Habitat patch size and breeding site quality drive relative abundance of *Ambystoma* salamander larvae

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Abstract

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Biodiversity loss can arise from a range of factors, and amphibians are particularly vulnerable to these threats. On Pelee Island, *Ambystoma* salamanders form an assemblage comprised of parental species (*Ambystoma texanum, A. laterale*) and unisexual salamanders that act as reproductive parasites. This thesis explores ecological drivers of relative abundance in *Ambystoma* salamanders by examining terrestrial and aquatic habitat quality, patch size and isolation. I sampled 34 breeding sites across wetland and forest habitats on the island using dipnet surveys and tested for correlations between catch-per-unit-effort of salamander larvae and a suite of environmental variables (habitat quality, isolation, and surrounding landscape composition). I found that relative abundance of salamander larvae is influenced by the additive effects of aquatic habitat quality and size of the terrestrial habitat patch that the breeding site is located within. No effects of patch connectivity on larval abundance were detected. My results underscore the importance of both high-quality breeding sites and large patches of surrounding forested area in determining *Ambystoma* larvae abundance.

Keywords: Amphibian, habitat fragmentation, salamanders, habitat suitability, biodiversity conservation, metapopulation dynamics, ecological connectivity, anthropogenic impacts

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Chapter 1: General Introduction

Ecological Drivers of Population Density and Abundance

Biodiversity is critical for maintaining ecosystem stability and functionality but is increasingly imperiled by anthropogenic pressures. Habitat degradation and fragmentation are particularly notable drivers of biodiversity loss, and these processes reduce availability of suitable habitats and increase isolation among populations, disrupting ecological interactions and ecosystem resilience (Fahrig, 2003; Haddad et al., 2015). Habitat fragmentation reduces connectivity, impedes gene flow, and lowers genetic diversity, making populations more vulnerable to stochastic events and environmental changes (Hanski, 1998; Ewers & Didham, 2006). Species with specialized habitat needs or limited dispersal capacities are disproportionately affected, as fragmented landscapes exacerbate their inability to locate new resources or breeding grounds (Fischer & Lindenmayer, 2007), and they have limited ability to adjust to newly fragmented environments (Ewers & Didham, 2006). These consequences can ripple through ecosystems by reducing biodiversity, altering interspecific interactions, and undermining system-level dynamics (Fischer & Lindenmayer, 2007; Watson et al., 2014). Fragmented habitats often fail to support species that rely on larger, contiguous landscapes, often leading to local extinctions and ecosystem instability (Fahrig, 2003). The severity of these effects may depend on habitat quality, patch size, and the degree of isolation, but the role of these factors, both individually and in tandem, remains poorly understood for many organisms.

The impacts of habitat loss and fragmentation are particularly severe for amphibians, which are highly sensitive to a variety of changes due to their strong reliance on both aquatic and terrestrial environments (Semlitsch, 2000; Gagné & Fahrig, 2007).

Amphibians in human-dominated landscapes face especially demanding challenges because, for instance, small or isolated breeding pools may not support diverse amphibian communities (Laan & Verboom, 1990; Houlahan & Findlay, 1999). Landscape composition, including configuration of forests and agricultural areas, further influences amphibian distributions (Houlahan et al., 1999; Herrmann et al., 2005), and in agricultural landscapes in particular, habitat patches surrounded by intensive land use are rarely used by amphibians (Gagné & Fahrig, 2007). Whereas small pool sizes and breeding site isolation have been shown to contribute to population instability (Laan & Verboom, 1990; Semlitsch, 2000). Efforts to restore breeding habitats and establish connectivity between isolated patches have proven essential for some species (Crawford et al., 2019). These approaches are particularly relevant for amphibian conservation on Pelee Island, Ontario, as maintaining connectivity between aquatic and terrestrial habitats is vital for sustaining their *Ambystoma* salamander populations. Furthermore, understanding the species-specific responses to landscape changes that *Ambystoma* salamanders on Pelee Island face, and incorporating this knowledge into land-use planning can help minimize biodiversity loss and promote ecosystem health in increasingly human-dominated landscapes (Parris, 2006; Semlitsch, 2000).

Ecological Determinants of Density in Pond-Breeding Amphibians

The quality, size, and spatial arrangement of both aquatic and terrestrial habitats are factors that play critical roles in determining population density and the long-term viability of amphibian populations. The unique dual dependency on aquatic environments for breeding and terrestrial habitats for foraging and overwintering makes *Ambystoma* salamanders on Pelee Island, ON, particularly sensitive to habitat quality and landscape structure (Semlitsch, 2000; Hamer & Parris, 2011). The quality of aquatic habitats is a primary determinant of amphibian population density (Marsh, Fegraus, & Harrison, 2001, Moor, et al., 2024), with key factors including water quality, vegetation cover, and the absence of pollutants or invasive predators. High-quality ponds support greater larval survival and recruitment, which are crucial for sustaining populations (Hamer & McDonnell, 2008; Scheffers & Paszkowski, 2012). Terrestrial habitat quality is equally important, as amphibians often rely on adjacent forested areas for food and shelter. Degraded terrestrial habitats, resulting from deforestation or urbanization, can limit survival during non-breeding periods and reduce overall population density (Gagné & Fahrig, 2007). Amphibians in landscapes with high-quality terrestrial habitats often exhibit higher densities due to the availability of refuge and feeding opportunities (Rittenhouse & Semlitsch, 2007).

Understanding how aquatic breeding site quality, terrestrial habitat characteristics, and site isolation influence salamander populations is crucial for effective conservation planning. Factors such as water quality, hydroperiod, and vegetation structure in breeding ponds significantly affect the development and survival of amphibian larvae (Semlitsch & Bodie, 2003; Skelly et al., 1999). Terrestrial habitat characteristics, including forest cover, soil moisture, pond size and terrestrial habitat size are critical for post-breeding adult survival and dispersal as they can support more individuals and reduce competition for resources (Richter et al., 2003; Cushman, 2006; Anderson et al., 2015). Pond-breeding amphibians often exist as metapopulations, providing a buffer against local extinctions by enabling recolonization from neighboring populations (Marsh & Trenham, 2001). Isolated habitat patches, often a result of habitat fragmentation, restrict dispersal and lead to genetic bottlenecks, which can reduce population resilience to environmental change (Marsh & Trenham, 2001; Fahrig, 2003; Gibbs, 1998). Amphibians in highly fragmented landscapes often exhibit reduced metapopulation stability due to limited dispersal and lower colonization rates (Cushman, 2006; Scheffers & Paszkowski, 2012). Research on habitat fragmentation has consistently demonstrated its role in reducing population sizes and limiting species distributions, particularly for organisms with complex life cycles like amphibians (Fahrig, 2003; Cushman, 2006; Hammer and Paris, 2011). By analyzing how these habitat features interact to shape salamander distribution and abundance, conservation strategies can be designed to mitigate the adverse effects of habitat loss and fragmentation, ensuring long-term population viability (Semlitsch, 2000; Cushman, 2006).

Study System: Pelee Island and Its Salamander Assemblage

Pelee Island, situated in Lake Erie, Ontario, Canada, serves as an ideal natural laboratory to explore the effects of habitat fragmentation on amphibian populations. Its diverse landscape comprises a mosaic of natural and human-made wetlands interspersed with agricultural fields and urbanized areas. This arrangement provides a spectrum of habitat patches differing in size and isolation, enabling investigations into how ecological dynamics function in fragmented systems (Fahrig, 2003; Cushman, 2006). The focus of this study is the relative abundance of *Ambystoma* salamander larvae across the island's wetland habitats. Salamanders in the genus *Ambystoma*—comprising 33 species widely distributed across North America—are obligate aquatic breeders. Most species depend on temporary or permanent ponds and wetlands for reproduction while spending the majority of their lives in terrestrial habitats.

