.12.2016, https://www.aargauerzeitung.ch/aargau/brugg/kostenpunkt-4-8-millionen-die-habsburgstrasse-erhalt-einen-neuen-belag-ld.1597784.

[10] Gemeinde Habsburg: Aktuelles, http://www.habsburg.ch/News.htm.

[11] AGIS Online Karten Kanton Aargau: Wildtierkorridore. https://www.ag.ch/de/verwaltung/dfr/geoportal/online-karten.

3.3.2 Environmental variables

The environmental variables of the 17 identified corridors are very diverse (Table 7). The same pattern is visible in the according violin plots (Figure A9 in the Appendix): There is a high variety of corridors with different environmental conditions.

Table 7: Area and means of ten environmental variables in the 17 main corridors for amphibian movement in the study area Baden-Brugg.

corridor	area (m^2)	VHM mean (m)	VHMsd mean (m)	distforest mean (m)	distwater mean (m)	distroad mean (m)	urban mean	NDVI mean	NDVIsd mean	soilmoist mean	traffic mean (vehicles/day)
1	1'585'800	5.3	2.3	8.6	24.6	104.8	83.7	4162	1191	1.87	119
2	1'101'600	5.4	2.5	10.7	55.1	59.2	136.0	4577	1089	1.85	78
3	47'700	5.9	3.1	7.8	20.2	24.3	288.2	4064	1131	1.80	128
4	23'400	5.5	2.6	4.0	267.6	56.9	58.6	6372	1066	1.68	0
5	103'500	10.4	3.0	1.4	72.3	68.9	0.1	6897	1288	1.89	0
6	53'100	4.8	2.9	5.2	40.7	117.5	2.3	6301	1326	2.04	0
7	267'300	7.3	2.9	6.3	24.2	50.1	130.7	4304	1137	1.85	233
8	27'900	4.1	1.6	9.6	222.3	34.4	88.8	5212	996	1.71	61
9	126'000	4.3	2.0	10.0	421.6	100.9	17.3	5652	1063	1.65	76
10	24'300	0.4	0.4	41.0	309.1	6.9	2.3	2816	901	1.80	3364
11	24'300	1.0	0.8	23.9	55.1	62.1	27.4	3447	933	1.79	82
12	26'100	10.9	2.9	0.6	297.0	36.6	0.0	6236	1257	1.96	28
13	414'000	3.6	1.9	7.8	56.5	37.6	68.1	4111	1154	1.82	1147
14	919'800	7.5	2.5	8.6	31.4	63.7	21.5	5002	1153	2.01	267
15	31'500	8.2	2.3	5.7	470.3	232.8	0.9	6656	1314	1.90	0
16	1'860'300	9.9	2.8	5.6	37.8	131.8	38.6	4765	1275	1.86	194
17	66'600	8.7	2.7	4.4	598.4	41.7	5.6	5172	1252	1.92	1904
overall mean		6.1	2.3	9.5	176.7	72.4	57.1	5044	1149	1.85	452

3.3.3 Land-use and assigned zones

The 17 main corridors are very diverse concerning land-use (Figure 9). There are some corridors with a special feature; for example corridor 3 that doesn't include any forest, corridor 8 with a high share of buildings and an extraction or dumping site, or corridors 10 and 11 with very high shares of impervious surfaces. Possible barriers for amphibian movement can be found in every corridor: streets, railway tracks, or buildings.

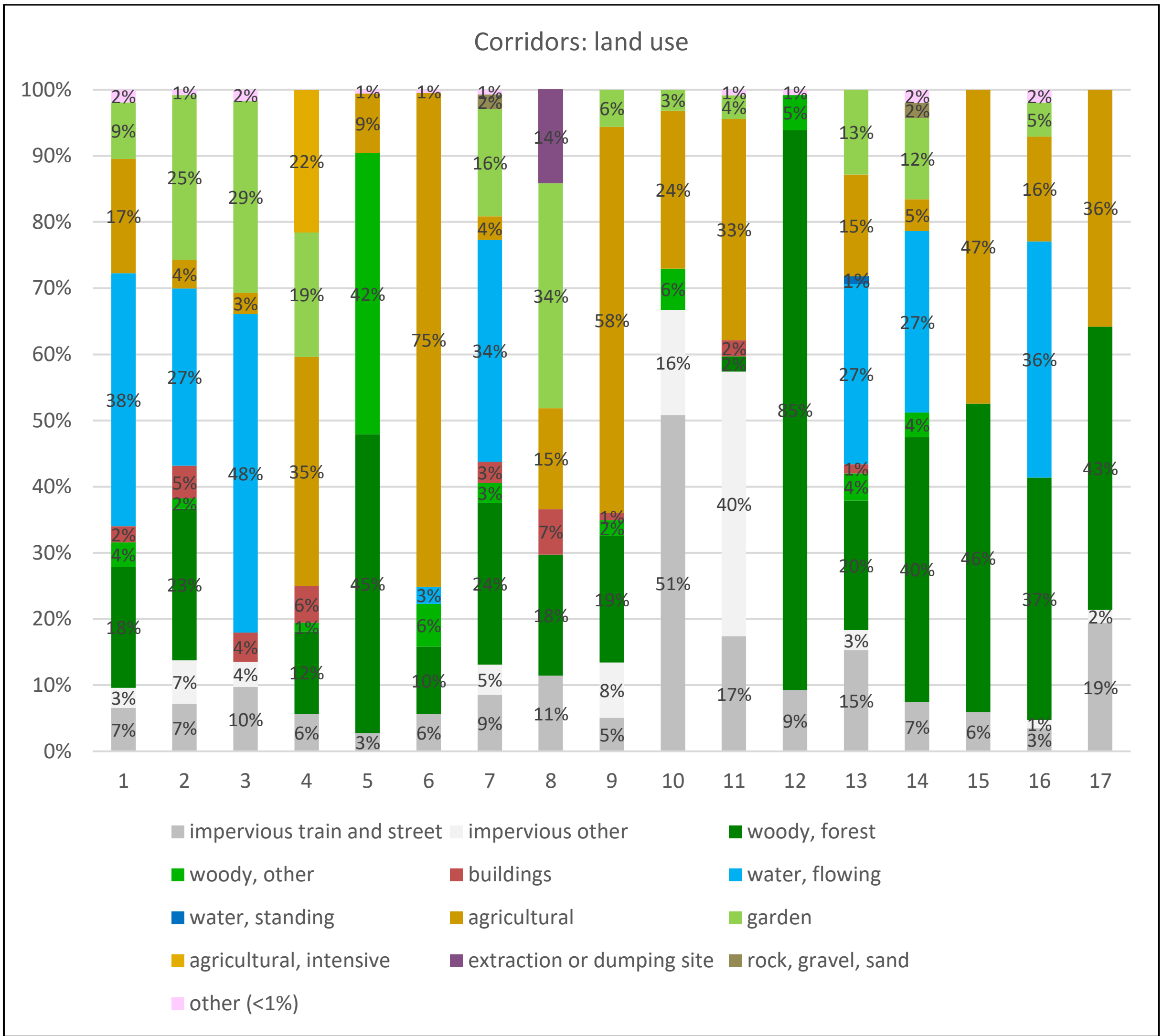

Figure 9: Shares of different land uses in the 17 identified corridors in the study area Baden-Brugg.

The zonal uses complete the understanding of land-uses in the corridors. For example, corridors 4, 6, 9, and 15 all have a high share of agricultural land, but while in corridors 4, 6, and 15 this land can be used intensively, the agricultural land in corridor 9 mostly consists of protected extensive dry meadows (Figure 10). The zonal uses also point to some possible challenges in the future: While the landcover in corridor 8 mostly consists of gardens at the moment, this area belongs to residential or industrial zones that give the landowners the possibility to increase the share of impervious surfaces in the future.

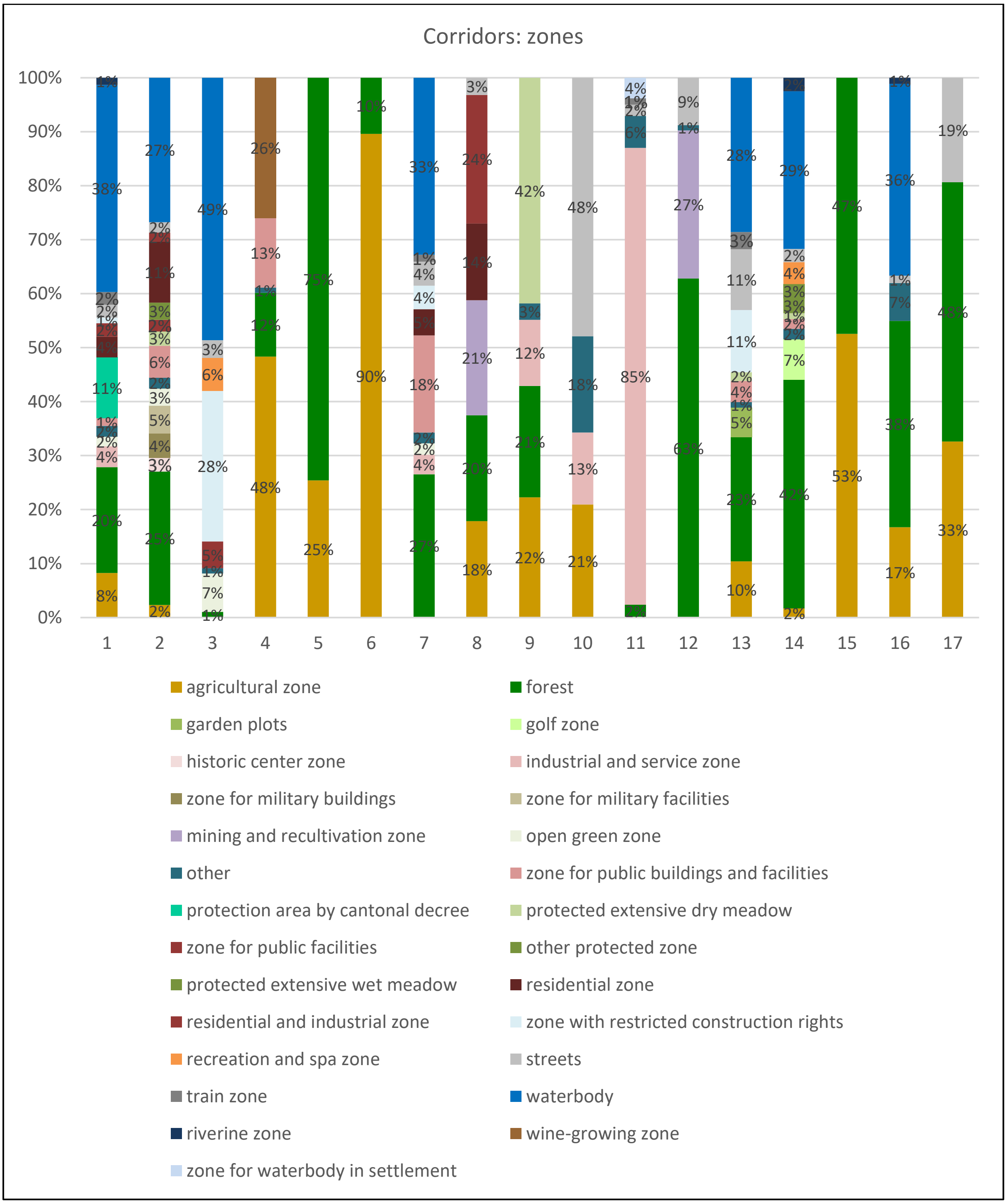

Figure 10: Shares of different zones in the protected amphibian breeding sites of national importance in the study area Baden-Brugg.

4 Discussion

4.1 Amphibian occurrence areas

Amphibians are relatively widespread in the study area. *Bufo bufo*, the most common species, has a modelled occurrence range of over 50% of the study area. According to the model, the conjunction between the three major rivers (Aare, Reuss, Limmat) in the study area is an amphibian species diversity hotspot (with eight to nine species). Seven species can be found along the Aare and the Reuss. Interestingly, the Limmat is much less occupied (max. five species). The Limmat valley is strongly urbanized and there are eight hydropower plants alone in the 20 km stretch in canton Aargau (Schelbert et al., 2015, p. 101). The eco-morphology of the Limmat in the study area is mostly classified as non-natural (category 3 of 4, with 4=completely artificial)[12]. Still, according to Schelbert et al. (2015, p. 102), the river is an important corridor for the movement of many species. Therefore, an implementation of BGI should be considered to support biodiversity and connectivity along the river further (Liao et al., 2017). BGI design for amphibian conservation includes for example engineered wetlands and ponds with natural aquatic vegetation. Important is also the restoration of terrestrial habitats surrounding these waterbodies (Scheffers & Paszkowski, 2013).

Amphibian species diversity is highest in areas a short distance from the closest waterbody and in areas with a high soil moisture variability, highlighting the animals' dependency on wet habitats (Table 3). Traffic clearly affects amphibian species diversity negatively. While the mean urbanization index showed no such relation to the number of co-occurring species in an area, indicating that amphibians can adapt to certain types of human infrastructures, the urbanization index was much higher in the entire study area (104) than in areas where several amphibian species occur (max. 43). In addition, the land-use analysis showed a negative correlation between the amount of impervious surface and the number of species occurring in an area, raising the question as to how urban blue-green areas should be designed to protect species diversity in settlement areas. Beninde et al. (2015) who included amphibians and other taxa in their analysis, found that patch area size and corridor connectivity have the highest positive effects on biodiversity in urban areas. Vegetation structure and biodiversity-friendly management were also found to benefit species diversity (Beninde et al., 2015; Aronson et al., 2017).

Analyzing the planning zones showed that the highest species diversity was correlated not only to shares of forest and water, but also to agricultural land that is managed extensively. In such diversity hotspots, there are no residential or industrial zones, but zones assigned for public infrastructures such as military facilities, wastewater treatment plants, and open green spaces. In this study area, farmers and public landowners play therefore an important role for the conservation of existing amphibian diversity hotspots.

The least common species in the study area were also the species with the lowest share of suitable habitat and the species that occupy the smallest share of that potentially suitable habitat according to the model. It shows that in the Baden-Brugg region, there are generally two possible approaches for the promotion of endangered species: (1) increase occupancy of the existing suitable habitats and (2) enlargement of these potentially suitable habitats.

A closer look at the unoccupied, but suitable and larger habitats of *Lissotriton vulgaris*, the only modelled species that does not occur in the study area, and *Triturus cristatus*, a species that only uses 12% of its suitable habitat, reveals that these newts' modelled suitable habitats mostly overlap with areas of high diversity of other amphibian species, mainly in forests, streams, and ponds along the three rivers Aare, Reuss, and Limmat. More isolated suitable habitats can be found around ponds and streams in forested areas. Since *Lissotriton vulgaris* usually does not move more than half a kilometer (karch, 2022), the species will not be able to directly recolonize the suitable habitats in the study area.

