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Review

Restoration of Geographically Isolated Wetlands: An Amphibian-Centric Review of Methods and Effectiveness

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Abstract: Geographically isolated wetlands provide a critical habitat for pond-breeding amphibians, a taxa of broad conservation concern. Global wetland loss and degradation has made restoration essential for amphibian conservation. Restoration goals typically include recovering the wetlands' physiochemical, hydrological, and ecological functions. However, for pond-breeding amphibians, successful restoration should also result in sustained populations, which is difficult to assess and infrequently reported. In this paper, we review the available evidence that restoration of geographically isolated wetlands promotes pond-breeding amphibian occupancy and population persistence. We provide an overview of restoration practices addressing hydrology, vegetation, and ecological processes within these unique environments and across spatial scales. We then summarize the evidence, and discuss the limitations, for evaluating successful restoration within the context of amphibian conservation across these categories. Finally, we provide recommendations for researchers and practitioners to leverage prior successes and establish systematic data collection and dissemination. Moving restoration of wetlands for amphibian conservation forward will require more robust data collection and reporting.

Keywords: pond; vernal pool; Carolina bay; prairie pothole; flatwoods; frog; tadpole; salamander; newt; habitat

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1. Introduction

While "geographically isolated" is a disputed term, it is a useful framework for unique aquatic habitats surrounded by uplands that have frequent wetting and drying cycles, are characterized by minimal to no surface-water connections to other waters, and typically do not support fish populations [1,2]. Various habitats fit within this framework, including vernal pools, Carolina bays, prairie potholes, limesinks, and playas, among others [1]. Geographically isolated wetlands are a critical resource for conserving biodiversity and the provision of other ecosystem services (e.g., habitat provisioning, nutrient cycling) [3,4]. The unique features of geographically isolated wetlands make them particularly important as breeding and developmental sites for amphibians [5,6]. For amphibian eggs and developing larvae, the relative isolation of geographically isolated wetlands from other waters and the absence of fish can reduce predation and competition. Seasonal inundation releases nutrients and creates a temporary but highly productive habitat. Globally, many endangered and threatened amphibians (e.g., Amboli toad, *Xanthophryne tigerina*; crested newt, *Triturus cristatus*; California tiger salamander *Ambystoma californiense*; dusky gopher frog, *Rana sevosa*; flatwoods salamander, *Ambystoma cingulatum/A. bishopi*; green and golden bell frog, *Litoria aurea*; Olongburra frog, *Litoria olongburensis*; Moroccan spadefoot, *Pelobates varaldii*; Rancho Redondo frog, *Lithobates vibicarius*; striped newt, *Notophthalmus perstriatus*; yellow-legged frog, *Rana muscosa*) rely on geographically isolated wetlands [7]. Numerous unlisted but declining species and common species also depend on the global conservation of geographically isolated wetland habitats. However, like other small aquatic habitats, geographically isolated wetlands have few legal protections [8]. Historical and current wetland loss and degradation have made the restoration of geographically isolated wetlands a high priority for the conservation of pond-breeding amphibians [9,10].

There is a large body of literature on the practice and effectiveness of wetland restoration. However, geographically isolated wetlands present a unique set of restoration and conservation problems. This is mainly due to the difficulties in restoring and managing hydroperiods—the timing and duration of ponding—that is the main ecological control (i.e., regulating a suite of responses, including biodiversity, nutrient fluxes, and community development, among others) in these systems. Furthermore, restoration of wetland habitats for the express purpose of conserving amphibian populations has been primarily species-, region-, and project-specific. Many individual projects reporting on different approaches with oftentimes limited inference for amphibian conservation makes it difficult for practitioners to find clear guidance. The widely dispersed literature also inhibits researchers from developing clear lines of inquiry to improve conservation outcomes. By taking an amphibian-centric view of the practices, successes, and challenges of restoring these critical habitats specifically for amphibian conservation, this paper fills this gap by:

(1) Providing an overview of the main approaches for restoring geographically isolated wetlands, particularly for pond-breeding amphibian conservation;
(2) Reviewing the evidence that habitat restoration in geographically isolated wetlands benefits pond-breeding amphibian populations;
(3) Providing literature-based recommendations to practitioners;
(4) Highlighting areas of future research for amphibian-centric geographically isolated wetland restoration.