Thesis Objectives

By combining environmental data and relative abundance data collected from field surveys in 34 wetlands across Pelee Island, with spatial data from land classification layers, I seek to identify the key environmental variables that predict the abundance of larval *Ambystoma* salamanders across a human-dominated landscape. Specifically, I employ a model selection framework using Akaike Information Criterion corrected (AICc) to test competing hypotheses that could explain the observed spatial variation in relative abundance. The research question I seek to answer is what determines the relative abundance of *Ambystoma* salamander larvae in breeding sites across a human-dominated landscape which gives rise to three hypotheses. The first hypothesis is that aquatic habitat suitability alone influences relative abundance of *Ambystoma* larvae at a given site. If this hypothesis is supported, I predict that sites with higher aquatic habitat suitability (e.g., large fishless ponds with high canopy cover around the margins) will have a higher relative abundance of *Ambystoma* larvae than sites with low aquatic habitat suitability (e.g., small ponds with low canopy cover around the margin, presence of fish, etc.). The second hypothesis is that terrestrial habitat suitability alone influences relative abundance of salamander larvae at a given site. If this hypothesis is supported, I predict that sites with higher terrestrial habitat suitability (i.e., larger patches of suitable terrestrial habitat, greater proportion of forest and wetland cover, etc.) will have a higher relative abundance of *Ambystoma* larvae than sites with lower terrestrial habitat suitability (i.e., smaller patches of suitable terrestrial habitat, lower proportion of forest and wetland cover in the surrounding area, etc.). Finally, the third hypothesis is that the interaction between both aquatic and terrestrial habitat variables will influence the relative abundance of salamander larvae at a given site. If this hypothesis is supported, I predict that sites with both high aquatic and terrestrial habitat suitability (i.e., large fishless ponds with high canopy cover embedded in larger patches of terrestrial habitat, etc.) will have a higher relative abundance of *Ambystoma* larvae than sites that do not have high values of both measures of suitability (i.e., small ponds with low canopy cover embedded in smaller patches of terrestrial habitat, etc.). The findings from this research will contribute to the broader understanding of amphibian ecology and inform conservation strategies aimed at preserving these important species in fragmented landscapes.

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Chapter 2: Habitat patch size and breeding site quality drive relative abundance of *Ambystoma* salamander larvae

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Abstract

Amphibian biodiversity is in global decline, driven primarily by habitat loss and fragmentation arising from landcover alteration. For pond-breeding amphibians, larval abundance should be governed by aquatic breeding site quality, surrounding terrestrial habitat characteristics, and proximity to neighbouring populations. If safeguarding salamander populations is a priority, conservation efforts will benefit from understanding the relative importance of each feature on salamander populations. I sought to identify the factors associated with relative abundance of *Ambystoma* salamander larvae across habitat patches on Pelee Island, Ontario, Canada. Larval density and a suite of environmental variables were measured at 34 breeding sites across the island. Using spatial analysis, I also determined landcover features surrounding the breeding site, including, terrestrial habitat type, terrestrial patch size, and indices of isolation (e.g., nearest neighbour distance, proximity index). The relative abundance of *Ambystoma* larvae was best predicted by additive effects of breeding site quality (e.g., canopy cover, submergent vegetation, and cooler water temperature) and size of surrounding terrestrial habitat patches. I did not detect any influence of agricultural land cover within 300 m of the breeding sites on larval count, implying that *Ambystoma* can persist within agriculture-dominated landscapes provided that high breeding habitat quality is maintained, and ponds are embedded within large forest patches. Further, I failed to detect any impact of breeding site isolation on larval numbers, indicating that local habitat quality and terrestrial patch size more strongly determine larval abundance than patch connectivity. My research highlights the critical importance of conserving high-quality aquatic breeding habitats and maintaining large contiguous patches of terrestrial habitat for amphibian conservation.

Keywords: Amphibian, habitat fragmentation, salamanders, habitat suitability, biodiversity conservation, metapopulation dynamics, ecological connectivity, anthropogenic impacts

Introduction

Habitat loss and fragmentation are major threats to biodiversity worldwide (Hanski, 2011, Wiegand et al., 2005), with many species facing widespread and severe impacts. Amphibians are particularly vulnerable to habitat degradation and loss because of their biphasic life cycle that requires both suitable terrestrial and aquatic habitat (Wood, et al., 2003, Gallant, et al., 2007). Research conducted over the last decade indicates that separation of distinct habitat types required for each life stage (i.e., habitat split) can exacerbate impacts from habitat fragmentation and loss (Fonseca, et al., 2013, Becker, et al., 2023). Conservation efforts focusing exclusively on protecting or rebuilding only aquatic or terrestrial habitats in isolation may therefore be insufficient to adequately support viable populations of many amphibians. Furthermore, many species persist as metapopulations, with individuals occurring within a network of habitat patches that vary in size, quality, and proximity to neighbouring patches (e.g., Heard et al., 2012, but see Smith & Green, 2005). Thus, patterns of local abundance across the landscape may reflect aquatic and terrestrial habitat quality as well as connectivity within the network (Lowe & Bolger, 2002, Petranka et al., 2004). Ultimately, identifying the environmental and biotic influences of among-patch variation in abundance or recruitment success is central to understanding amphibian population viability and planning effective conservation efforts.

Pond-breeding amphibians use aquatic habitats as places to breed, develop as larvae and avoid desiccation or terrestrial predators as adults, and rely on terrestrial habitats for adult survival (Lowe & Bolger, 2002, Drayer et al., 2020). Breeding site quality is impacted by a species-specific set of abiotic and biotic environmental conditions that influence recruitment through their impacts on larval survival and growth (Petranka et al., 2004). Larval *Ambystoma* salamanders are more abundant in ponds with higher canopy cover, more leaf litter in the substrate, more submergent vegetation, and cooler water temperatures (Thompson *et al.*, 1980, Ward and Hossie, 2020). In addition, Lowe and Bolger (2002) found that factors such as fish presence/absence, landscape configuration, and population connectivity explain much variation in Spring salamander (*Gyrinophilus porphyriticus)* abundance. Similar studies on Streamside salamanders (*Ambystoma barbouri*) found that streams without fish had more eggs than streams with fish (Petranka, 1983, Kats and Sih, 1992, Davenport et al., 2017). Yet, successful reproduction is only part of the juvenile recruitment process, and habitat patches must also provide necessary terrestrial habitat to facilitate survival of new metamorphic juvenile and adult salamanders (Dias, 1996, Bodinof Jachowski & Hopkins, 2018). For example, Moor et al. (2024) found that terrestrial habitat conditions such as land cover type, nearest inhabited neighbouring pond, patch connectivity, and breeding site size were crucial for *Ambystoma* salamander survival, meaning that a combination of aquatic and terrestrial habitat features should be necessary to support the biphasic amphibian life cycle and therefore underpin relative abundance of individuals within a habitat patch.

For many amphibians, areas of suitable habitat are patchily distributed across the landscape (Smith & Green, 2005, Greenwald et al., 2009). In theory, larger patches should support larger populations increasing their long-term viability (MacArthur and Wilson, 1976, Whittaker et al., 2017). Additionally, populations in more isolated patches should experience lower immigration rates and have reduced viability because of limited demographic or genetic rescue (Souza et al., 2023, Nunziata et al., 2015). Variation in number of suitable patches may therefore be directly related to terrestrial patch size and isolation (e.g., Greenwald et al., 2009, Thornton et al., 2010). These patterns have been previously observed in amphibians using constructed ponds where increased abundance was associated with population connectivity, closer nearest neighbour distance, larger terrestrial patch and breeding site sizes, and breeding sites surrounded by forest (Moor, et al., 2024).