[12] AGIS Online Karten Kanton Aargau: Ökomorphologie Fliessgewässer und Seen. https://www.ag.ch/de/verwaltung/dfr/geoportal/online-karten.

About half of all *Triturus cristatus* populations in Switzerland perished over the past 25 years. The main reason is the destruction and pollution of both aquatic and terrestrial habitats (karch, 2022). The remaining populations of *Triturus cristatus* in the study area can be found at the conjunction of the Aare and Reuss, protected by amphibian breeding sites of national importance and an alluvial zone of national importance. This newt species was also found to be very sensitive towards habitat fragmentation (Edgar & Bird, 2006). Since *Triturus cristatus* usually does not move more than a few hundred meters (Churko et al., 2020), it is unlikely that the species is able to re-colonize many suitable habitats in the study area under the current circumstances as they are too far apart or separated by barriers like streets. If the creation and restoration of ponds considering spatial connectivity (O'Brien et al., 2021) is not feasible in an area, the translocation and re-introduction of *Triturus cristatus* could be an alternative tool to enhance the species' usage of suitable habitats (Edgar & Bird, 2006; Edgar et al., 2005).

The frog species with the smallest occupied habitat (19%) in the study area is *Hyla arborea*. The European tree frog only occurs in 1.45% of the study area, but this population is very important: It is the last population at the Aare river between the Lake Biel and the Rhine (Schelbert et al., 2015, p. 102). For *Hyla arborea*, strong efforts have been made to restore parts of the natural floodplain in the lower Reuss valley since the 1990s (Flory, 2006).

4.2 Amphibian breeding sites of national importance

The amphibian breeding sites of national importance cover 1.85% of the study area and are mostly situated along the Aare river. While all protected sites have high shares of forested areas, they still differ in their vegetation structure and land-use composition, offering different natural habitats to amphibians, including waterbodies, shrubbery, and wet meadows. It is apparent that natural habitats dominate in amphibian breeding sites of national importance. Still, every protected site has at least some impervious human infrastructures; with up to 5% in AG149 and AG260. These infrastructures include mostly roads and railway tracks and in one case (AG881) public buildings. Seeing as the sites are designed to protect biotopes of national importance, it is concerning none of the sites consist of only natural habitats.

The analysis could show that in this study area, two parameters influence the number of species in breeding sites of national importance the most: traffic intensity and distance to closest waterbody. Both findings are supported by literature (Hamer & McDonnell, 2008; Hillmann et al., 2008; Jochimsen et al., 2004; Pellet, Guisan, & Perrin, 2004). In this study area, the patch metrics (Table 5) fail to predict species diversity. For example, according to the model, the biggest protected breeding site (AG260) hosts one species, while the smallest (AG881) hosts nine.

All amphibian breeding sites of national importance would offer suitable habitat to one to nine additional species, raising the question as to why certain species do not occur. Inter-species competition is usually not a problem with these native species (karch, 2022). Other possible threads include high predation pressure (Beranek et al., 2021), or illnesses (Downie et al., 2019). Most likely though the habitat quality is lowered by something the habitat suitability model does not account for, for example disturbances (BAFU, 2010, p. 13), or poor management (Scroggie et al., 2019), or the habitat is inadequately connected to wetlands where the local birth rate exceeds mortality (Zamberletti et al., 2018).

4.2.1 Species diversity trends and the amphibian breeding site AG260

Overall, there was a positive trend in species diversity in amphibian breeding sites of national importance in the study area over the past two decades: Three breeding sites host more species than 2001, two breeding sites the same number of species, one breeding site was established later and one breeding site lost species. However, there are two concerning developments: As the last population of *Lissotriton vulgaris* vanished in AG881, this species is now extinct in the study area, and the breeding site AG260 clearly missed the conservation goals.

The breeding site AG260 lost three (*Ichthyosaura alpestris, Rana temporaria, Lissotriton helveticus*) of its four amphibian species since 2001, only the widespread *Bufo bufo* survived. The three species no longer occurring in the site according to the model data, are also relatively common: *Ichthyosaura alpestris* and *Rana temporaria* are not on the red list, *Lissotriton helveticus* is classified as vulnerable. AG260 is a site that consists of forested area with a stream and several ponds along the stream (engineered as flood protection) as well as the Binsenweiher, a bigger pond with several smaller pools around it in the middle of the protected site. The ponds are managed regularly by the forest service Birretholz[13]. A cantonal street (Habsburgerstrasse) passes right through the middle of the protected area. The street is classified as a local narrow street, but the environmental variables show that the traffic intensity is still the highest of all analyzed breeding sites. Since 2010, the cantonal authorities started to restore the site by implementing a new guiding system and under-street passages. Such measurements proved effective in many cases (Helldin & Petrovan, 2019; Jarvis et al., 2019). Before, conservation volunteers saved amphibians by catching them in buckets and carrying them over the street by hand.

It remains unclear what exactly lead to the extinction of the three species in this site and whether the model depicts the current situation correctly. It could be that traffic affected the amphibians negatively either directly through roadkill before the restoration as migration seasons change and it gets increasingly difficult for volunteers to catch all amphibians (Todd et al., 2010; Brzeziński et al., 2012), or indirectly through disturbances despite the restoration efforts (Jochimsen et al., 2004; Grace & Noss, 2018). The extinction of certain species in the study area during the past two decades shows that time is an important factor in restoring habitats. The Binsenweiher pond is a popular recreation site and practitioners observed heavy disturbances such as the release of goldfish into the pond or visitors leaving the trails[14]. These disturbances should be mitigated better. Since some restoration measures were implemented after 2018, it will be advisable to monitor these effects – maybe species diversity is already increasing again. AG260 has also the highest value for distance to closest waterbody. There was no decline of ponds inside the area though. The site is about 600 m from the Aare river and another amphibian breeding site of national importance (AG843). This is a distance that most amphibian species could overcome, but a railway line, a street with high traffic intensity, and an industrial area hinder the connection between the two habitats.

4.3 Inter-breeding site corridors

The three major rivers act as main corridors for amphibian movement in the study area Baden-Brugg. Very important are also smaller streams and forest edges. The identified corridors are very diverse in their land-use, ecological conditions, and composition. It is striking though that there are streets and/or railway lines in every main corridor. Some of the corridors (1, 4, 17) overlap with wildlife corridors of regional importance and the authorities plan to restore them with tunnels or passages that cross traffic infrastructure. However, while the need for conservation measures is recognized, most of these plans have not yet been implemented – the cantonal authorities improve the identified problematic amphibian road crossings according to a priority plan and while using synergies with ordinary street maintenance work[15]. This can be a major issue considering that time is an important factor in the reconnection and protection of isolated populations (Sterrett et al., 2019).

For corridors that are neither part of annual migration routes nor of a wildlife corridor of regional importance, there have not yet been any measure implemented to facilitate amphibian movement across the landscape. The cantonal authorities work with different approaches to enhance connectivity in the landscape and are currently developing a strategic plan for an ecological infrastructure on the landscape level[16]. While some connectivity measures have shown to be effective (Angelone &

[13] Forstbetrieb Birretholz: https://www.forst-birretholz.ch/68/home.
[14] FDP Hausen: Binsenweiher. https://www.fdp-hausen-ag.ch/hauser-blickpunkte/binsenweiher/.
[15] Kanton Aargau, Sektion Natur und Landschaft: Betreuung der Amphibienzugstellen. https://www.ag.ch/media/kanton-aargau/bvu/umwelt-natur/natur-und-landschaftsschutz/biodiversitaet/54223-amphibienzugstellen.pdf [2022-05-24].
[16] Kanton Aargau: Ökologische Infrastruktur. https://www.ag.ch/de/verwaltung/bvu/umwelt-natur-landschaft/natur-und-landschaftsschutz/oekologische-infrastruktur.

Holderegger, 2009), measures like underpasses were often found to focus more on local outcomes than on habitat connectivity and population preservation at the landscape level (Matos et al., 2019). An example of a road crossing that is not yet identified as problematic by the authorities is the crossing of Birrfeldstrasse in corridor 8. Also challenging are streets right next to rivers that serve as important corridors, for example Ländistrasse in corridor 2. There are also some examples of corridors that are at least partially managed according to conservation goals, for example corridors 8 and 9 that overlap with cantonal protection sites.

Movement corridors do not need to fulfill the same conditions as breeding habitats (Pittman et al., 2014). For example, amphibians can cross agricultural land that is unsuitable habitat (Churko et al., 2020). However, railways and streets can come with a high cost in amphibians lives and should be restored not only considering annual migration patterns but also for dispersal across the landscape, for example the connection between AG260 and AG843. Another important measure is the facilitation of movement along major rivers and streams. The Aare and Reuss river in the study area are usually channeled in the stretches where they flow through settlements and the Limmat is even channeled for the most part. However, amphibians mostly rely on floodplain structures, not the main river itself (Holgerson et al., 2019). It is therefore important to design and manage the riverbanks and surroundings accordingly (Knutti et al., 2021).

4.4 Study limitations

Some of the areas important to amphibian conservation were identified based on the model from Donati et al. (2022). Even though the underlying model is up to the latest standard, this approach comes with limitations, including that the model is based on presence-only data and there was no data about population sizes that could have been taken into account (Donati et al., 2022). As discussed above, there is uncertainty regarding the accuracy of the model in detecting species diversity correctly in an amphibian breeding site of national importance and this analysis could have benefited from additional species sampling in the identified BGAs important for amphibian conservation to verify the findings based on the model. While this approach was chosen for the very reason that models can support the identification and assessment of important areas for biodiversity conservation without expensive and time-consuming field surveys, there is still a high uncertainty connected to the use of species distribution models (Villero et al., 2017; Muscatello et al., 2020).

The resolution of the environmental data and the model can also limit the analysis of spatially small areas. The most important example here are the extremely high traffic values in corridor 10, where a stream right next to the highway is an important movement route. The 10 m resolution is not fine enough to differentiate between the two environments and while it is valuable to know that a highway is right next to the corridor – as it might influence the habitat – the highway itself is fenced and not part of the amphibians' movement route.

An important limitation in my analysis is the interdependency of the environmental variables: They were used to describe BGAs that were identified based on the model (occurrence areas and corridors) while also being used to build the model in the first place. However, this way it was possible to describe all areas with the same relevant variables.

For the connectivity model, the breeding sites of national importance were chosen as nodes. This can lead to an overestimation of the connectivity for rarer species (Donati et al., 2022), but also ignores breeding sites that are protected on the cantonal or local level. The model assumes that animal movement behavior is based on similar factors as habitat selection which might not be the case (Donati et al., 2022). There is generally a high uncertainty when it comes to the correct estimation of resistance values for connectivity analyses (Bolliger & Silbernagel, 2020).

A weakness of the chosen approach is certainly the small number of analyzed sites, especially for the correlation analyses. For example, the findings showed a negative correlation between the size of a breeding site and the number of species present. The results suggest that other factors such as distance to water are more relevant to explain species diversity. For patch metrics like the perimeter-area ratio, raster data needed to be transformed into smooth polygons which lead to slight changes in area measurements. Overall, environmental variables seem better suited to explain species occurrence and overlie possible influences of landscape or patch metrics when looking at a limited number of protected sites in a relatively small area.

The inclusion of zonal plans besides the land-use data had two major advantages: First, it did allow for finer distinctions between different forms of land management. Many analyses are based solely on land-use data which usually cannot account for areas assigned for biodiversity promotion, for example protected wet meadows compared to intensively used meadows. Secondly, while zonal plans do not actually give information about the ownership status of a parcel, they do distinguish between private and public zones which is valuable to assess the potential for conservation measures. While zonal plans cannot replace land-use data as they do not represent the actual situation, they are a valuable asset for a more in-depth view and can complement land-use analyses well, especially in countries where their implementation is strict.

The inclusion of other taxa could have added even more insights to the conservation of blue-green areas. However, the use of a multi-species, whole life cycle suitability model of one of the most diverse vertebrate groups is a valuable indicator for biodiversity that can aid decisions for actual conservation management (Bolliger & Silbernagel, 2020).

5 Conclusions and recommendations

Blue-green areas in human-dominated landscapes are important habitats and movement corridors for a variety of different species (e.g. Beninde et al., 2015). They are also relevant for many other ecosystem services such as water retention, climate change mitigation, and human well-being (e.g. Dearborn & Kark, 2010). While amphibians are relatively widespread in the study area Baden-Brugg, there is high pressure on their blue-green habitats and not even protected amphibian breeding sites of national importance are spared from anthropogenic disturbances. The findings and supporting literature indicate that the quality of these breeding sites needs to be monitored better, especially in regard to visitors, non-native species, and influence of traffic.

As the amphibian diversity hotspot at the conjunction of the Aare and the Reuss that includes the regionally important population of *Hyla arborea* is not yet completely protected, I recommend expanding the protected amphibian breeding sites of national importance further upstream along the Reuss. This first river stretch is already mostly protected by an alluvial zone of national importance. On both, the Aare and the Reuss, it would be possible to enhance ecological infrastructure upstream of the conjunction. In this stretch of the Aare there are many garden plots (Sommerau) that could be improved for biodiversity protection, for example by implementing a project like “Natur findet Stadt”[17]. Further upstream on the same river site is the public sports facility Mülimatt, which is a good example for how to increase connectivity along the river as the surroundings were designed naturally with several ponds[18].

Upstream of the protected sites along the Reuss, there are sports facilities (a dog park and a shooting range) as well as a cemetery. These spaces are no physical barrier for amphibian movement, but cause noise and physical disturbances. In Gebenstorf, a weir (Spinnereiwehr) disrupts the Reuss, and settlement areas border the river. There are also intensive agricultural areas right next to the stream (Rüssguet in Gebenstorf and Faarguet in Windisch) that could be ecologically upgraded by adding stepping-stone habitat elements like hedges or ponds, or by using wet arable land, for example to produce rice as it is already done along the Aare (Gramlich et al., 2020). At the inside of the meander bend in Gebenstorf there is a little public park with a swimming pool (Reussbädli). While the park should still offer space for recreation, I recommend enhancing it with natural habitat elements, and replacing the small artificial swimming pool with a natural pond, especially since the area gets flooded regularly[19].

Habitat fragmentation is of high concern in the study area. While the distances between the breeding sites would mostly be crossable for amphibians, their movement is often hindered by streets and railway lines. Therefore, I recommend to not only implement road underpasses in migration zones but also in important dispersal corridors, for example under the Birrfeldstrasse in corridor 8. Especially important is the connectivity between breeding sites, as movement across the landscape has consequences for gene flow, natural selection, adaptation, population persistence, metapopulation dynamics, and species distribution (Pittman et al., 2014). Hindered movement also leads to increased mortality and genetic diversity reduction (Pisa et al., 2015). For efficient and effective measures for amphibian protection it is important to base decisions on functional connectivity (Le Lay et al., 2015).