1.1. Geographically Isolated Wetlands and Pond-Breeding Amphibians

Globally, amphibians are the most at-risk taxa, with nearly one-third listed in one of the IUCN Red List threatened categories [7]. While disease and climate change impact many species, habitat loss and degradation are the primary causes of decline [11]. Geographically isolated wetlands are an essential habitat for many common amphibian species, as well as species of conservation concern. In the ecology of pond-breeding amphibians, geographically isolated wetlands primarily serve as breeding and larval developmental sites. In these systems, predator (e.g., fish) and competitor populations occur along a gradient often related to hydrology and degree of isolation. Reduced or absent predator and competitor populations release many species of pond-breeding amphibians from some predation and competition pressure [12,13]. Pond-breeding amphibians are not a uniform group: local amphibian community structure is driven by adaptations to habitat gradients, including hydroperiod, predator presence, degree of isolation, and canopy cover [14–16]. Amphibians that utilize geographically isolated wetlands range from habitat specialists that require highly specific habitats for successful breeding and development to habitat generalists that are successful in many habitats [14,17,18]. One feature they share is adaptation to a stochastic environment [15,19]. In any given year, an individual geographically isolated wetland may host a fish population, not fill with water, dry early, or otherwise be unsuitable for amphibian breeding and development. Pond-breeding amphibians are resilient to these stochastic disturbances, provided that abundant wetlands are available across the landscape, in relative proximity to one another, and represent a range of hydroperiods [6,10,20–22]. Historical and current destruction of wetlands disproportionately affects geographically isolated wetlands [3,8,23–25]. Some land management and agricultural practices, including ditching and (or) draining, intensive site preparation, intensive livestock grazing, as well as fire exclusion, among others, have also contributed to past and current degradation of wetland conditions [3,8]. Given these pervasive threats and the historical destruction of many geographically isolated wetlands, restoring remaining habitat is essential for the conservation of pond-breeding amphibians [6,8,9].

1.2. Defining Restoration Success

The goal of ecological restoration is the "substantial recovery of the native biota and ecosystem functions", often defined by historical or reference conditions [26]. For wetlands specifically, restoration aims to recover the system's physiochemical, hydrological, and ecological functions prior to degradation [27]. Recovery of a system to defined, predetermined endpoints may not always be possible or desirable; however, ecological restoration should result in systems with increased ecosystem services and resilience to stressors [28]. For pond-breeding amphibians, successful restoration should result in sustained populations [29]. While simply stated, this goal is difficult to assess. Pond-breeding amphibian occupancy, abundance, and recruitment within a particular geographically isolated wetland is highly variable among years [30,31]. Further, successful breeding (e.g., chorusing, oviposition) does not necessarily imply successful recruitment [32]: juveniles typically only join the breeding population after a period of growth and development in the terrestrial landscape surrounding ponds. Environmental or demographic stochasticity may result in recruitment failure at any developmental stage [33]. Therefore, long-term monitoring (>5 years) of amphibian occupancy and abundance with robust methods for estimation of population parameters including survival and recruitment are the gold standard for ensuring population persistence [32,34]. Unfortunately, most wetland restoration research is short-term ($\leq$5 years) and small-scale (i.e., individual wetlands), which limits inference, particularly for the recovery of vertebrate communities [35,36]. Further, there is evidence that even long-term wetland monitoring of amphibian populations may fail to detect population trends [34]. In this paper, we present and evaluate the available evidence that restoration of geographically isolated wetlands promotes pond-breeding amphibian occupancy and population persistence in light of the known inferential limitations.

2. Materials and Methods

We searched the literature using Web of Science and within selected journals for articles that had reported on a restoration project or research that included any metric of amphibian success (details in Supplementary Materials File S1 and Table S1). We included multiple terms for geographically isolated wetlands, but recognize that these terms may not capture all relevant literature. Therefore, we also reviewed the citations in each included article for additional relevant literature. We considered wetland creation as distinct from wetland restoration and excluded articles that solely reported on wetland creation. Using this process, we identified 31 articles that met our search criteria (ST1). Seventeen articles reported results on independent projects in individual or multiple wetlands following the same methods or protocols. Ten articles reported results or analysis of data from multiple sources or projects following different methods or protocols (e.g., wetlands enrolled in the United States Wetland Reserve Program). Some projects resulted in multiple publications, each reporting on different aspects of the amphibian response. Four articles that did not provide details of the restoration methods were excluded from the review of methods, but overall amphibian outcomes were considered. Of these, one assessed wetlands enrolled in the United States Wetland Reserve Program, one assessed prairie pothole wetlands restored by various federal and private entities in Minnesota, USA, and the remaining two reported results within the same two wetlands in New Jersey, USA.