I sought to identify the landscape factors that influence the relative abundance of salamander larvae in breeding sites for an endangered salamander complex located on an island that has experienced dramatic habitat loss and fragmentation. Specifically, I test three hypotheses that focus on the idea that variation in relative abundance of *Ambystoma* larvae is determined by environmental conditions at the breeding site, the amount of suitable habitat surrounding those breeding sites, and the relative isolation of the breeding site from neighbouring sites. The first hypothesis is that aquatic habitat suitability alone influences relative abundance of salamander larvae at a given site. Based on this hypothesis, I predict that the relative abundance of salamander larvae will be higher in sites with only higher measures of aquatic habitat suitability, such as higher amounts of aquatic vegetation present, absence of aquatic predators, and larger breeding pond surface areas. The second hypothesis I wish to test is that terrestrial habitat suitability alone influences relative abundance of salamander larvae at a given site. To test this hypothesis, I predict that the relative abundance of salamander larvae will be higher at sites with only higher measures of terrestrial habitat suitability, such as a greater amount of surrounding forest and wetland habitats and lower amounts of surrounding agricultural land. The third and final hypothesis that I wish to test is that the interaction between both aquatic and terrestrial habitat variables will influence the relative abundance of salamander larvae at a given site. If this hypothesis is correct, I predict that the relative abundance of salamander larvae will be higher at sites possessing both high quality aquatic and terrestrial habitats, such as fishless ponds with aquatic vegetation and high canopy embedded within large patches of forest.

Methods

Study System:

The study took place on Pelee Island, Ontario, Canada, a 42 km^2 island located in the western basin of Lake Erie (41.7745° N, 82.6591° W). Small-mouthed salamanders (*A. texanum*), blue-spotted salamanders (*A. laterale*), and unisexual *Ambystoma* (*A. laterale-texanum*) form a unique salamander complex involving parental species and unisexual *Ambystoma* that are reproductive parasites of parentals (Hossie, 2018; Bare et al 2023). All three species of *Ambystoma* salamanders on Pelee Island are pond-breeding, with larvae that metamorphose mid-summer and occupy forested terrestrial habitats for their juvenile and adult life stages (Environment and Climate Change Canada, 2020). Despite extensive wetland drainage in the late 1800s spanning nearly half the island, and widespread logging in the 1950-70s (NCC Staff, 2024), these salamanders have persisted in patches of habitat across the island (Figure 1). Since that time several ponds have been constructed in an effort to mitigate the impact of lost breeding habitat, and additional ecosystem-centered habitat remediation has involved construction of larger wetlands and forest regeneration. These efforts could improve both aquatic and terrestrial habitat for salamanders on the island, but wide variation in breeding site occupancy and relative abundance suggests that not all habitat patches on the island are of suitable quality for salamanders (Ward and Hossie, 2020).

Aquatic Habitat & Larval Surveys:

Between May 25 and June 2, 2022, I surveyed 34 waterbodies across the island for *Ambystoma* salamander larvae using a systematic dip-net approach consisting of 80 sweeps per waterbody. Each waterbody was visited a single time, and dip-net sweeps covered all microhabitat types in each pond (Van Buskirk, 2005; Hossie and Ward 2020). The number of larvae captured was converted to catch per unit effort (CPUE = total number of larvae captured / number of sweeps). For each waterbody I also quantified several environmental variables following the methods outlined Ward and Hossie (2020). Specifically, canopy cover around the pond margin was estimated using a spherical densiometer, and maximum depth of the pond was measured to the nearest 5 cm. Water temperature, pH, dissolved solids, salinity, conductivity, and dissolved oxygen were measured within 1 m from the pond edge using a standard instrument (Hoskin Scientific pH Meter, ExStik II dissolved oxygen meter (ExTech Instruments®)). Water temperature was standardized to noon-corrected temperatures (Ward and Hossie 2020; see Supplementary Material). Presence/absence of submergent aquatic vegetation was determined visually, and presence of crayfish or fish was assessed as by-catch or direct observation during dip-net surveys. Crayfish presence was also inferred if fresh burrows were present around the pond margins. The amount of aquatic leaf litter in the substrate was recorded qualitatively on a scale of 0-2 (0 = no leaf litter, 1 = thin or patchy later of leaf litter, 2 = thick layer or leaf litter). Pond surface area and proximity to the nearest forest edge was measured using Google Earth imagery, with direct measurements in the field replacing this method when imagery was not available (n = 4).

Habitat & Patch Isolation:

I used ArcGIS Pro (ArcGIS Pro 2.9) to quantify landcover characteristics related to the habitat surrounding the breeding sites. To identify landcover types I used the Ontario GeoHub's Southern Ontario Land Resource Information System (SOLRIS 3.0) land cover layer, with a 10 m x 10 m resolution (Mostoway, 2023). This map contained 32 different landcover classifications which I collapsed to 7 categories (Agriculture, Forest, Wetland, Tallgrass Community, Human Disturbance, Transportation, and Water (Table S6)). *Ambystoma* salamanders prefer habitats composed primarily of forest and wetland areas during their terrestrial stage (Petranka, 1998, Pfingsten et al., 2013), so I combined these two categories to reflect suitable habitat across the landscape. In contrast, agricultural land can limit gene flow in *Ambystoma* (Greenwald et al., 2009), so I calculated proportion of Forest/Wetland area and proportion of Agricultural area within a 300 m buffer around each of the 34 aquatic breeding sites. Next, I determined size of the terrestrial habitat patches within which breeding ponds were embedded by creating a new layer containing only patches of suitable habitat (i.e., Forest and Wetland) by using the package Fragstats in ArcGIS. I then used the Patch Analyst function to calculate Forest and Wetland area; this work revealed 85 suitable terrestrial habitat patches scattered across the 42 km^2 island. When a surveyed waterbody was > 25 m from the edge of a terrestrial habitat patch they were assigned a patch size of 0 km^2. Finally, I calculated Proximity Index using Fragstats in ArcGIS, which described how close a given pond is to all available ponds, including known ponds not sampled during this work, using sf and spatialEco packages in R (Pebesma 2018, Pebesma & Bivand 2023, and Evans & Murphy, 2021). The proximity.index function was set with maximum distance of 1 km, which corresponds to the approximate maximum dispersal distance of *Ambystoma* salamanders (Beriault, 2007, COSEWIC, 2016, COSSARO, 2016).

Statistical Analysis:

To quantify aquatic habitat quality I conducted Principal Component Analysis (PCA) using R package 'FactoMineR' (Lê, Josse, & Husson, 2008) and included as predictors: pond surface area, maximum depth, canopy cover, proximity to forest edge, presence/absence of fish, presence/absence of submergent aquatic vegetation, noon-corrected water temperature, presence/absence of crayfish, and amount of leaf litter in the substrate (see also Ward and Hossie 2020). Next, I developed a set of candidate models to explain CPUE, including main effects models with up to 2 predictors, as well as a null (intercept-only) model. To test for a possible interactive effect between aquatic habitat quality and the surrounding habitat conditions, I also considered models that included an interaction term with the principal component variable generated by the PCA outlined above. Prior to analysis, I confirmed that predictors were not correlated (all $r < 0.45$) but found that some predictors were spatially autocorrelated (Moran's Test with 999 simulations, see Supplementary Table S5). I therefore used generalized least squares (GLS) models to allow the inclusion of a Gaussian correlation structure that accounts for spatial autocorrelation (Logan, 2018). Variables were transformed to achieve normality of the residuals (Quinn and Keough, 2002) with a square-root transformation being applied to CPUE and the Proportion of Agriculture within 300 m, and a log transformation being applied to the proportion of Forest/Wetland area within 300 m and the Proximity Index (Quinn and Keough 2002). Fitted models were compared using AICc (Anderson & Burnham, 2002) with the R package MuMIn (Barton 2023). The weight of support for each model was estimated by calculating the AICc weight. Models with a ΔAICc < 2 of the best fit model were considered statistically indistinguishable. All statistical analyses were conducted in R, version 4.2.1 (R Core Team, 2021).