High priority should be given to restoring the connection between the amphibian breeding site of national importance AG260 and the Aare river. To further enhance the movement of amphibians across the landscape, I recommend stepping-stone habitat elements like ponds, hedges, or branch and stone piles to be realized inside the identified important corridors. Most important for connectivity are the

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[17] Naturama & Kanton Aargau: Natur findet Stadt. https://www.naturfindetstadt.ch/de.

[18] Kanton Aargau: Biodiversität bei kantonalen Liegenschaften. https://www.ag.ch/de/verwaltung/bvu/umwelt-natur-landschaft/natur-und-landschaftsschutz/natur-im-siedlungsraum/biodiversitaet-bei-kantonalen-liegenschaften.

[19] AGIS Online Karten Kanton Aargau: Gefahrenkarte Hochwasser. https://www.ag.ch/de/verwaltung/dfr/geoportal/online-karten.

three big rivers; their banks and immediate surroundings should be restored and BGI measures should be implemented close to the river where they flow through urban areas.

The need for additional conservation measures for blue-green areas has also been recognized by the authorities and the canton pursues different strategies, including climate-resilient ecological infrastructure that also involves wetland restoration[20], or the restoration of degraded wetlands in agricultural areas[21]. The production of rice on wet arable land for example offers habitats to amphibians in all development stages (Gramlich et al., 2020). A strategic plan for an ecological infrastructure on the landscape level is currently in preparation. However, timely implementation and implementation through all government levels are major challenges and need to be improved in order to enhance blue-green areas and protect amphibian species diversity in the study area.

[20] Kanton Aargau: Klimaresiliente Ökologische Infrastruktur. https://www.ag.ch/de/themen/klimawandel/klimastrategie-kanton-aargau/klimakompass?dc=18c6d388-6708-4a51-96cb-f970b19416c6_de.

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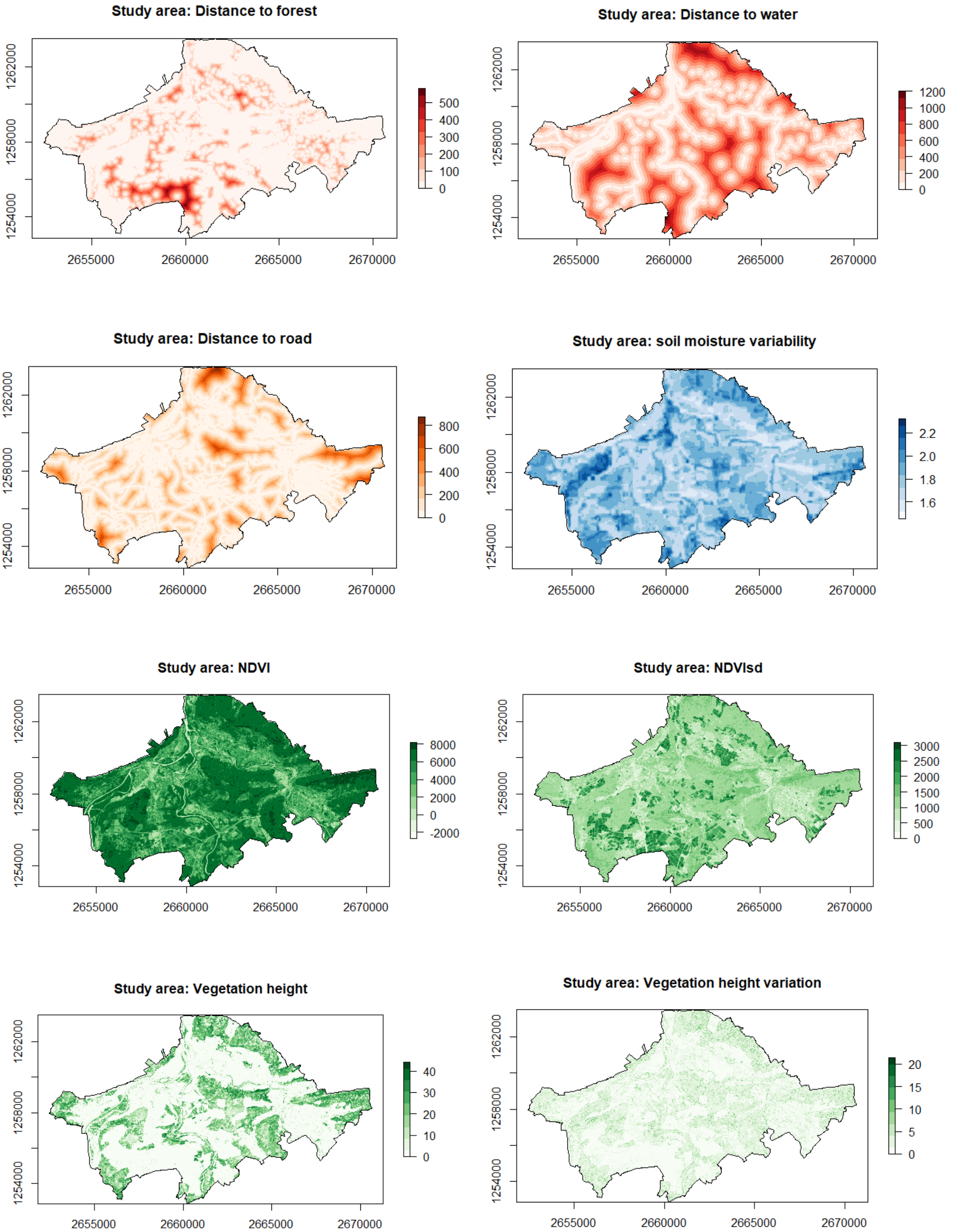
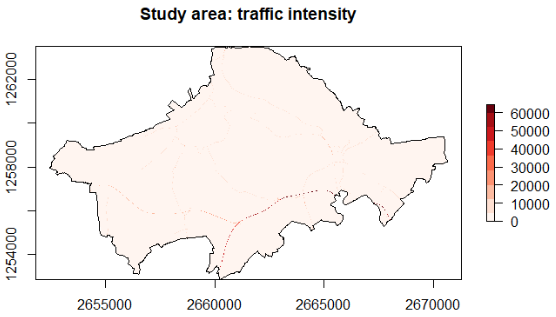
Appendixes

Appendix for Chapter 2.3

Figure A1: The ten examined environmental variables for the entire study area Baden-Brugg.




Study area: traffic intensity
1262000
1258000
1254000
2655000
2660000
2665000
2670000
60000
50000
40000
30000
20000
10000
0

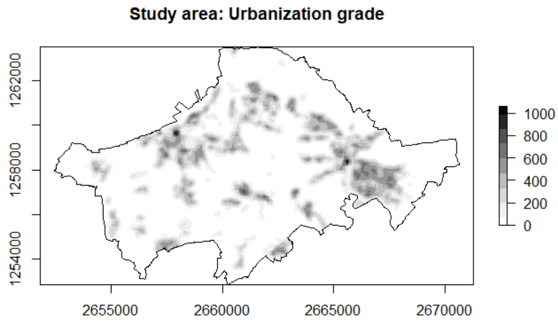

Study area: Urbanization grade
1262000
1258000
1254000
2655000
2660000
2665000
2670000
1000
800
600
400
200
0

Table A1: Land-use categories derived from the cantonal cadaster map.

Bodenbedeckung Art	**Land-use category**
befestigt.Bahn	impervious train and street
befestigt.Strasse_Weg	impervious train and street
befestigt.Trottoir	impervious other
befestigt.uebrige_befestigte	impervious other
befestigt.Verkehrsinsel	impervious other
befestigt.Wasserbecken	water basin
bestockt.geschlossener_Wald	woody, forest
bestockt.uebrige_bestockte	woody, other
Gebaeude	buildings
Gewaesser.fliessendes	water, flowing
Gewaesser.Schilfguertel	water, standing
Gewaesser.stehendes	water, standing
humusiert.Acker_Wiese_Weide	agricultural
humusiert.Gartenanlage	garden
humusiert.Intensivkultur.Reben	agricultural, intensive
humusiert.Intensivkultur.uebrige_Intensivkultur	agricultural, intensive
vegetationslos.Abbau_Deponie	extraction or dumping site
vegetationslos.Fels	rock, gravel, sand
vegetationslos.Geroell_Sand	rock, gravel, sand

Table A2: Utilization zones that appear in the study area, according to the cantonal allocation system. Note that municipal streets inside settlements are added to the neighboring zone of the most intensive utilization by default.

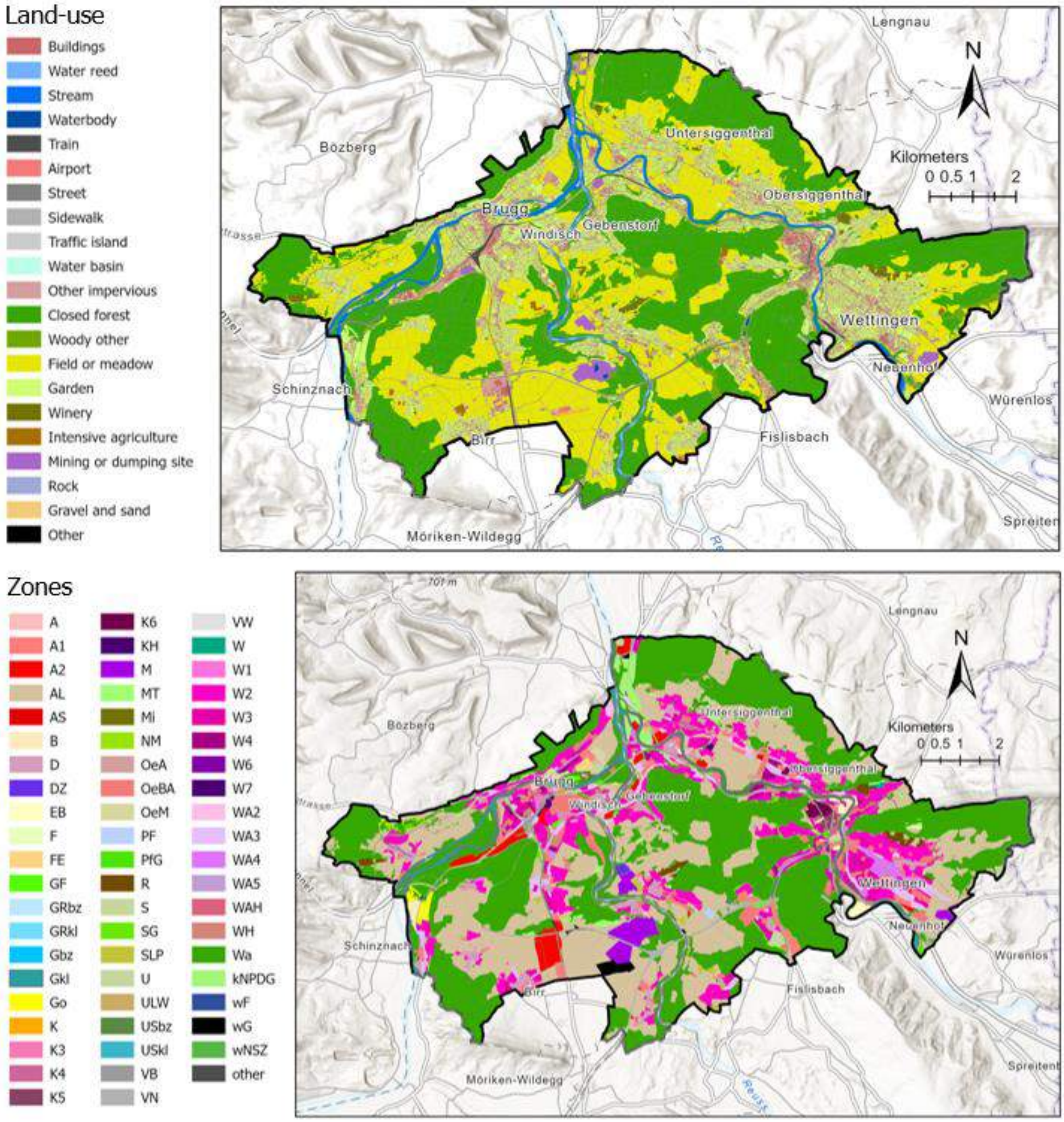
Zone code	Original zone name	Zone	Class	Class code	Allowed uses/class description
W2	Wohnzone 2	residential zone 2	residential zone	res	Zones restricted to residential use.
W3	Wohnzone 3	residential zone 3	residential zone	res	Zones restricted to residential use.
W4	Wohnzone 4	residential zone 4	residential zone	res	Zones restricted to residential use.
WH	Wohnzone mit höheren Bauten	residential zone with higher buildings	residential zone	res	Zones restricted to residential use.
A1	Arbeitszone I	industrial and service zone I	industrial and service zone	ind	Zones for industrial, service, and commercial uses.
A2	Arbeitszone II	industrial and service zone II	industrial and service zone	ind	Zones for industrial, service, and commercial uses.
AS	Spezielle Arbeitszone	special industrial zone	industrial and service zone	ind	Zones for industrial, service, and commercial uses.
WA2	Wohn- und Arbeitszone 2	residential and industrial zone 2	residential and industrial zone	rin	Combined residential and commercial uses allowed.
WA3	Wohn- und Arbeitszone 3	residential and industrial zone 3	residential and industrial zone	rin	Combined residential and commercial uses allowed.
WA4	Wohn- und Arbeitszone 4	residential and industrial zone 4	residential and industrial zone	rin	Combined residential and commercial uses allowed.
WAH	Wohn- und Arbeitszone mit höheren Bauten	residential and industrial zone with higher buildings	residential and industrial zone	rin	Combined residential and commercial uses allowed.
D	Dorfkernzone	village center zone	historic center zone	hce	Zones serve to preserve historic valuable city and village centers.
A	Altstadtzone	historic city center zone	historic center zone	hce	Zones serve to preserve historic valuable city and village centers.
K3	Kernzone / Zentrumszone 3	center zone 3	center zone	ce	Zones serve to develop the city or village centers.
K4	Kernzone / Zentrumszone 4	center zone 4	center zone	ce	Zones serve to develop the city or village centers.
OeBA	Zone für öffentliche Bauten und Anlagen	zone for public buildings and facilities	zone for public buildings and facilities	pb	Allowed are buildings and facilities that serve the public interest.