3. Restoration Approaches for Pond-Breeding Amphibians in GIW

Restoration practices fell into three broad focal areas: hydrology, vegetation, and ecological processes. This article does not provide a "how-to" manual or instructions on particular restoration practices. Our goal was to provide a summary of common amphibian-centric restoration practices and their importance to amphibian populations along with a review of the evidence of their efficacy. Readers interested in technical guidance should refer to the papers cited in this review and materials available through the Society for Ecological Restoration [26], the RAMSAR Convention [37], the United States Environmental Protection Agency [38], and Natural Resource Conservation Service [39], among others.

Most restoration projects employ multiple techniques; therefore, following a review of methods, we holistically review the evidence that restoration of geographically isolated wetland habitat benefits pond-breeding amphibians.

3.1. Hydrology

Pool hydrology is perhaps the single most important factor determining wetland suitability for any given pond-breeding amphibian species. Climate and hydrogeomorphic setting (i.e., landscape type and position) are the dominant controls of geographically isolated wetland hydrology [40]. While climate determines the amount of available water, hydrogeomorphic setting influences the flow of water into and out of the wetland [40–42]. Hydrology in geographically isolated wetlands is often defined in terms of hydroperiod, which refers to the timing and duration of inundation. In these habitats, hydroperiod varies along a continuum from nearly permanent (water present throughout the year) to extremely temporary (water limited to weeks or even days) and additionally fluctuates by season and year [43]. Similarly, breeding and developmental phenology differs widely among pond-breeding amphibians. For instance, some species require wetlands that fill early in the breeding season to prevent desiccation of eggs deposited terrestrially in anticipation of filling (e.g., *Ambystoma* spp.). Others rely on short hydroperiods to limit predators and competitors (e.g., *Anaxyrus americanus*, *Hyla chrysoscelis*, *Litoria aurea*), while extended hydroperiods support the longer developmental periods of some species (e.g., *Rana clamitans*, *Rana capito*, *Rana muscosa*) [12,15]. Ideally, ponds of varying hydroperiods are distributed throughout the landscape such that in most years optimal habitat is available for the greatest number of species [44,45]. Changes in hydroperiod may have critical consequences to amphibian populations, particularly those that are adapted to specific hydroperiod regimes [31,43,44,46]. This can be especially apparent when restoration is focused on a single pond or species [47–49].

Hydrological Restoration

Outside of landscape-level projects (discussed below), hydrogeomorphic setting is rarely a restoration target. More often, restoration focuses on local controls including pool form (e.g., area, depth), vegetation cover, and water movement. These secondary controls fine-tune wetland hydroperiod; however, achieving a precise hydroperiod, except permanent ponding, within a single wetland is unlikely [50]. Restoration of pondscapes (i.e., multiple ponds in a given area) is more likely to provide suitable wetland hydroperiods for the greatest number of species [51,52]. While wetland hydrology can be difficult to manage, hydrological restoration is a common goal of many restoration projects.

In current or former agricultural areas, geographically isolated wetlands are commonly drained to increase the acreage of arable land [23,24]. Hydrological restoration may require plugging of ditches, removal of berms and dikes, or disabling subsurface drainage systems (e.g., tile drains) [53–57]. Removal of accumulated sediments can also increase wetland area and depth [58]. Sedimentation frequently occurs in agricultural areas, but may also occur in other human-altered landscapes, including via succession in the absence of disturbance [52,59–61]. Artificial methods to extend hydroperiods have been used to protect critical populations from premature pond drying. For instance, a number of studies report installation of rubber or concrete liners within pond basins or barriers to prevent outflow [48,49,62,63]. Water supplementation has been used on rare occasions for high-risk populations; logistical and cost constraints limit the feasibility of this strategy for most geographically isolated wetlands [47,64,65]. While not reported among the articles reviewed here, upland snow and runoff management offer promise for hydrologic management [66]. Other upland management practices including vegetation management, burning, and grazing can also influence wetland hydrology [67]. Restoring vegetation has multiple benefits; therefore, we discuss it more fully and separately below.

3.2. Vegetation

Plant communities exert strong influence on the distribution, abundance, and performance of amphibians (reviewed in [68]). For many amphibians, wetland vegetation is used as a structure for calling during courtship and as a substrate for oviposition, where eggs are physically attached to plant stalks, branches, or leaves. Living plants, detritus, and downed woody debris also create surfaces for the growth of biofilms grazed by herbivorous tadpoles [69,70]. Variation in plant nutrients (e.g., carbon, nitrogen) and phytochemical concentrations (i.e., secondary plant metabolites such as phenolics, tannins, and saponins) can have substantial effects on larval amphibian performance through effects on primary and heterotrophic production [69]. Structurally complex environments can also create a wide range of microclimates, as well as moderate competition and predation risk [71–73].