Results:

Ambystoma larvae were captured in 25 (74%) of the 34 surveyed breeding sites on Pelee Island, ON, with larvae being detected across all four quadrants of the island. Mean CPUE for occupied sites was 0.54 larvae/sweep (standard deviation ± 0.54 larvae/sweep), ranging from 0.013 – 1.9 larvae/sweep (Table S1). Captured larvae ranged in size from 13-64 mm in total length The PCA produced four principal components which each explained >10% of the variation in the dataset, but only three of these had an eigenvalue > 1 (Eigenvalues: PC1 = 2.37, PC2 = 1.94, PC3 = 1.19, PC4 = 0.97). PC1 explained 26.3% of the variation within the dataset and was strongly associated with breeding site variables such as estimated maximum depth, canopy cover, aquatic vegetation, presence/absence of predators, substrate type, pond surface area, and noon-corrected temperature (Table 1). PC2 explained 21.57% of the variation within the dataset and was strongly associated with canopy cover and proximity to the forest edge (Table 1). PC3 explained 13.17% of the variation and was strongly associated with presence/absence of aquatic predators within the pond (Table 1). Finally, PC4 explained only 10.75% of the variation within the dataset, and was only strongly associated with pond surface area (Table 1).

A linear model assessing predictive relationships from PCA factors indicated that only PC1 predicted salamander CUPE (PC1: $t = 2.41$, $p = 0.023$, df = 29, all other PCs $p > 0.15$). Large PC1 values reflect waterbodies that have dense canopy cover around the margins, deep accumulated leaf litter in the aquatic substrate, cooler water temperature, submergent vegetation present, and larger surface area and estimated maximum depth (Figure 2). Therefore, I considered PC1 as the best index of aquatic habitat quality to be included as predictor in the model selection exercise.

Relative abundance of *Ambystoma* larvae (CPUE) was best predicted by additive effects of aquatic habitat quality (PC1) and terrestrial patch size (km^2) of suitable habitat surrounding the breeding site (Table 2, Figure 3). The next best fit model was the interactive model between PC1 and terrestrial patch size, with substantially less support (Table 2). Both the additive and interactive models including PC1 and terrestrial patch size outperformed the null model, and no other models had an AICc weight > 0.004 (Table 2, Table S1).

Discussion:

The results of this study support my third hypothesis, suggesting that both aquatic and terrestrial habitat variables influence the relative abundance of salamander larvae at a given site. Relative abundance of salamander larvae appears to by determined by the additive effects of aquatic habitat quality and the size of terrestrial habitat patch within which the breeding site is embedded. Interestingly, there was no detectable effect of amount of agriculture within 300 m of the waterbody on larval abundance, perhaps indicating that viable populations can persist alongside agriculture provided that agricultural practices do not degrade breeding site quality and large contiguous patches of forest cover remain available. I did not detect any effect of patch connectivity, which may reflect the primary role that habitat quality and amount play in governing larval abundance, or low functional connectivity among sub-populations across the fragmented landscape. PC1 was the only principal component variable that was related to relative abundance of salamander larvae in the breeding site (i.e., CPUE) indicating that salamander breeding sites with higher catch-per-unit effort had higher canopy cover around their margins, more leaf litter in the substrate, deeper maximum depth (m), greater pond surface area (m^2), lower water temperatures, and presence of submergent aquatic vegetation. My findings emphasize the importance of maintaining high quality breeding sites embedded within large patches of suitable terrestrial habitat for *Ambystoma*, especially given their biphasic life cycle.

The key finding is that both aquatic habitat quality and the amount of surrounding terrestrial habitat influences abundance of *Ambystoma* salamander larvae. One interpretation is that *Ambystoma* are less likely to breed in low quality aquatic habitats or in waterbodies that are not embedded within large patches of suitable terrestrial habitat (Thompson, Gates, & Taylor, 1980, Figiel & Semlitsch, 1995). For example, a wide number of pond-breeding amphibians avoid egg laying in ponds containing fish (Figiel & Semlitsch, 1995, Kats & Sih, 1992), and are more likely to deposit eggs in ponds with >75% canopy cover embedded within patches of suitable terrestrial habitat (Felix, Wang, & Schweitzer, 2010). Alternatively, observed patterns of larval abundance may reflect the outcome of multiple related processes: short-term processes related to pond quality influence on larval survival and development, and longer-term processes reflecting how terrestrial habitat affects survival of juveniles and reproductive success of adults. These scenarios are consistent with previous work indicating that larval survival in *Ambystoma* salamanders depends on aquatic habitat suitability (Petranka & Sih, 1987, Peterman et al., 2013), and that adult and juvenile survival depends on availability of suitable terrestrial habitat (Titus et al., 2014, Todd et al., 2009, Peterman & Seimlitsch, 2013). Accordingly, this work reinforces that conservation of amphibians with a biphasic life history hinges on protecting high quality breeding sites in tandem with the surrounding terrestrial habitat.

These analyses failed to detect any influence of habitat connectivity metrics on the larval salamander abundance. Abundance may be primarily governed by habitat quality and amount, with connectivity and metapopulation dynamics (immigration/emigration) playing a limited role (e.g., Smith & Green, 2005, Beebee & Griffiths, 2005, Greenwald et al, 2009). Importantly, lack of detectable effects of subpopulation connectivity may also reflect isolation of contemporary subpopulations on Pelee Island and that observed numbers of salamander larvae are not in equilibrium. Patches of remnant forest and wetlands are situated within a predominantly agricultural landscape on the island (>60% of land cover), and most subpopulations are separated by >1 km through unsuitable habitat. While I cannot exclude the possibility that low statistical power prevented us from detecting an influence of connectivity metrics on larval salamander numbers, model selection indicated that aquatic habitat quality and forest habitat patch size were stronger predictors. I note that even if patch connectivity plays a limited role in determining patterns of larval abundance, connectivity may be necessary to maintain adequate gene flow to counterbalance the effects of genetic drift and inbreeding depression (Titus et al., 2014, Becker et al., 2008).

In the past, there has been considerable debate around whether biodiversity conservation can be improved by protecting several small habitat patches versus a smaller number of much larger patches of habitat (Thornton et al., 2010, Weigand et al, 2005), and my results serve to support the now widely accepted consensus that protecting multiple large areas of suitable habitat was the most effective for species conservation (Fahrig et al, 2022, Greenwald et al, 2009). I found that the size of the surrounding terrestrial habitat patch had an important impact on the relative abundance of larvae. Thus, protecting or restoring large patches of habitat may be more effective for *Ambystoma* salamander conservation rather than protecting a network of small habitat patches for this species. Larger patches likely provide better opportunities for juvenile survival and adult reproduction, likely providing sufficient resources and refuge from predators and environmental stressors (Cabrera-Guzmán & Reynoso, 2012, Almeida-Gomes et al., 2016, Moor et al., 2024; Petranka & Sih, 1987). This result aligns with prevailing theory that larger habitat patches support more robust populations due to increased resource availability and reduced edge effects (MacArthur & Wilson, 1967, Schneider-Maunoury, et al., 2016, Demaynadier & Hunter, 2008). Furthermore, aquatic habitat quality clearly plays a key role in determining larval abundance, with newly constructed ponds having substantially lower measurable quality compared to natural breeding sites (Ward and Hossie 2020).

In conclusion, this study highlights the critical importance of conserving high-quality aquatic habitats and large, contiguous terrestrial patches for the survival of *Ambystoma* salamander populations. The significant influence of both aquatic habitat quality and surrounding terrestrial habitat patch size on larval abundance suggests that conservation efforts should prioritize not only restoration of isolated ponds but also protection of broader landscapes that provide essential resources and connectivity for juvenile and adult life stages. Encouragingly, some amphibian species may be able to persist in landscapes dominated by human influence, so long as suitable aquatic habitat and sufficient terrestrial habitat remains available (Cayuela et al., 2022, Greenwald et al., 2009, Smith et al., 2023). Contrary to expectations, patch connectivity and proximity of agricultural land had minimal effects, underscoring that habitat quality may sometimes be more critical than landscape-level connectivity, even in highly fragmented systems. Nevertheless, maintaining habitat connectivity has been found to be important for promoting gene flow and mitigating risks of inbreeding depression, especially for species in highly isolated patches (Titus et al. 2014; Becker et al. 2023). This research provides valuable insights into habitat management practices that can mitigate the effects of human-induced environmental change on vulnerable amphibian species (Beebee & Griffiths 2005; Cushman 2006).