OeA	Zone für öffentliche Anlagen	zone for public facilities	zone for public facilities	pf	Allowed are facilities that serve the public interest such as sports fields and parks, buildings are restricted.
OeM	Zone für militärische Anlagen	zone for military facilities	zone for military facilities	mf	Zone for military education with buildings and facilities for military use.
Mi	Zone für militärische Bauten	zone for military buildings	zone for military buildings	mb	Allowed are buildings and facilities for military use.
GF	Grünzone, Freihaltezone	open green zone	open green zone	op	Zone to keep open inside the settlement, e.g. for a historical monument, urban greenery, or an ecological corridor, very restricted construction rights.
USbz	Uferschutzzone altrechtlich	stream bank zone under former law	zone for waterbody inside residential and industrial zones	wre	Zone for the protection of waterbodies and their banks inside settlements.
Gbz	Gewässer innerhalb Bauzone	waterbody inside residential zone	zone for waterbody inside residential and industrial zones	wre	Zone for the protection of waterbodies and their banks inside settlements.
EB	Eingeschränkte Bauzone	zone with restricted construction rights	zone with restricted construction rights	rz	Only buildings and facilities for the maintenance of the zone are allowed.
FE	Zone für Freizeit und Erholung	recreation and leisure zone	recreation and leisure zone	rec	Allowed are buildings and facilities for tourism and recreation.
wF	Weitere Zone für Freiraumaktivitäten	other outdoor recreational zone	recreation and leisure zone	rec	Allowed are buildings and facilities for tourism and recreation.
B	Bäderzone / Kurzone	bath and spa zone	recreation and spa zone	spa	Zone for the development of health resorts and recreational facilities.
K	Erholungszone, Kuranlage	recreation and spa zone	recreation and spa zone	spa	Zone for the development of health resorts and recreational facilities.
Go	Golfzone	golf zone	golf zone	gol	Zone for golf courses outside the settlement.
PfG	Pflanzgarten	seedling nurseries and garden plots	garden plots	gar	Allowed are seedling nurseries, community gardens, and garden plots inside settlements.
VN	Kantons- und Nationalstrasse	cantonal and national streets	streets	str	Streets inside settlements or through forests.
VW	Kommunale Strasse durch den Wald	municipal street through forest	streets	str	Streets inside settlements or through forests.

VB	Bahnfläche	train zone	train zone	tra	Railway tracks and associated facilities inside settlements.
AL	Allgemeine Landwirtschaftszone	common agricultural zone	agricultural zone	agr	Agricultural zone for the production of food and other agricultural goods as well as ecological compensation.
SLP	Speziallandwirtschaftszone ausschliesslich Pflanzenproduktion	special agricultural zone for plant production	agricultural zone	agr	Agricultural zone for the production of food and other agricultural goods as well as ecological compensation.
R	Rebbauzone	wine-growing zone	wine-growing zone	win	Agricultural zones specifically for wine production.
PF	Spezialzone Pferdehaltung, Reitsportzone	zone for horse keeping and equitation	zone for horse breeding and equitation	hor	Recreational zone where buildings and facilities for horse keeping and equitation are allowed.
ULW	Bereich ohne genehmigte Festlegung (nur für interne Verwendung)	area without valid allocation	area without valid allocation	aw	Zones outside settlements (agricultural zones) without valid allocation at the moment.
MT	Magerwiese / Trockenstandort	protected extensive dry meadow	protected extensive dry meadow	pdm	Strictly protected area for the conservation of dry, nutrient-poor habitats.
S	Streuwiese / Feuchtstandort	protected extensive wet meadow	protected extensive wet meadow	pwm	Strictly protected area for the conservation of wet, nutrient-poor habitats.
W	Extensive Weide	protected extensive pasture	protected extensive pasture	pep	Strictly protected area for the conservation of extensive pastures.
F	Fromentalwiese	protected meadow	protected meadow	pme	Strictly protected area for the conservation of extensive meadows.
NM	Naturschutzzone mit Mehrfachfunktion	protected zone with multifunctionality	protected zone with multifunctionality	pmf	Protected area for nature conservation together with other functions, e.g. recreation.
wNSZ	Weitere Naturschutzzone	other protected zone	other protected zone	pot	Strictly protected area for the conservation of protected species.
GRkl	Gewässerraumzone	riverine zone	riverine zone	wb	Zone for the protection of waterbodies and their banks outside of settlements.
USkl	Uferschutzzone altrechtlich	stream bank zone under former law	riverine zone	wb	Zone for the protection of waterbodies and their banks outside of settlements.

Gkl	Gewässer	waterbody	waterbody	wat	Area of big streams and lakes.
Wa	Wald	forest	forest	for	Forest, only forest-related facilities allowed.
M	Materialabbau und Rekultivierung	mining and recultivation zone	mining and recultivation zone	min	Area where the mining of sand, gravel, and clay is allowed, including the following recultivation.
DZ	Deponiezone	dumping ground	dumping ground	dum	Area where the dumping of sand, gravel, and clay is allowed.
kNPDG	Kantonaler Nutzungsplan über die Dekrete	protection area by cantonal decree	protection area by cantonal decree	pde	Protected landscapes according to cantonal decrees.
wG	Weiteres übriges Gemeindegebiet	other municipal area	other municipal area	oth	Areas that are not yet allocated to a zone because of their uniqueness.

Figure A2: Comparison of the land-use and zonal uses in the study area to illustrate the different classification systems. For an explanation of the zone abbreviations refer to Table A2.



Maps credits and data sources: Esri, Intermap, METI/NASA, NGA, USGS, swisstopo, HERE, Garmin, GeoTechnologies Inc, Kanton Aargau (2022)

Appendix for Chapter 3.1

Table A3: Modelled areas for different numbers of species co-occurring.

modelled area with	**modelled area (m^2)**	**share of study area**
min 4 species	19’866’954	20.60%
min 5 species	14’561’314	15.10%
min 6 species	8’861’299	9.19%
min 7 species	4’710’036	4.88%
min 8 species	1’111’256	1.15%
min 9 species	346’762	0.36%

Figure A3: Map of the study area Baden-Brugg with modelled areas where four to nine amphibian species co-occur as well as the permanent amphibian breeding sites of national importance.

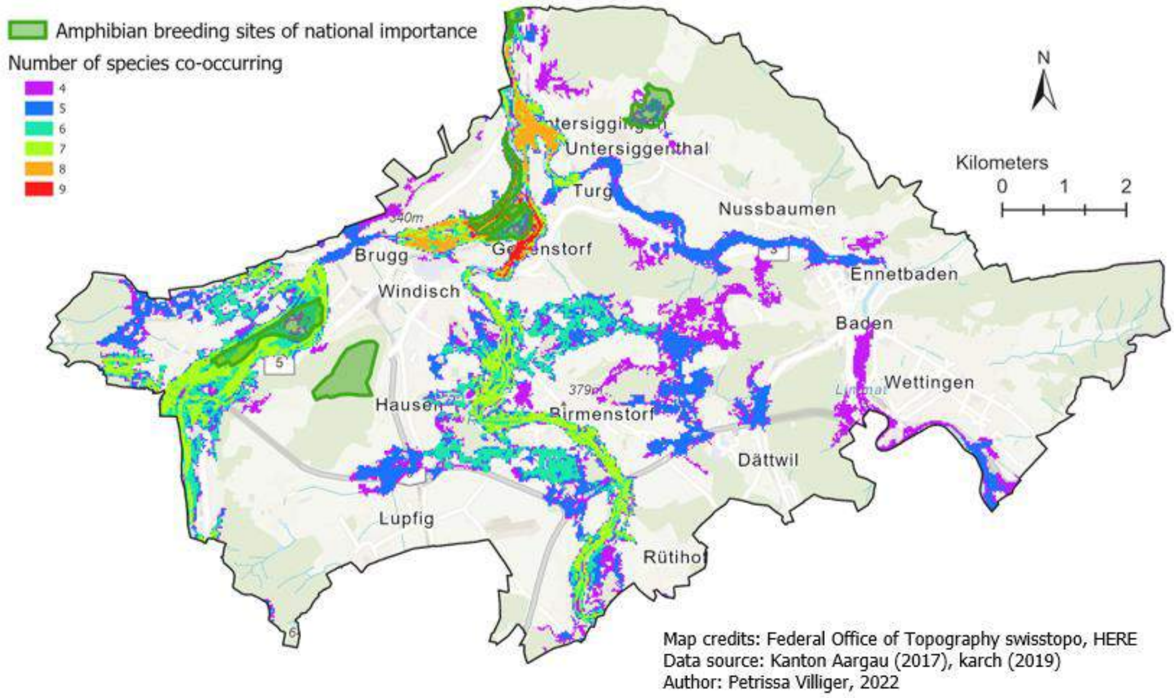
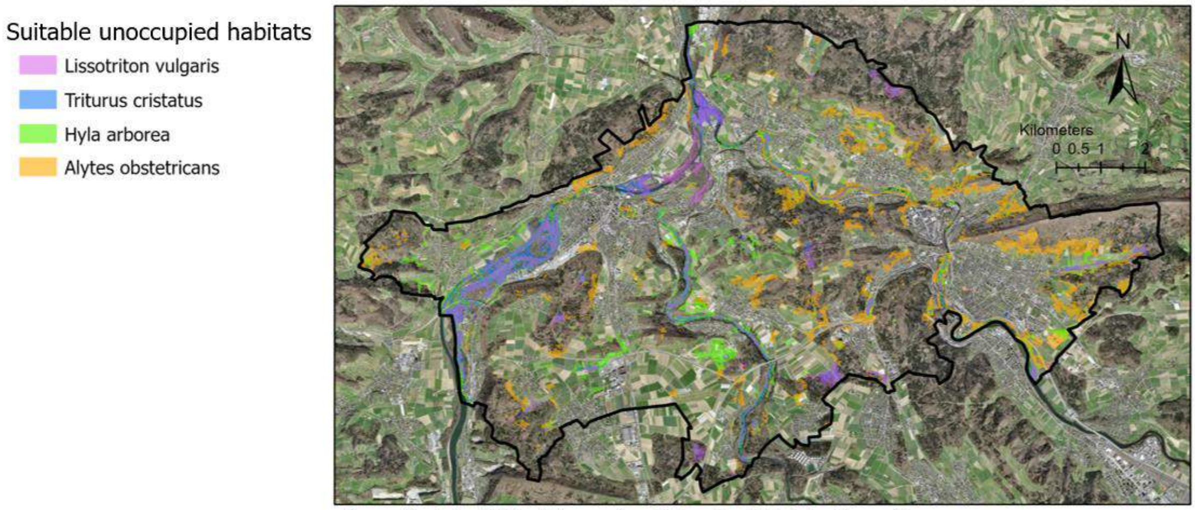


Table A4: Suitable habitat of all examined species in the study area Baden-Brugg (CSA) and the shares of unoccupied suitable habitats.

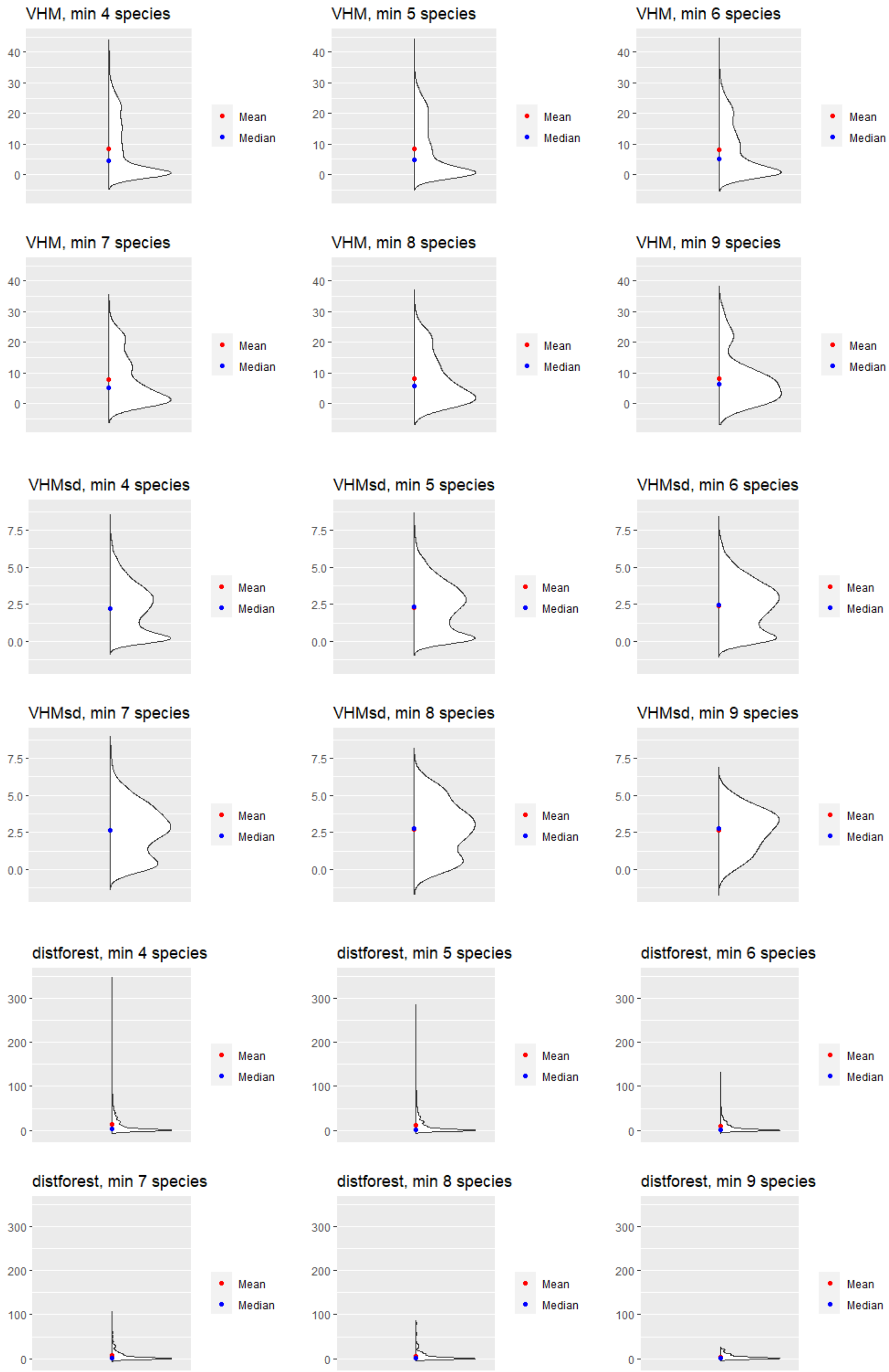
Species name	**suitable habitat total (m^2)**	**suitable habitat, share of CSA**	**suitable habitat unoccupied (m^2)**	**suitable habitat unoccupied, share of CSA**	**suitable habitat unoccupied, share of suitable habitat**
Alytes obstetricans	18’843’800	20%	8’448’738	9%	45%
Bombina variegata	29’061’108	30%	10’331’322	11%	36%
Bufo bufo	51’874’764	54%	3’159’187	3%	6%
Hyla arborea	7’206’250	7%	5’809’349	6%	81%
Ichthyosaura alpestris	37’830’343	39%	8’844’646	9%	23%
Lissotriton helveticus	27’071’691	28%	10’370’823	11%	38%
Lissotriton vulgaris	3’845’967	4%	3’845’967	4%	100%
Rana temporaria	34’480’833	36%	8’883’249	9%	26%
Salamandra salamandra	23’900’833	25%	8’229’686	9%	34%
Triturus cristatus	4’284’069	4%	3’757’089	4%	88%