Plant community change can cause variation in biotic and abiotic conditions that adversely affect amphibian populations. For instance, increased vegetation cover can cause variations in water temperature that influence larval growth and development [14,74,75]. Among wetlands, differences in productivity are often attributed to variation in leaf litter chemistry [69,70]. Generally, allochthonous tree litter is more nutrient poor, more recalcitrant to decomposition, and contains higher levels of phytochemicals than herbaceous vegetation [76,77]. Differences in detritus quantity or quality can have large effects on larval amphibian performance (reviewed in [68,69]). Additionally, high concentrations of leached phytochemicals are capable of disrupting larval amphibian physiology, leading to increased mortality and decreased growth (reviewed [68,69]). Invasion by nonnative plants may pose additional risks for developing tadpoles and favor generalist or nonnative amphibians [78–80]. Increasing tree, shrub, or perennial plant cover within wetland basins and surrounding uplands can also contribute to a self-reinforcing cycle of decreasing hydroperiods and accelerated succession, ultimately converting wetlands to more terrestrial conditions [81,82].

Vegetation Restoration

Restoration of wetland or surrounding upland vegetation, whether removal or revegetation, is frequently paired with hydrological restoration. More than half of the restoration projects in this review included some form of vegetation management, with removal slightly more common than revegetation. Removal of vegetation is undertaken most frequently to counteract seral succession within wetland basins and margins [17,48,52,83,84]. In the absence of natural disturbance or management, many geographically isolated wetland types will succeed to upland habitats. Succession via effects on light and detritus quality alters wetland ecology, including productivity, predator–prey dynamics, and amphibian occupancy [69]. Excess vegetation and sediment also influence wetland hydrology via effects on evaporation, transpiration, and precipitation runoff [42]. Sediment removal or dredging may be conducted with dual goals of restoring wetland hydrology and removal of excess vegetative growth [52,58]. Invasive plant species may need to be controlled in some habitats [46,55–57]. Revegetation may be required in highly disturbed or former agricultural areas to restore native plant communities [54,85–88].

Removal of vegetation in fire-dominated systems frequently involves prescribed fire or fire surrogates and is often paired with mechanical (e.g., mulching, felling) and herbicide treatments [56,83,84]. In forested wetlands, tree girdling and felling, particularly within the wetland margin, are used to increase light penetration and reduce evapotranspiration [17,55]. In current or former agricultural landscapes, active revegetation of uplands surrounding wetlands via seeding or tree planting is common [54,86–88]. Increased herbaceous or emergent plant cover within wetland basins and margins via passive regeneration (i.e., from soil seedbanks) is often expected following vegetation or sediment removal treatments [59,83,84]. However, naturally regenerating plant communities may be slow to respond to these restoration treatments [59,83,84]. Microtopography (small variations in basin surface height) can influence plant community development; however, no studies reported efforts to restore microtopography [89]. It is important to note that restoration of ecological processes (e.g., prescribed fire, grazing) also impacts plant community structure and function (discussed below).

3.3. Ecological Processes

Many ecological processes are important in shaping geographically isolated wetlands and their amphibian communities, including competition, disturbance, nutrient flux, predator–prey dynamics, and primary production. Within the context of processes commonly targeted for restoration and management, there are three key ecological processes vital to the maintenance of these unique habitats: natural disturbance, its converse succession, and predation. A variety of natural disturbances shape geographically isolated wetlands, including fire, wind, flooding, and ungulate grazing [1,78,90]. The effects of natural disturbance are often most apparent in alterations to vegetation. In the absence of natural disturbance, geographically isolated wetlands are prone to seral succession leading to wetland conversion to more terrestrial states [91,92]. As wetland hydroperiods and plant communities change, amphibian populations are affected through alterations of the abiotic (e.g., temperature, nutrients) and biotic (e.g., resource availability, competition) environment [68,92]. Frequent drying and wetting cycles may interact with these disturbances to impact community development [81]. Wetland drying, also a form of disturbance, prevents many geographically isolated wetlands from harboring resident fish communities [1,51,64]. Fish are effective predators of amphibian eggs and larvae [6,44,93,94]. While some amphibians are successful in wetlands with fish or other predators, amphibian richness and abundance sharply decline in geographically isolated wetlands with fish [93,95]. Fish may be introduced to wetlands naturally, e.g., via flooding [96], but in many cases are intentionally released by humans [94,97].