Table 1: Output tables from the Principal Component Analysis describing correlations between variables and dimensions (PCs), as well as contributions of each variable to each principal component.

	PC1	**PC2**	**PC3**	**PC4**	**PC5**
Eigenvalue	2.365	1.941	1.186	0.968	0.868
Variance %	26.28	21.57	13.17	10.75	9.646
Cumulative % variance	26.28	47.85	61.02	71.78	81.42

Correlations between variables and dimensions

Estimated Maximum Depth	0.548	-0.001	0.112	0.204	-0.744
Canopy Cover	0.522	0.639	-0.161	-0.196	0.212
Aquatic Vegetation	0.609	-0.451	0.176	-0.073	0.318
Crayfish (Presence/Absence)	-0.218	0.541	0.590	-0.417	0.092
Fish (Presence/Absence)	-0.291	-0.226	0.819	0.198	-0.032
Substrate	0.707	0.429	0.069	-0.124	-0.106
Proximity to Forest Edge	-0.075	0.815	0.129	0.344	-0.028
Pond Surface Area	0.629	-0.031	0.166	0.599	0.375
Noon-corrected Temperature	-0.623	0.368	-0.221	0.420	0.080

Percent Contribution of each variable to each PC

	PC1	**PC2**	**PC3**	**PC4**	**PC5**
Estimated Maximum Depth	12.7	<0.001	1.06	4.31	63.7
Canopy Cover	11.5	21.1	2.19	3.98	5.20
Aquatic Vegetation	15.7	10.5	2.62	0.56	11.7
Crayfish (Presence/Absence)	2.0	15.1	29.4	17.1	0.98
Fish (Presence/Absence)	3.6	2.63	56.5	4.05	0.12
Substrate	21.1	9.48	0.41	1.58	1.29
Proximity to Forest Edge	0.2	34.2	1.40	12.2	0.09
Pond Surface Area	16.7	0.05	2.34	37.1	16.2
Noon-corrected Temperature	16.4	6.97	4.12	18.2	0.74

Table 2: The top five models predicting the catch-per-unit-effort (CPUE) of *Ambystoma* larvae in ponds on Pelee Island, ON during surveys conducted between May 25th – June 2, 2022. Ranking based on ΔAICc. Null model (intercept only) also included for comparison.

Model Description	df	AICc	ΔAICc	AICc Weight
Pond Quality (PC1) + Patch Size	6	41.47	0	0.87
Pond Quality (PC1) * Patch Size	7	45.78	4.31	0.101
NULL	4	50.65	9.18	0.009
Pond Quality (PC1)	5	52.27	10.80	0.004
Patch Size	5	52.37	10.90	0.004
PC1 * Proportion Agriculture within 300 m	7	52.62	11.15	0.003

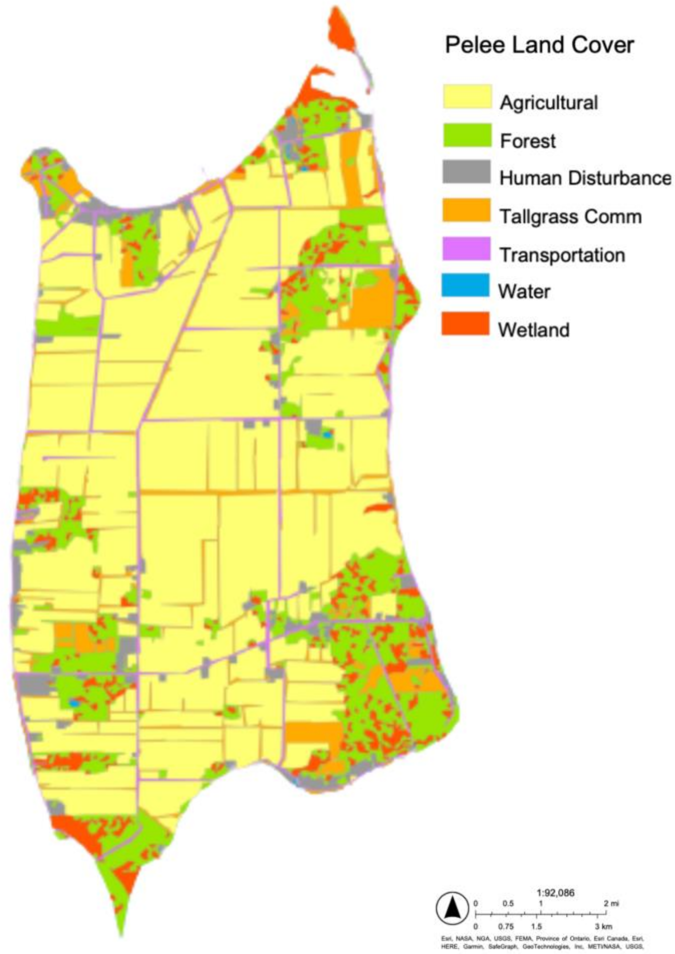

Figure 1: A land cover classification map of Pelee Island, ON, produced in ArcGIS Pro, illustrating available land cover types from SOLRIS (2022) and Google Earth imagery.

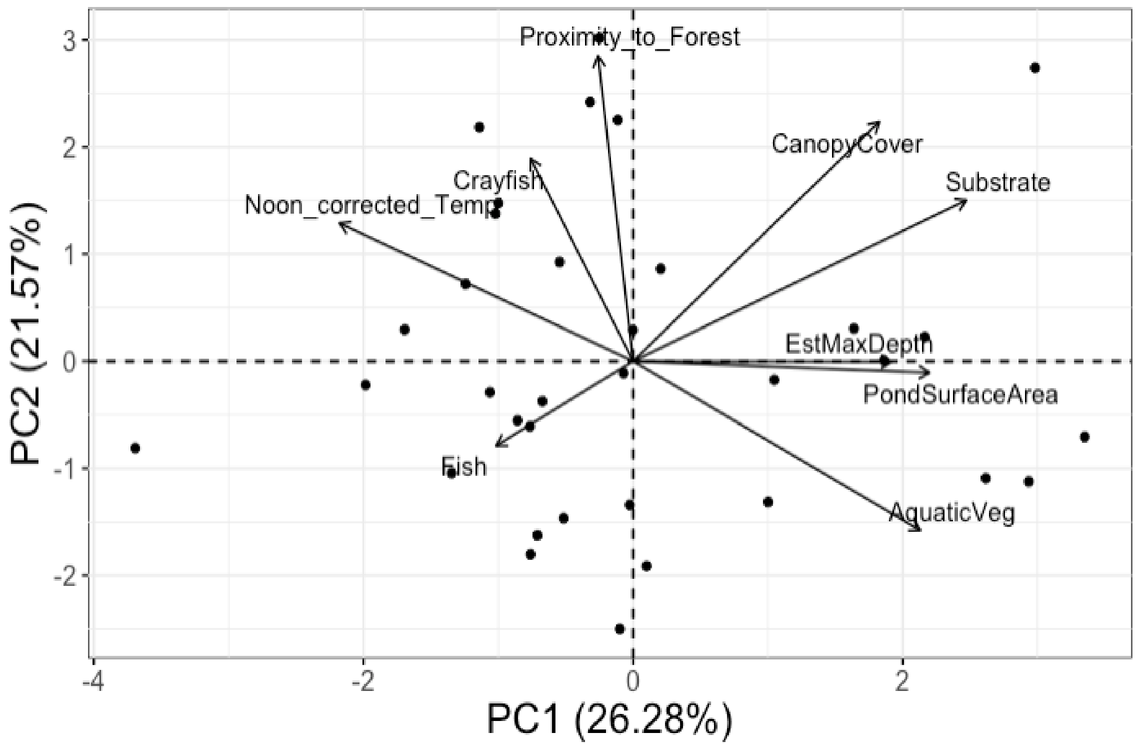

Figure 2: Biplot from a Principal Component Analysis examining environmental characteristics of breeding sites for *Ambystoma* salamanders on Pelee Island, ON. PC1 was the only principal component variable that had a significant relationship with relative abundance of salamander larvae in the breeding site (i.e., CPUE) indicating that ponds with higher catch-per-unit effort had higher canopy cover around their margins, more leaf litter in the substrate, deeper maximum depth (m), greater pond surface area (m^2), lower water temperatures, and presence of submergent aquatic vegetation in salamander breeding sites.