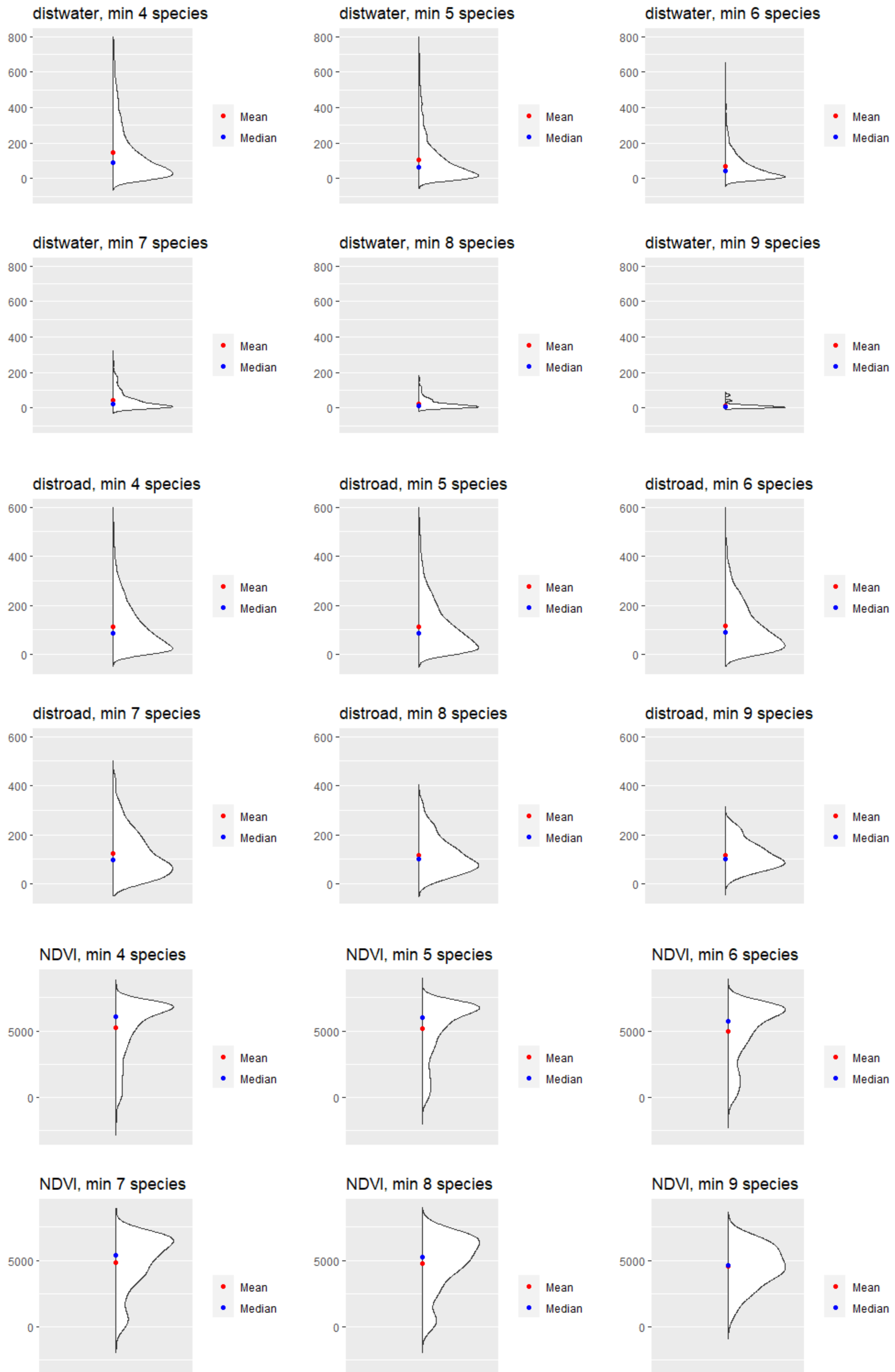
Figure A4: Suitable unoccupied habitats of the four species that can use the least percentages of their suitable habitat in the study area Baden-Brugg according to the model by Donati et al. (2022).

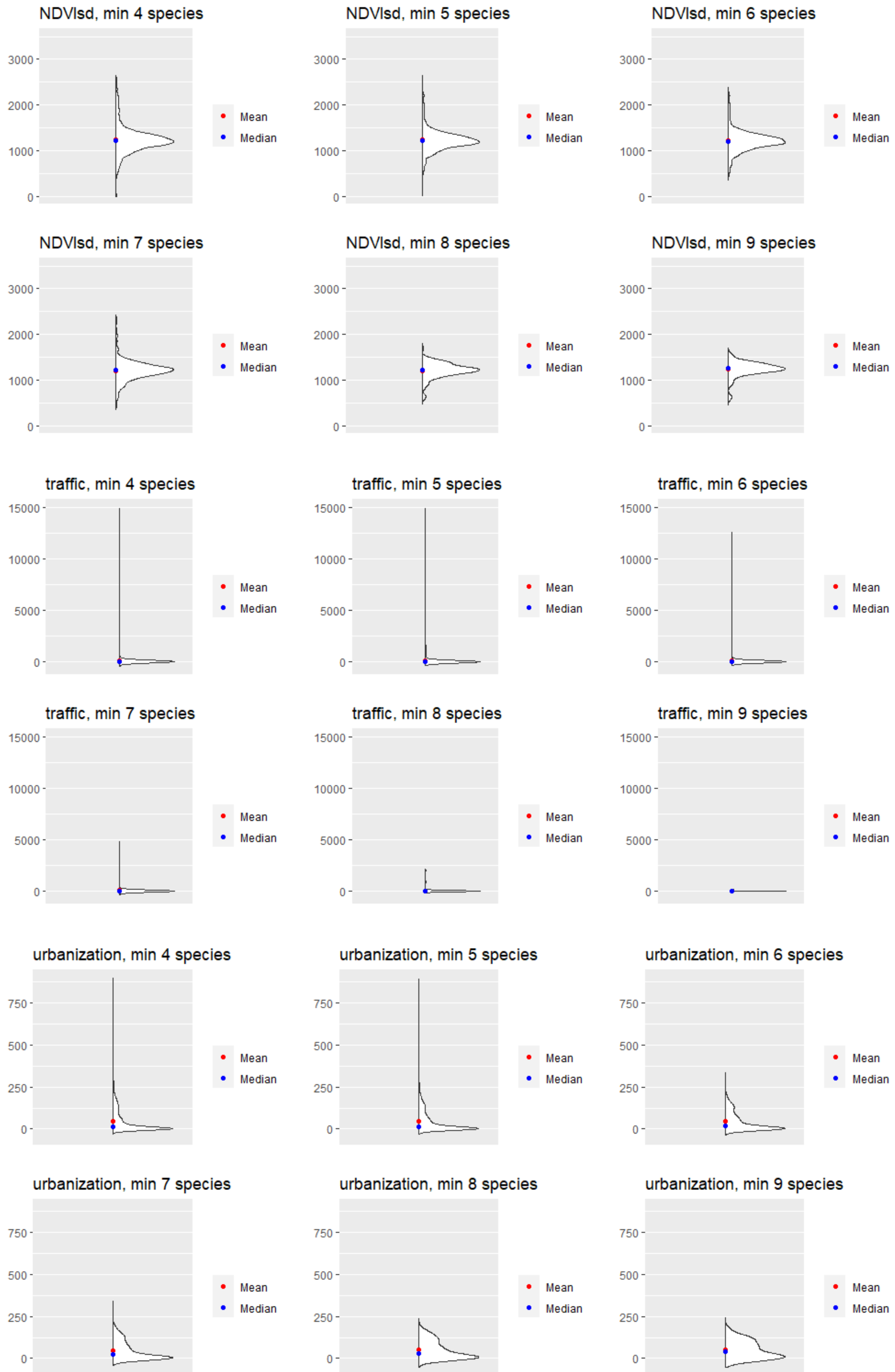


Map credits: Federal Office of Topography swisstopo, Planet, Earthstar Geographics
Data source: Donati et al., 2022

Figure A5: Violin plots of the ten environmental variables in the areas with medium to high species diversity (min. 4 co-occurring species).




distwater, min 4 species
distwater, min 5 species
distwater, min 6 species
distwater, min 7 species
distwater, min 8 species
distwater, min 9 species
800
600
400
200
0
distroad, min 4 species
distroad, min 5 species
distroad, min 6 species
distroad, min 7 species
distroad, min 8 species
distroad, min 9 species
600
400
200
0
NDVI, min 4 species
NDVI, min 5 species
NDVI, min 6 species
NDVI, min 7 species
NDVI, min 8 species
NDVI, min 9 species
5000
0
Mean
Median


NDVIsd, min 4 species
NDVIsd, min 5 species
NDVIsd, min 6 species
NDVIsd, min 7 species
NDVIsd, min 8 species
NDVIsd, min 9 species
0
1000
2000
3000
traffic, min 4 species
traffic, min 5 species
traffic, min 6 species
traffic, min 7 species
traffic, min 8 species
traffic, min 9 species
0
5000
10000
15000
urbanization, min 4 species
urbanization, min 5 species
urbanization, min 6 species
urbanization, min 7 species
urbanization, min 8 species
urbanization, min 9 species
0
250
500
750
Mean
Median

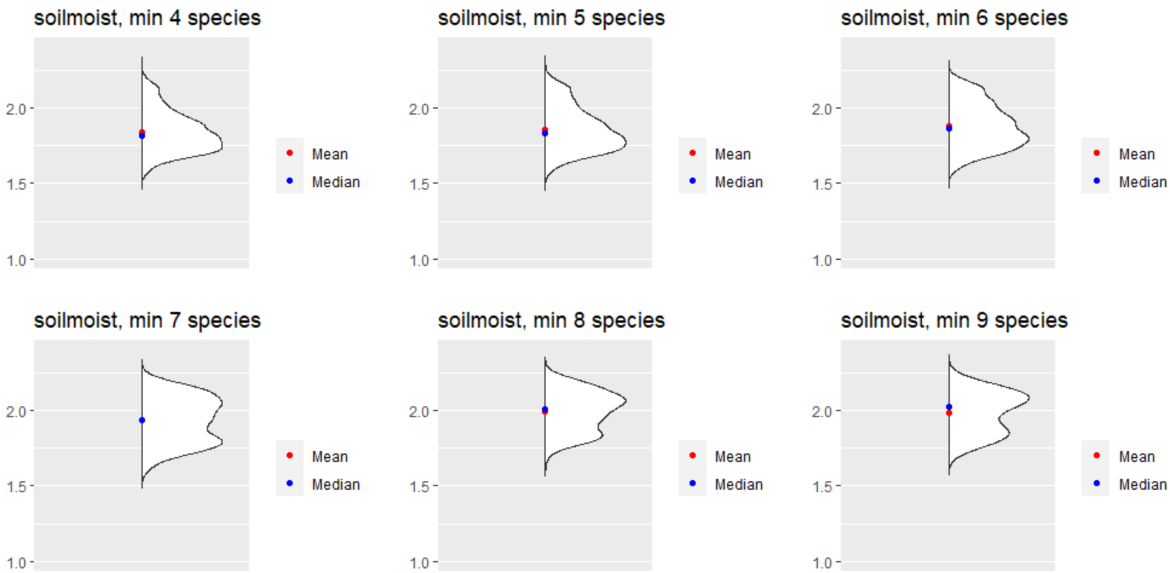
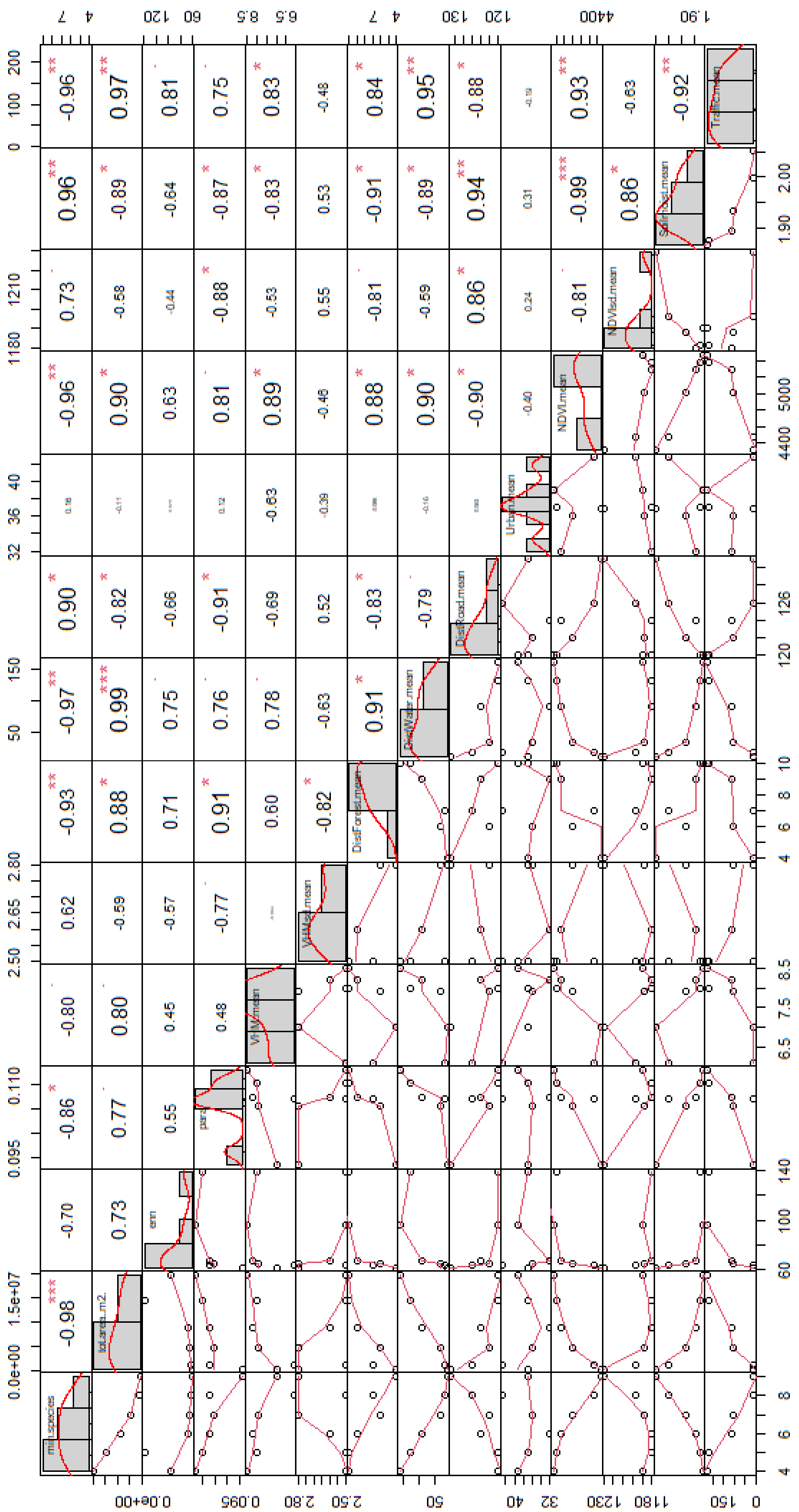

soilmoist, min 4 species
soilmoist, min 5 species
soilmoist, min 6 species
soilmoist, min 7 species
soilmoist, min 8 species
soilmoist, min 9 species
2.0
1.5
1.0
Mean
Median