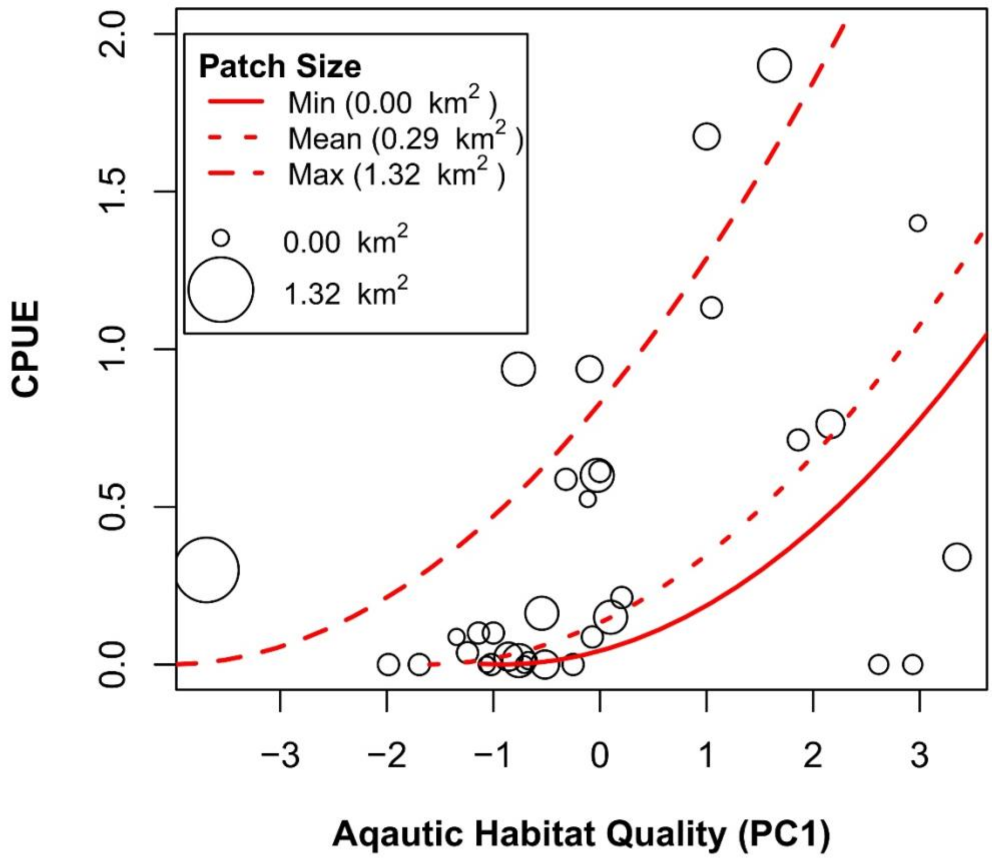

Figure 3: Salamander catch-per-unit-effort (CPUE) from dipnet surveys in 34 ponds across Pelee Island, ON sampled between May 25 – June 2, 2022. Circle size corresponds to the size of the surrounding terrestrial habitat patch. Lines depict the predicted CPUE for the minimum (0 km^2, dotted line), mean (0.29 km^2, dashed line), and maximum (1.32 km^2, long-dash line) observed patch sizes, depending on aquatic habitat quality.

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Chapter 3: General Discussion

Thesis Goals Revisited

The central goal of this study was to investigate factors that influence relative abundance of *Ambystoma* salamander larvae in waterbodies across a human-dominated landscape. The findings emphasize the necessity of maintaining both high-quality aquatic breeding sites and the large parcels of terrestrial habitats that they are embedded within to support viable populations of amphibians with complex life cycles. These findings align with previous calls for the protection and management of suitable aquatic and terrestrial habitat to conserve amphibians with broader conservation biology goals (Luedtke et al., 2023, Titus et al., 2014, Hanski, 2011). The results also reinforce that management efforts aimed at assisting imperilled populations should not focus solely on preserving isolated high-quality patches of terrestrial or aquatic habitat, but also on optimizing conservation efforts to protect and maintain both types of habitats that species such as amphibians rely on for continued survival (Wintle et al, 2018). The need for integrated conservation approaches which consider both aquatic and terrestrial requirements is crucial, not only for amphibians but also for many other taxa with complex life histories (Ferraz et al., 2007). This study, while focused on amphibians, echoes similar concerns in other taxa where habitat fragmentation and degradation similarly threaten biodiversity (Fahrig 2003, Cushman 2006, Haddad et al. 2015). Therefore, the results from this study contribute to the larger body of conservation literature, emphasizing the importance of multi-faceted conservation strategies that address both spatial and temporal habitat needs (Elith and Leathwick, 2009).

Implications for Ambystoma Conservation on Pelee Island

If *Ambystoma* conservation is a priority, then implications of these findings are clear: both aquatic and terrestrial habitats should be protected, improved, and expanded where possible. Conservation strategies that focus on a single habitat type, such as breeding ponds, may overlook the critical role of surrounding terrestrial areas which are essential for juvenile and adult life stages. Protecting large patches of habitat that offer refuge from predators and environmental stressors is paramount to ensure the survival of *Ambystoma* salamanders. Newly constructed ponds, while potentially useful, may not offer the same habitat quality as natural wetlands unless designed carefully to mimic environmental conditions of natural breeding sites. Research suggests that factors such as canopy cover, aquatic vegetation, and water temperature play crucial roles in supporting larval abundance, and these variables should be considered when designing artificial ponds (Ward & Hossie 2020).

Despite the emphasis on connectivity in metapopulation theory, this study found no significant effect of patch isolation on *Ambystoma* larvae abundance. This unexpected result could be attributed to the fragmented agricultural landscape of Pelee Island, where terrestrial barriers limit dispersal. Detecting distance effects may have been hampered by low statistical power, however, which may have impaired our ability to detect any effect of patch isolation and connectivity. The lack of significant connectivity effects may reflect the low dispersal ability of amphibians or the fact that isolated patches are large enough to sustain populations in the short term. These findings suggest that habitat quality may be more critical than connectivity in determining local population success over short time scales.

Broader Implications Beyond Amphibian Systems:

Similar findings have been observed in other species with complex life cycles. For example, migratory birds depend on distinct stopover and breeding grounds, with habitat quality during migration being crucial for reproductive success. Poor-quality stopover sites can lead to reduced energy reserves, limiting the success of migration and reproduction (Cohen et al. 2021). Likewise, some large mammals require distinct habitats for feeding during summer and for hibernation during winter, and habitat fragmentation contributes to reduced genetic diversity, potentially compromising population viability (Halme 2013, Johnson et al. 2017). For a variety of species, conserving only one type of habitat is insufficient and instead an integrated approach that considers both aquatic and terrestrial habitats is necessary to maintain population viability (Dixon et al. 2006). As habitat quality plays a key role in population dynamics, conservationists must focus not only on increasing quantity of protected areas but also on improving quality of these areas by enhancing vegetation cover, restoring degraded sites, and maintaining key environmental variables such as water temperature.