*Figure A6: Pearson correlation matrix for patch metrics, environmental variables, and number of species co-occurring. The distribution of each variable is shown on the diagonal. On the bottom of the diagonal are the bivariate scatter plots displayed and on the top of the diagonal the correlation coefficients plus the significance level as stars: The p-values (0, 0.001, 0.01, 0.05, 0.1, 1) are associated with the symbols (“***”, “**”, “*”, “.”, " “).*

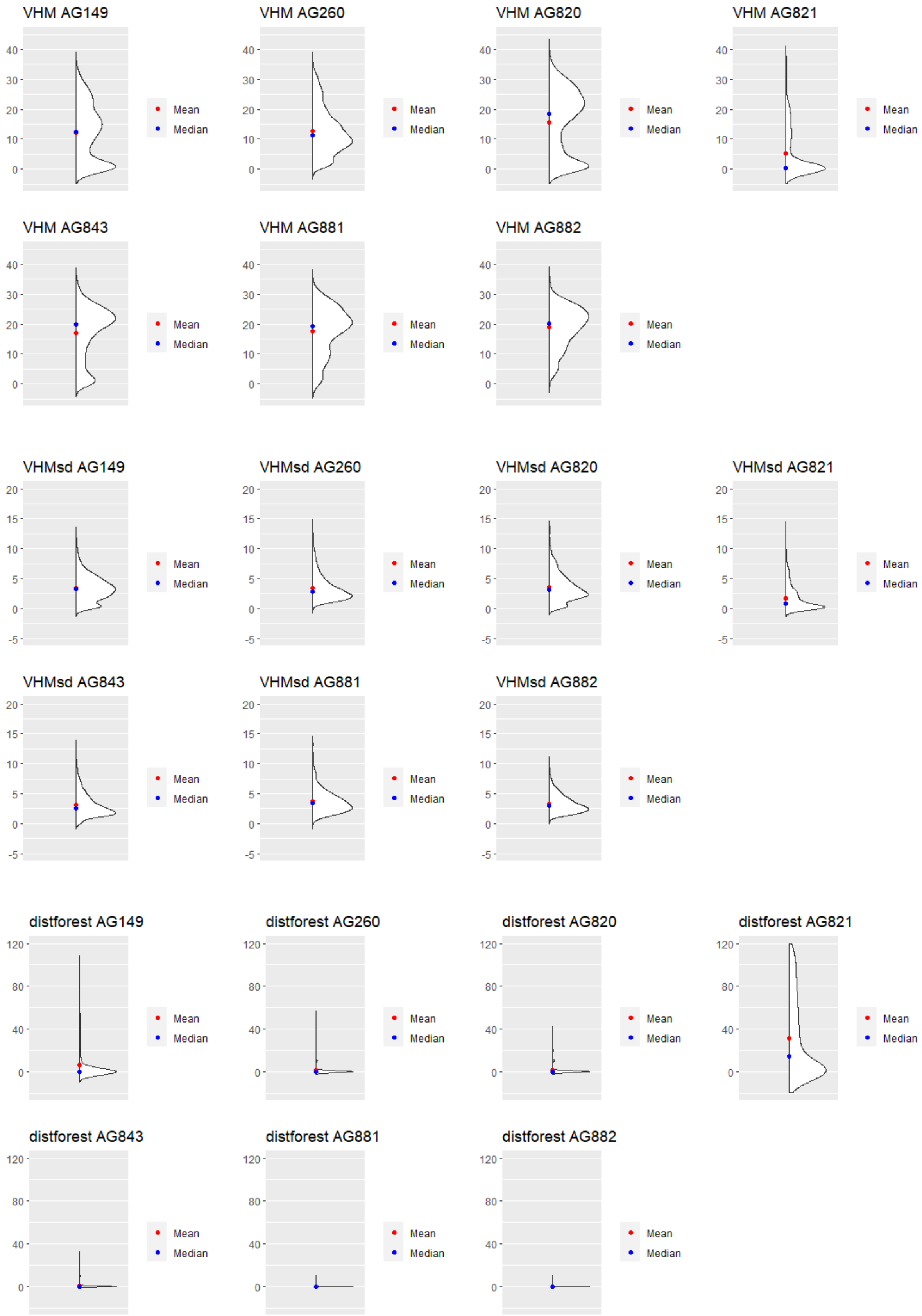


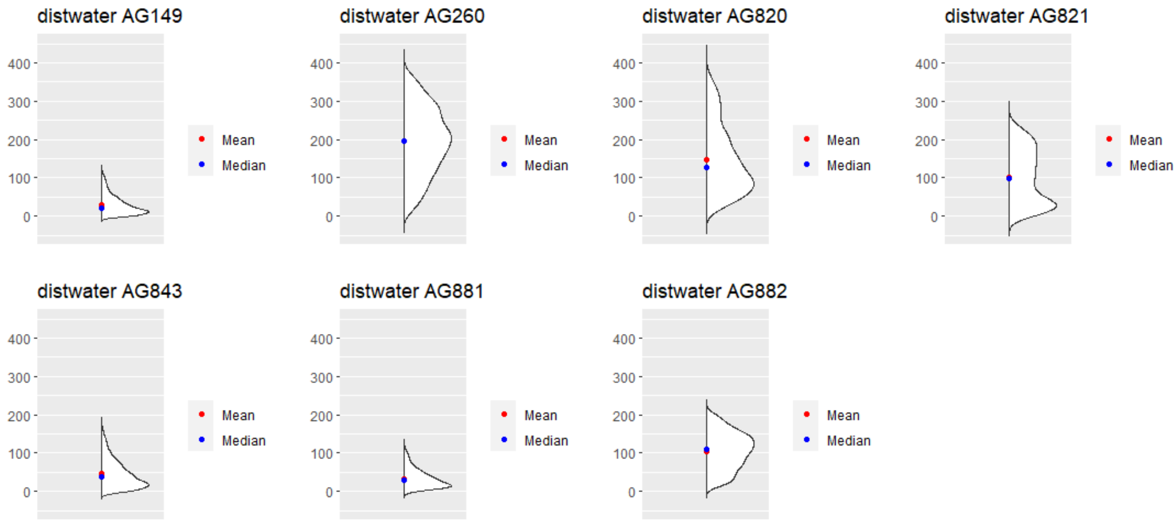
Appendix for Chapter 3.2

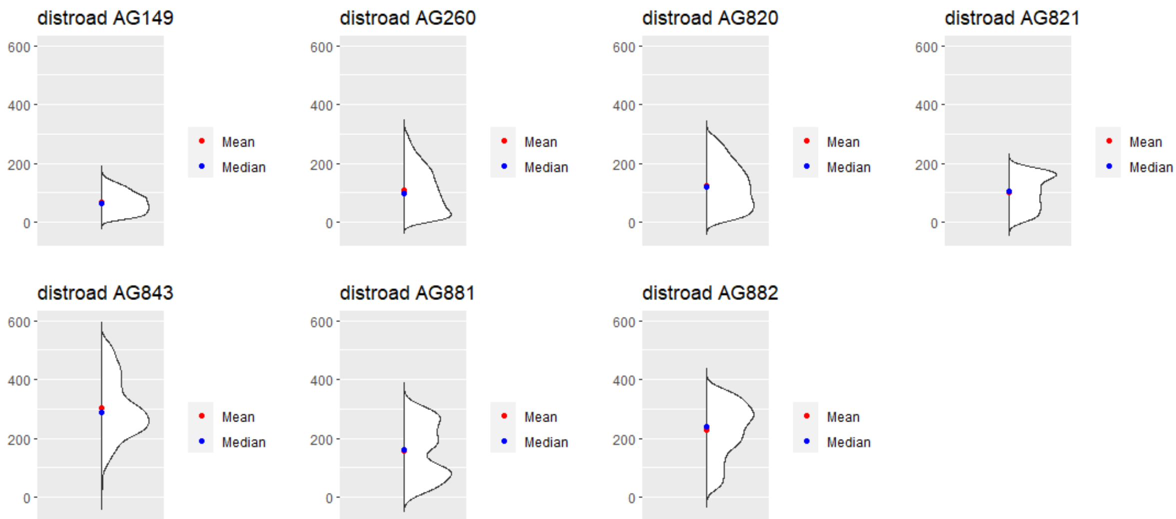
Table A5: Comparison of amphibian species occurrence in six permanent amphibian breeding sites of national importance in the study area Baden-Brugg. Three species are not considered in the table since they are missing in either the survey from FOEN (2001) or the model from Donati et al. (2022): Salamandra Salamandra, Epidalea calamita, Pelophylax sp. The names of the species that either re-colonized a site or disappeared from one are in bold italics.

Amphibian breeding site	Species according to survey 2001	Species based on model 2022
AG149	*Bombina variegata* *Bufo bufo* *Hyla arborea* *Ichthyosaura alpestris* *Lissotriton helveticus* *Rana temporaria* *Triturus cristatus*	***Alytes obstetricans*** *Bombina variegata* *Bufo bufo* *Hyla arborea* *Ichthyosaura alpestris* *Lissotriton helveticus* *Rana temporaria* *Triturus cristatus*
AG260	*Bufo bufo* ***Ichthyosaura alpestris*** ***Lissotriton helveticus*** ***Rana temporaria***	*Bufo bufo*
AG820	*Alytes obstetricans* *Bufo bufo* *Ichthyosaura alpestris* *Rana temporaria*	*Alytes obstetricans* *Bufo bufo* *Ichthyosaura alpestris* *Rana temporaria*
AG882	*Bombina variegata* *Bufo bufo* *Ichthyosaura alpestris* *Lissotriton helveticus* *Rana temporaria* *Triturus cristatus*	***Alytes obstetricans*** *Bombina variegata* *Bufo bufo* ***Hyla arborea*** *Ichthyosaura alpestris* *Lissotriton helveticus* *Rana temporaria* *Triturus cristatus*
AG843	*Alytes obstetricans* *Bombina variegata* *Bufo bufo* *Ichthyosaura alpestris* *Lissotriton helveticus* *Rana temporaria*	*Alytes obstetricans* *Bombina variegata* *Bufo bufo* *Ichthyosaura alpestris* *Lissotriton helveticus* *Rana temporaria*
AG881	*Bombina variegata* *Ichthyosaura alpestris* *Lissotriton helveticus* ***Lissotriton vulgaris*** *Rana temporaria* *Triturus cristatus*	***Alytes obstetricans*** *Bombina variegata* ***Bufo bufo*** ***Hyla arborea*** *Ichthyosaura alpestris* *Lissotriton helveticus* *Rana temporaria* *Triturus cristatus*

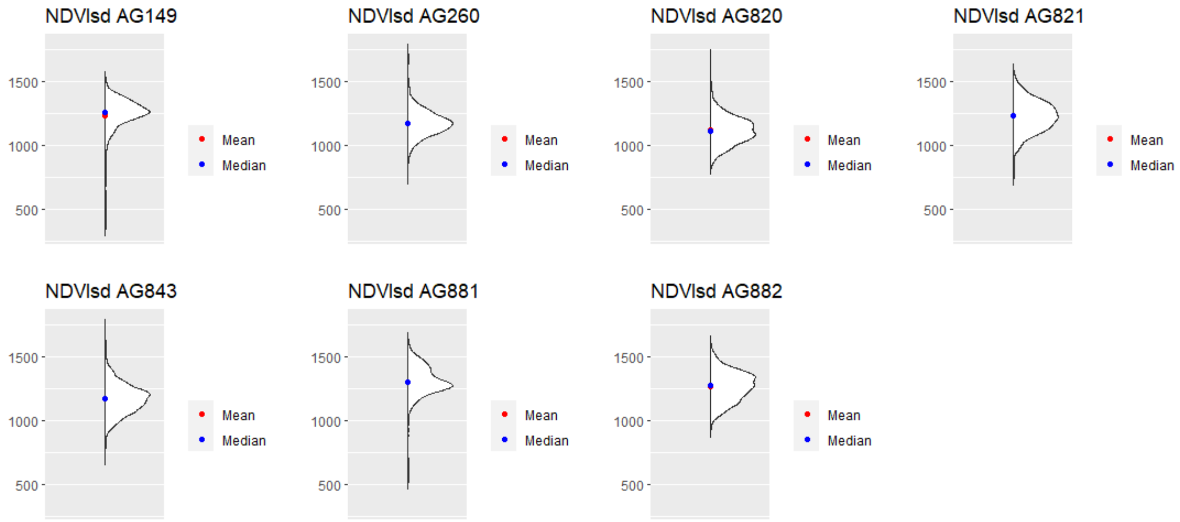
Figure A7: Violin plots of the ten environmental variables for the amphibian breeding sites of national importance in the study area Baden-Brugg.