Conclusions and Future Directions

The global decline of amphibians underscores the need for integrated conservation approaches that address these multifaceted threats. Strategies should focus on preserving habitat by addressing the key drivers of amphibian declines, conservation efforts can help ensure the persistence of these ecologically important species and the ecosystem services they provide. This study contributes to conservation efforts for imperilled salamanders by identifying the key environmental and landscape factors that underpin the observed variation in relative abundance of *Ambystoma* larvae across the landscape. This study underscores the critical role that both aquatic habitat quality and terrestrial patch size play in maintaining viable populations of *Ambystoma* salamanders. While habitat connectivity was not a strong predictor of larval abundance in this study at this scale, it remains possible that I failed to detect a true effect of connectivity because of low statistical power, or because our connectivity variables (i.e., Proximity Index, Nearest Neighbour) don't adequately capture connectivity (e.g., if Euclidean distance poorly reflects traversability of the intervening landscape) and better measures of landscape resistance to movement are needed. Fragmented landscapes such as those found on Pelee Island present significant conservation challenges, and future studies should explore how these factors influence population dynamics over longer time scales and across broader landscapes. Although I did not find a significant impact of pond isolation on the relative abundance of larvae in a waterbody, the limited number of sites I visited makes it difficult for us to fully exclude the impact of connectivity on key demographic processes in salamander populations. Future research should also explore how landscape-scale conservation strategies, such as the creation of wildlife corridors, can facilitate genetic exchange and population connectivity. As agricultural expansion and urban development continue to threaten biodiversity globally, integrating habitat quality improvements with connectivity enhancements will be essential for mitigating these impacts (Greenwald et al. 2009). Such strategies are not only relevant for amphibians but can also be applied to other taxa facing similar challenges due to habitat degradation.

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Supplementary Material

Table S1: Median and range of environmental variables for 34 *Ambystoma* breeding ponds on Pelee Island, ON, between May 25 - June 2, 2022. Sor summary purposes, data are partitioned based on presence of *Ambystoma* larvae.

Environmental Variable	Unoccupied Ponds (n=9)	Occupied Ponds (n=25)
CPUE	Median:0.000	Median: 0.341
	Range:0.000-0.000	Range:0.0125-1.9
Surface Area (m^2)	Median: 107.5	Median:188.50
	Range: 28.7-4306	Range:18.39-11,930
Maximum Depth (m)	Median:0.60	Median:0.60
	Range:0.15-2.00	Range:0.10-1.50
Canopy Cover (% Covered)	Median: 26.336	Median:50.375
	Range: 0.000-62.01	Range:0.000-81.12
Proximity to Forest Edge (m)	Median: 32	Median: 2
	Range:0.000-230	Range:0.000-259
Fish Presence (% of ponds with fish)	22%	8%
Percent with Aquatic Vegetation	44%	60%
Noon-corrected Water Temperature (°C)	Median: 22.22	Median: 22.50
	Range:19.40-25.48	Range:16.94-32.86
Crayfish Presence (% of ponds with Crayfish)	66.67%	76%
Substrate *	0: 0 pond (0%)	0: 3 ponds (12%)
	1: 6 ponds (66.67%)	1: 12 ponds (48%)
	2: 3 ponds (33.33%)	2:10 ponds (40%)
Proportion Forest and Wetland within 300 m	Median: 0.4805	Median: 0.4060
	Range: 0.2362-0.6218	Range: 0.0235-0.7407
Proportion Agriculture within 300 m	Median: 0.1578	Median: 0.3096
	Range: 0.000-0.5598	Range: 0.000-0.5992
Pond Quality (PC1)	Median: (-0.7100)	Median: (-0.0984)
	Range: (-1.984)-2.934	Range: (-3.693)-3.350
Proximity Index	Median: 0.0511	Median: 0.2059
	Range: 0.0309-6.393	Range: 0.0121-3.976
Patch Size (km^2)	Median: 0.1966	Median: 0.1966
	Range:0.000-0.4252	Range: 0.000-1.322

*Substrate: 0 = bare, 1 = some leaf litter, 2 = complete layer of leaf litter covering pond bottom.

Table S2: Median and range of environmental variables for 34 *Ambystoma* breeding ponds on Pelee Island, ON, between May 25 - June 2, 2022. Data are subdivided between Natural and Constructed, as well as all ponds where *Ambystoma* larvae were detected.

Environmental Variable	**Natural Ponds (n=9)**	**Constructed Ponds (n=25)**	**Occupied Ponds (n=25)**
CPUE	Median:0.7625	Median: 0.0875	Median: 0.341
	Range:0.000-1.9	Range: 0.000-1.4	Range:0.0125-1.9
Surface Area (m^2)	Median: 1472	Median:114.2	Median:188.50
	Range:166-11,930	Range: 10,118-18.39	Range:18.39-11,930
Maximum Depth (m)	Median:0.60	Median: 0.60	Median:0.60
	Range:0.25-2.00	Range:0.10-1.50	Range:0.10-1.50
Canopy Cover (% Covered)	Median:45.57	Median:40.86	Median:50.375
	Range:20.95-81.12	Range:0.000-80.21	Range:0.000-81.12
Proximity to Forest Edge (m)	Median: 0	Median:47	Median: 2
	Range:0.000-0.000	Range:0.000-259	Range:0.000-259
Fish Presence (% of ponds with fish)	0%	16%	8%
Percent with Aquatic Vegetation	100%	4%	60%
Noon-corrected Water Temperature (°C)	Median:19.12	Median:23.12	Median: 22.30
	Range:16.94-19.86	Range: 18.11-32.86	Range:16.94-32.86
Crayfish Presence (% of ponds with Crayfish)	44%	84%	76%
Substrate *	0: 1 pond (11.11%)	0: 2 ponds (8%)	0: 3 ponds (12%)
	1: 0 ponds (0%)	1: 18 ponds (72%)	1: 12 ponds (48%)
	2: 8 ponds (88.89%)	2: 5 ponds (20%)	2:10 ponds (40%)
Proportion Forest and Wetland within 300 m	Median: 0.4409	Median: 0.4060	Median: 0.4060
	Range: 0.2362-0.7407	Range:0.0235-0.6462	Range: 0.0235-0.7407
Proportion Agriculture within 300 m	Median: 0.000	Median: 0.4678	Median: 0.3096
	Range: 0.000-0.1481	Range: 0.000-0.5992	Range: 0.000-0.5992
Pond Quality (PC1)	Median: 1.860	Median: (-0.7100)	Median: (-0.0984)
	Range: (-0.0984)-3.350	Range: (-3.693)-2.983	Range: (-3.693)-3.350
Proximity Index	Median: 1.626	Median: 0.0904	Median: 0.2059
	Range: 0.0131-6.393	Range: 0.0121-3.976	Range: 0.0121-3.976
Patch Size (km^2)	Median: 0.3586	Median: 0.1966	Median: 0.1966
	Range:0.1195-0.5711	Range: 0.000-1.322	Range: 0.000-1.322

*Substrate: 0 = bare, 1 = some leaf litter, 2 = complete layer of leaf litter covering pond bottom.

Table S3: Principal Component Analysis output table showing eigenvalues, percent variance explained by each principal component, and cumulative variance explained by each principal component. Principal components 1-4 each explained >10% of the variation in the data set and were evaluated for a relationship with catch-per-unit-effort (CPUE).

Principal Component	**Eigenvalue**	**Variance %**	**Cumulative %**
PC1	2.365	26.28	26.28
PC2	1.941	21.57	47.85
PC3	1.186	13.17	61.02
PC4	0.968	10.75	71.78
PC5	0.868	9.646	81.42
PC6	0.623	6.926	88.35
PC7	0.474	5.266	93.61
PC8	0.336	3.730	97.34
PC9	0.239	2.656	100.00

Table S4: Output from the full set of 20 candidate models considered to explain the influence of terrestrial or aquatic habitat variables on catch-per-unit-effort (larvae/sweep) of salamander larvae in ponds across Pelee Island, ON, during surveys conducted between May 25th – June 2nd, 2022.