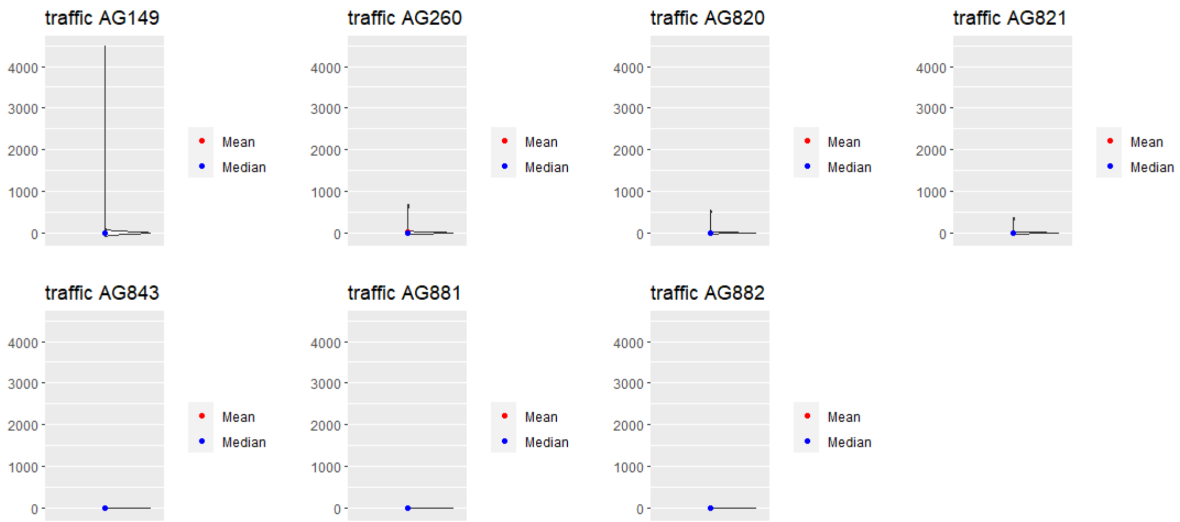


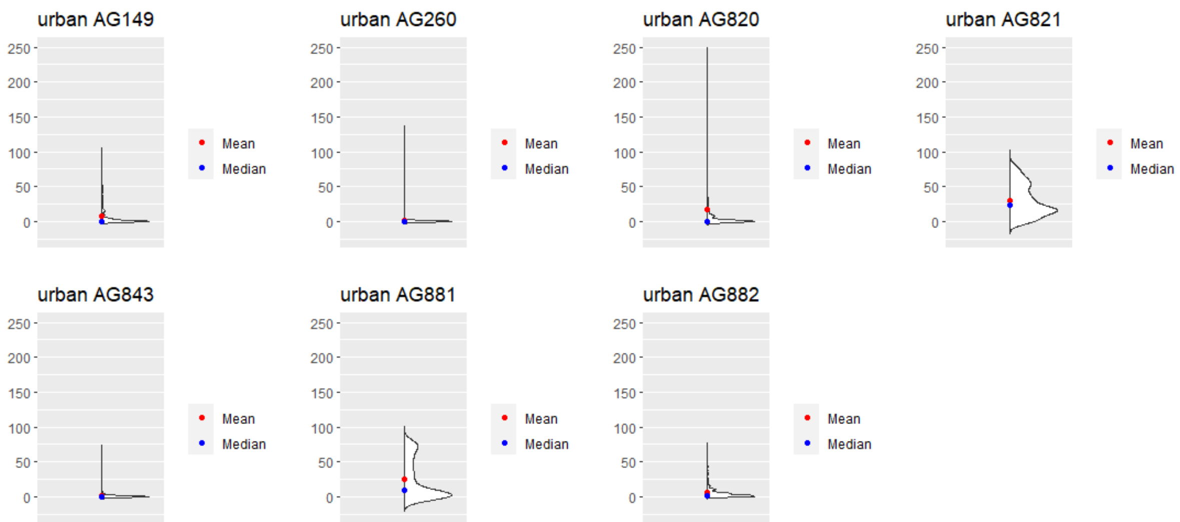

distwater AG149
distwater AG260
distwater AG820
distwater AG821
distwater AG843
distwater AG881
distwater AG882
0
100
200
300
400
Mean
Median


distroad AG149
distroad AG260
distroad AG820
distroad AG821
distroad AG843
distroad AG881
distroad AG882
0
200
400
600
Mean
Median


NDVI AG149
NDVI AG260
NDVI AG820
NDVI AG821
NDVI AG843
NDVI AG881
NDVI AG882
0
2000
4000
6000
8000
Mean
Median


NDVIsd AG149
NDVIsd AG260
NDVIsd AG820
NDVIsd AG821
NDVIsd AG843
NDVIsd AG881
NDVIsd AG882
1500
1000
500
Mean
Median


traffic AG149
traffic AG260
traffic AG820
traffic AG821
traffic AG843
traffic AG881
traffic AG882
4000
3000
2000
1000
0
Mean
Median


urban AG149
urban AG260
urban AG820
urban AG821
urban AG843
urban AG881
urban AG882
250
200
150
100
50
0
Mean
Median

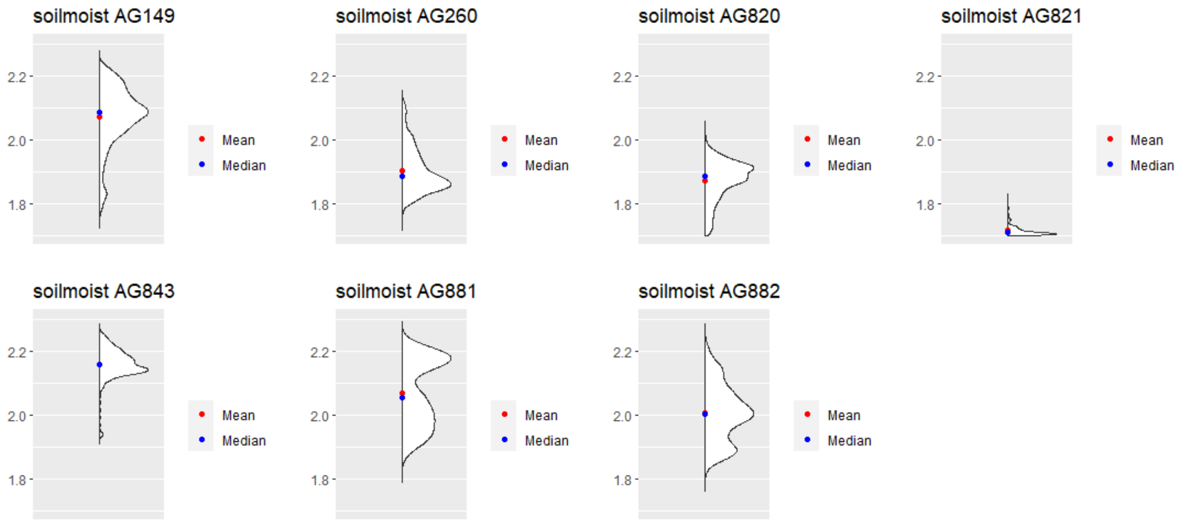
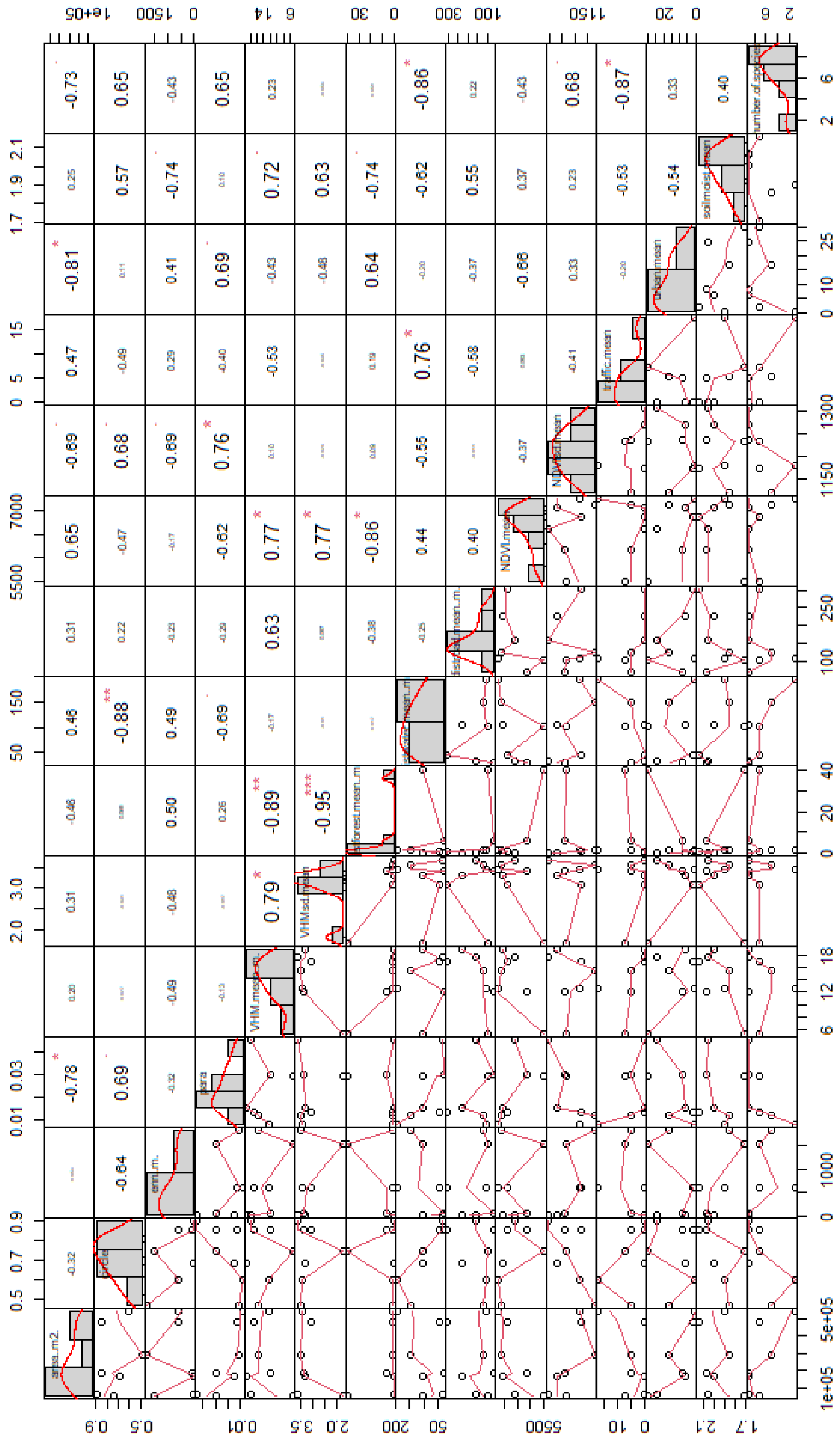

soilmoist AG149
soilmoist AG260
soilmoist AG820
soilmoist AG821
soilmoist AG843
soilmoist AG881
soilmoist AG882
2.2
2.0
1.8
Mean
Median

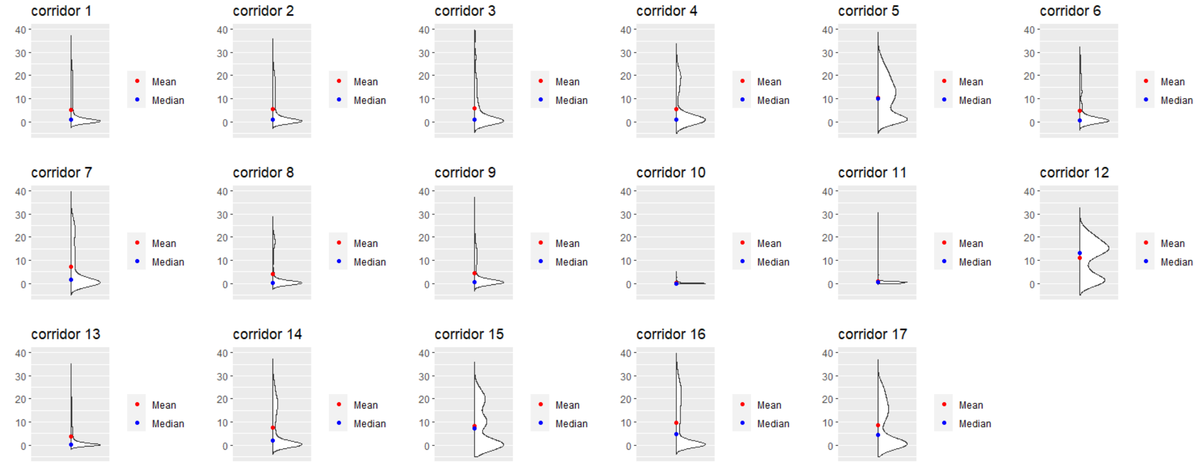
*Figure A8: Pearson correlation matrix for patch metrics, environmental variables, and number of species for the amphibian breeding sites of national importance. The distribution of each variable is shown on the diagonal. On the bottom of the diagonal are the bivariate scatter plots displayed and on the top of the diagonal the correlation coefficients plus the significance level as stars: The p-values (0, 0.001, 0.01, 0.05, 0.1, 1) are associated with the symbols (“***”, “**”, “*”, “.”, " “).*



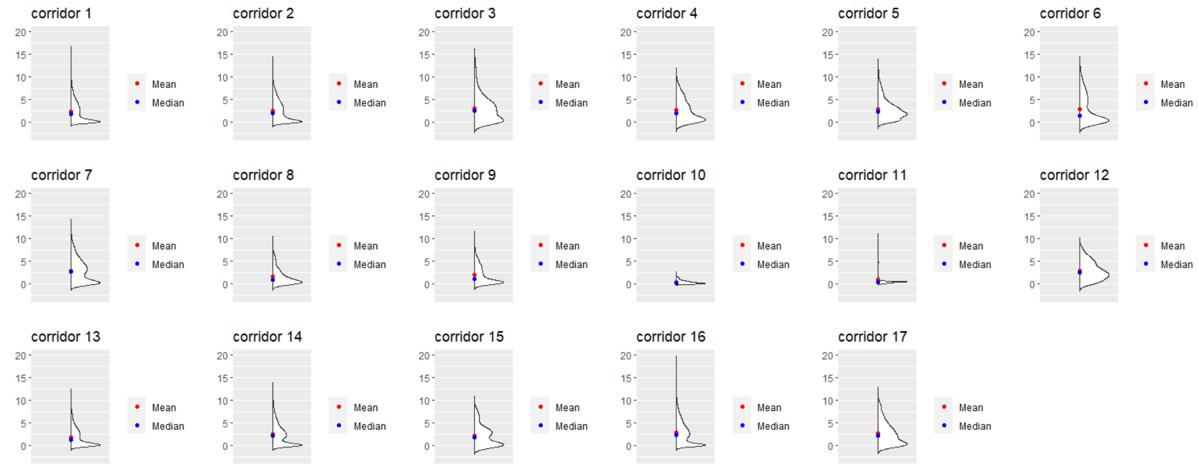
Appendix for Chapter 3.3

Figure A9: Violin plots of the ten environmental variables for the identified connectivity corridors in the study area Baden-Brugg.

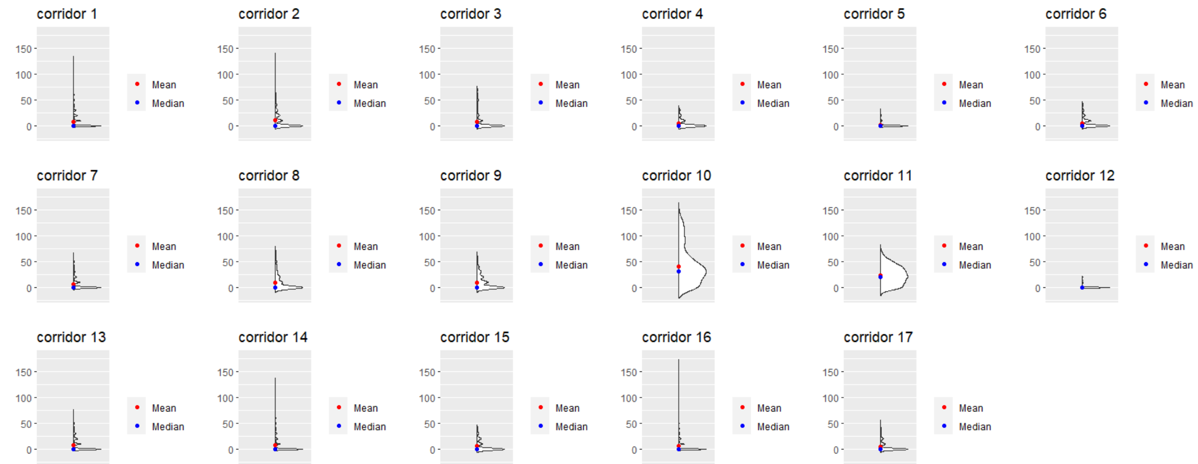
VHM



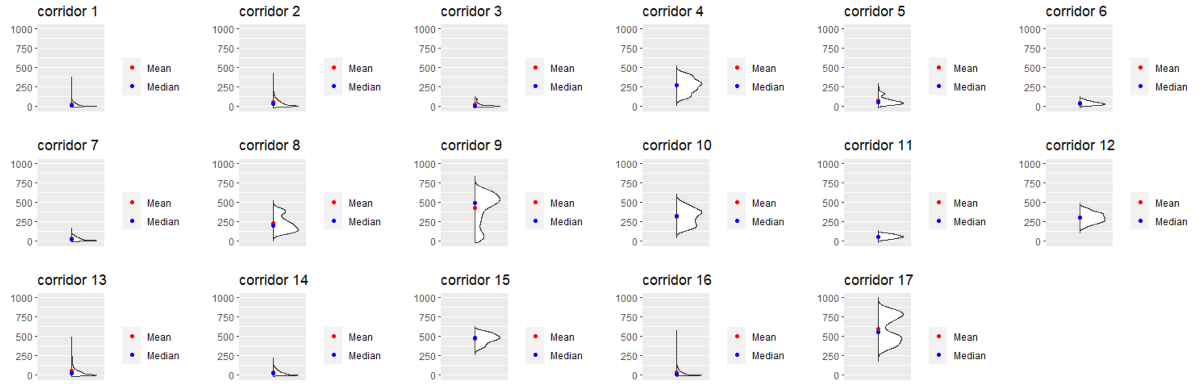
VHMsd



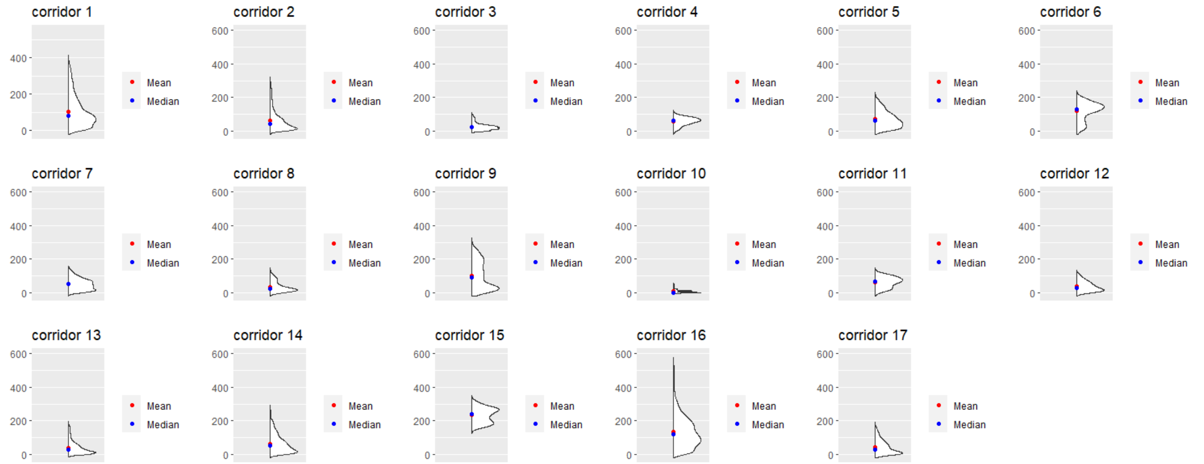
distforest



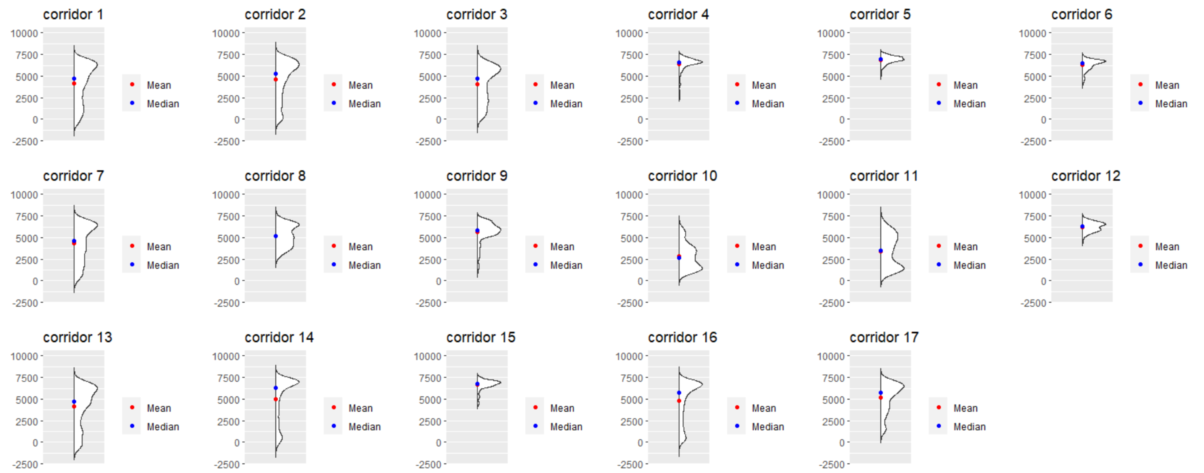
distwater



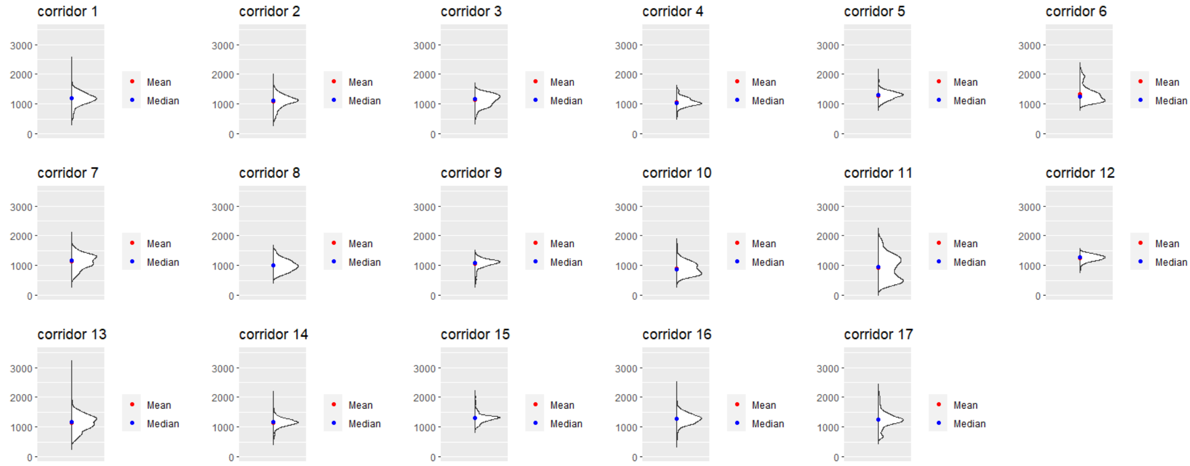
distroad



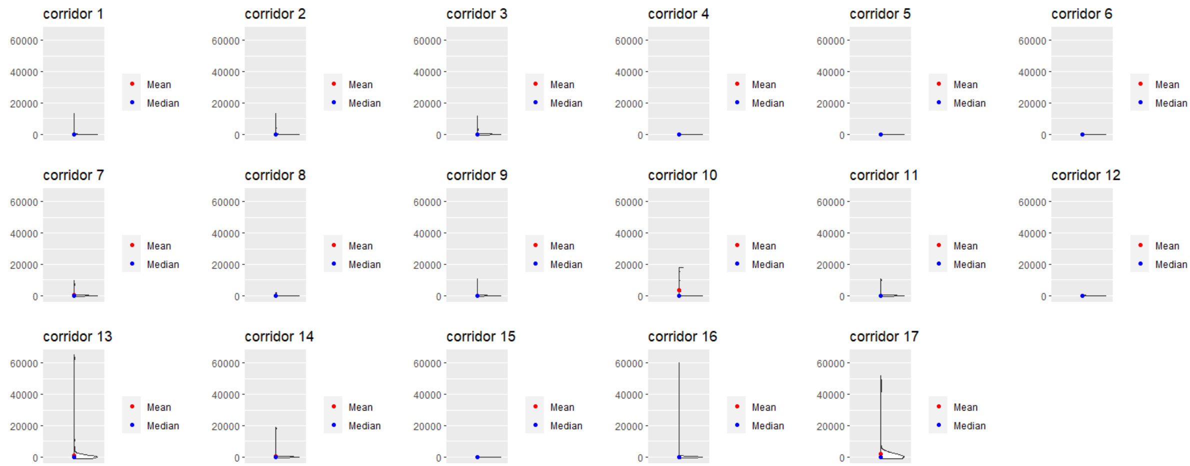
NDVI



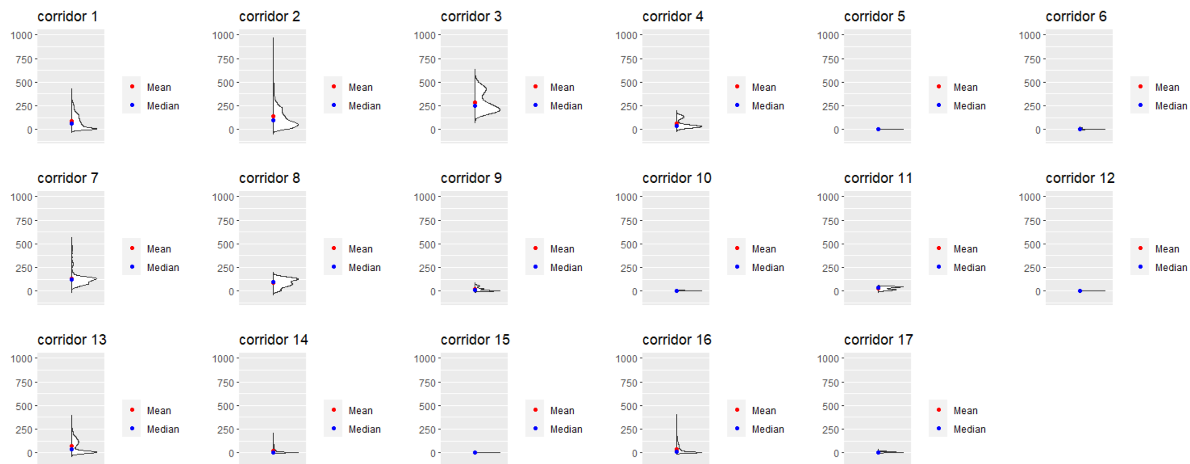
NDVIsd



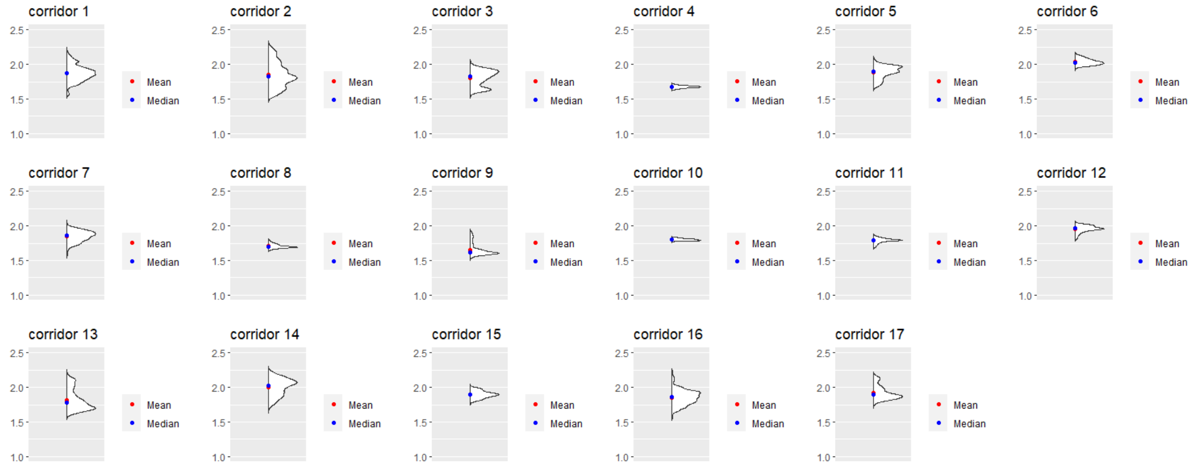
traffic



urban



soilomoist


corridor 1
corridor 2
corridor 3
corridor 4
corridor 5
corridor 6
corridor 7
corridor 8
corridor 9
corridor 10
corridor 11
corridor 12
corridor 13
corridor 14
corridor 15
corridor 16
corridor 17
2.5
2.0
1.5
1.0
Mean
Median

Appendix: Declaration of Originality

ETH

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Declaration of originality

The signed declaration of originality is a component of every semester paper, Bachelor's thesis, Master's thesis and any other degree paper undertaken during the course of studies, including the respective electronic versions.

Lecturers may also require a declaration of originality for other written papers compiled for their courses.

I hereby confirm that I am the sole author of the written work here enclosed and that I have compiled it in my own words. Parts excepted are corrections of form and content by the supervisor.

Title of work (in block letters):

Assessment of Blue-Green Areas to promote amphibian species diversity in the Baden-Brugg area

Authored by (in block letters):
For papers written by groups the names of all authors are required.

Name(s):	First name(s):
Villiger	Petrissa Alexandra

With my signature I confirm that
- I have committed none of the forms of plagiarism described in the 'Citation etiquette' information sheet.
- I have documented all methods, data and processes truthfully.
- I have not manipulated any data.
- I have mentioned all persons who were significant facilitators of the work.

I am aware that the work may be screened electronically for plagiarism.

Place, date
Auw, 21.06.2022

Signature(s)
P. Villiger