Model Description	**df**	**AICc**	**ΔAICc**	**AICc Weights**
PC1+Patch Size	6	41.47	0	0.87
PC1*Patch Size	7	45.78	4.31	0.101
NULL	4	50.65	9.18	0.009
PC1	5	52.27	10.80	0.004
Patch Size	5	52.37	10.90	0.004
PC1* Proportion Agriculture within 300 m	7	52.62	11.15	0.003
PC1* Proportion Forest or Wetland within 300 m	7	53.20	11.73	0.002
Proportion Agriculture within 300 m	5	53.90	12.43	0.002
Proportion Forest or Wetland within 300 m	5	54.97	13.50	0.001
PC1* Proximity Index	7	55.21	13.74	0.001
Proportion Forest or Wetland within 300 m + Patch Size	6	55.54	14.07	0.001
Proportion Agriculture within 300 m + Patch Size	6	55.76	14.29	0.001
PC1 + Proportion Agriculture within 300 m	6	55.96	14.49	0.001
Proximity Index	5	56.57	15.10	<0.001
PC1 + Proportion Forest or Wetland within 300 m	6	57.41	15.94	<0.001
Proportion Forest or Wetland within 300 m + Proportion Agriculture within 300m	6	58.13	16.66	<0.001
Patch Size + Proximity Index	6	58.57	17.10	<0.001
PC1 + Proximity Index	6	59.47	18.00	<0.001
Proportion Agriculture within 300 m + Proximity Index	6	60.19	18.72	<0.001
Proportion Forest or Wetland within 300 m + Proximity Index	6	61.27	19.79	<0.001

Table S5: Results from Moran's tests and permutation tests for Moran's I (with 999 simulations) used to evaluate presence of spatial autocorrelation in the data. Spatial autocorrelation was addressed by using Gaussian correction structure.

Variable	Moran's I Statistic	P-value	Monte-Carlo Simulation of Moran's I Statistic	P-value
CPUE	0.09	0.21	0.09	0.21
Proportion Forest and Wetland within 300 m	0.14	0.12	0.14	0.14
Proportion Agriculture within 300 m	0.80	<0.001	0.80	0.001
Pond Quality (PC1)	0.30	0.015	0.30	0.019
Proximity Index	0.24	0.021	0.24	0.048
Patch Size	0.09	0.19	0.09	0.19

Table S6: Land cover classifications used in statistical analysis to reduce variable dimensionality.

	Land Cover Type	Description
Wetland	Breeding Pond	Based on sample location data
	Pond; Thicket Swamp	No fish, no record of breeding; Thick growths of tall shrubs (willow, dogwood, alder)
Forest	Thicket	<10% tree cover and >25% tall shrub cover
	Treed Swamp	>25% tree or shrub cover, seasonally flooded
	Deciduous Forest	Tree cover >60%, upland deciduous tree sp. >2m
	Forest	Tree cover >60%, upland deciduous tree sp. >2m in height
	Alvar	Level, unfractured limestone, veg. cover <60%
	Marsh	Open, shrub and treed communities
Tall-grass comm.	Developing Forest	Some trees and vegetation
	Meadow	Open, vegetated by grass and non-woody plants
	Converted Field	Previously farmland, currently growing grasses and shrub cover
	Adjacent Agricultural Land	Windbreak
	Hedge Row; Culvert	Tree cover >60%, 2m in height, linear, min 10m width, max 30m width: Somewhat open water
	Treed Sand Dune	Exposed sands, veg. cover <60%
	Plantations; Beach	Tree cover >60%, min 2m in height, linear, uniform tree type, <25% veg. cover, sand
Agricultural	Agricultural Land	Used for various types of crops (soybeans, wheat, etc.)
	Orchard	Linear, ground cover is grass, grape fields
	Grass	
Transportation	Dirt Road	On properties or through farmland
	Road; Small Building	Paved, building that takes up <30% of cell
	Airway Road	
Human Disturbance	Small Building	Building that takes up 50% of cell
	Large Building	Building that takes up <75% of cell
	Built Up/Barns	Building that takes up 100% of cell
	Dock: Extraction	Boat docks, pits, quarries
Water	Lake	Open Water

Table S7: Proportion of land cover types across, Pelee Island, ON, Canada, based on work by Smith et al. (2023).

Land Cover	**Area (km^2)**	**Proportion of Terrestrial Area**
Wetland	2.3	5.7
Forest	6.7	16.5
Tall-grass comm.	3.1	7.5
Agricultural	25.3	62.1
Transportation	1.6	3.8
Human Disturbance	1.8	4.4

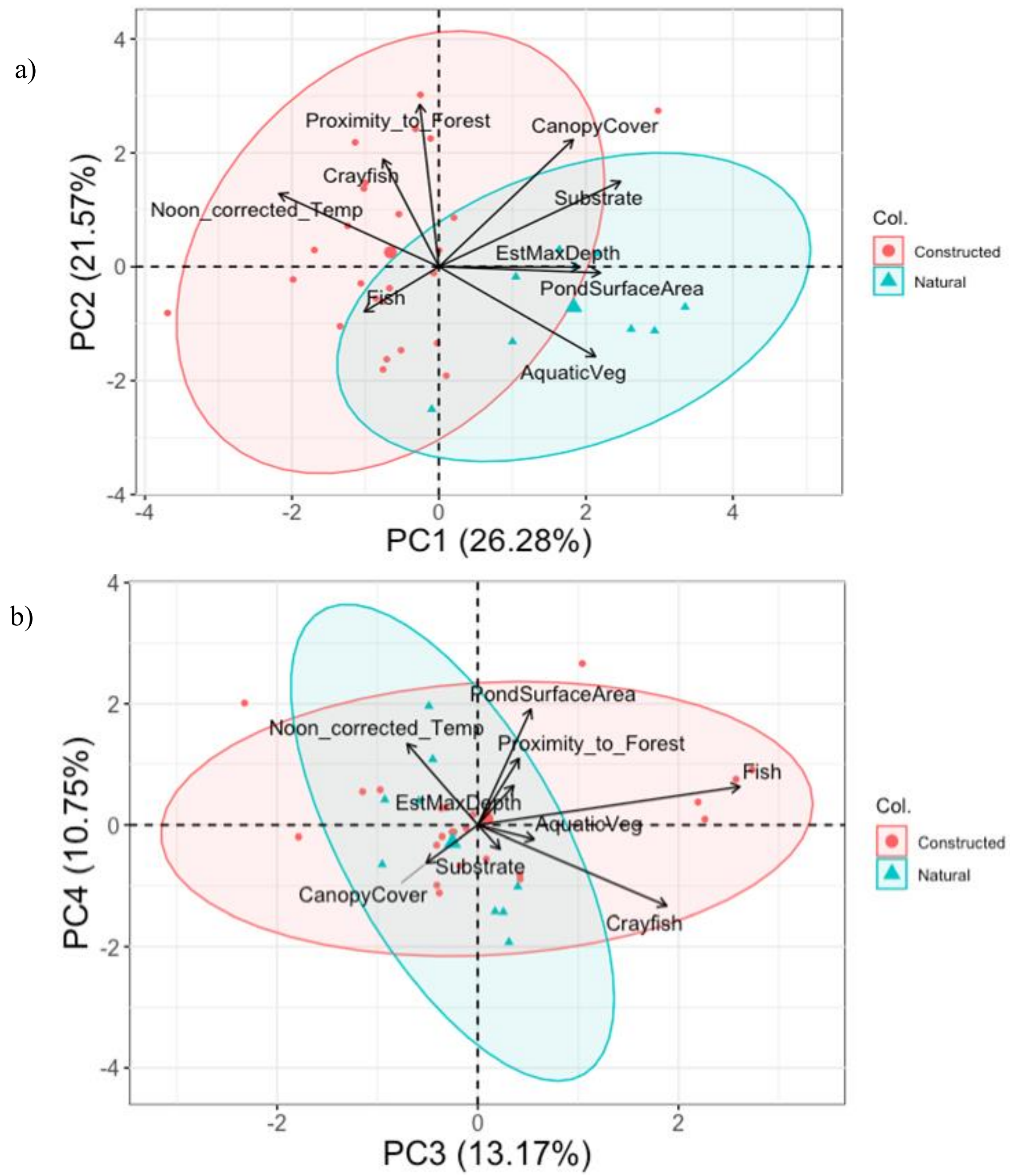

Figure S1: Biplots from the Principal Component Analysis conducted on the environmental characteristics of ponds across Pelee Island, ON, contrasting constructed ponds (Red) and natural ponds (Blue).