Ecological Process Restoration

While all restoration aims to restore ecosystem function [26,27], some projects specifically target the reinstatement or modification of specific ecological processes. Restoration of ecological processes is often required in disturbance-driven systems (e.g., fire, ungulate grazing, wind). Vegetation overgrowth is common in geographically isolated wetlands where natural disturbance processes (e.g., fire) have been eliminated or reduced below their historical range of variability (i.e., the historical frequency, intensity, and duration of disturbance) [81,91]. The need to maintain geographically isolated wetlands at an early seral stage is most often attributed to the presence of rare or threatened species [48,83,98], but may also be undertaken to restore communities in unique habitats [56,57,84]. Some wetlands may harbor fish introduced either naturally or deliberately [44,52,64,99]. Infrequent drying can also generate robust macroinvertebrate populations that prey on amphibian eggs and larvae [13]. Predator management, particularly of fish, may be essential to ensure successful amphibian reproduction and recruitment for sensitive species [44,100]. Restoration of specific ecological processes is often part of a broader suite of restoration methods used to restore a wetlandscape or habitat for species of special concern [48,52,56,57,64].

Fire disturbance in wetland basins and margins is the most frequently restored ecological process [56,57,83,84,98]. Reinstating historical fire-driven conditions may require pre- or postrestoration mechanical removal or herbicidal treatments of vegetation. Prescribed fires are conducted within a limited range of historical fire variability that balances effectiveness and safety [101]. In systems with long-term fire suppression, high fuel loads may prohibit safe fire application [101]. Conversely, low fuel loads or fire intensity may not kill mature trees or eliminate undesirable propagules, wasting valuable time and money [101].

Restoration of other disturbance-driven processes also targets plant community development. For instance, reinstatement of grazing pressure to maintain herbaceous communities and cessation of beach cleaning to reinstate dune-forming plant communities were used in the UK to restore natterjack toad (*Bufo clamitans*) habitats [48]. Predators, most often fish, are usually managed on an individual wetland basis. Artificial wetland drying via pumping was reported for fish removal in two studies [52,64], but chemical treatments (i.e., piscicides) may be used [99]. Chemical treatments affect target and nontarget gill-breathing organisms; therefore, this method should be reserved for special circumstances and only undertaken by licensed professionals. Furthermore, unless restoration addresses the root cause of fish introduction, treatments will likely be unsuccessful or need to be repeated.

3.4. Landscape Considerations

The above local controls and restoration practices should also be viewed within a landscape context. Geographically isolated wetlands are embedded in and intimately interconnected with their surrounding uplands [102]. For pond-breeding amphibians, aquatic and terrestrial habitats are unique but complementary habitats: both habitats are required to support healthy populations. While healthy wetlands are necessary for the production of juveniles, the terrestrial matrix supports survival and growth to maturity. Individual amphibian species have variable, and oftentimes specific, terrestrial habitat requirements; however, all uplands should have abundant natural vegetation including ground cover and (or) plant detritus. Terrestrial vegetation structure provides refuge from harsh environmental conditions and predators (reviewed in [68]). Plant productivity and diversity drives the abundance of invertebrates that form the basis of most amphibian diets post-metamorphosis [103]. The terrestrial matrix is also a critical factor for successful migration and dispersal movements of juveniles and adults. Among pond-breeding amphibians, juveniles are the primary dispersal stage, with most adults remaining near the same wetland or wetland complex [9,19]. Whether populations are primarily described as patchy (i.e., high dispersal rates between neighboring wetlands) [19] or metapopulations (i.e., low but consistent dispersal rates between neighboring wetlands) [9], connectivity is influenced by climate, wetland characteristics, and the quality of the terrestrial matrix [102,104]. Pond-breeding amphibian recruitment is highly stochastic and may fail annually due to unpredictable factors such as drought or disease outbreak. Maintaining connectivity between wetlands and wetland complexes allows recolonization to occur through juvenile dispersal and adult recolonization at the local and landscape scale [6,9,19,22]. The abundance, density, diversity, and spatial arrangement of wetlands is also important [102,104,105]. To support robust and diverse pond-breeding amphibian populations, wetlands should be abundant and represent a range of hydroperiods within the annual migration distances of adults, as well as within dispersal distance of emigrating juveniles. Ideally, this means clusters of interconnected wetlands at the local scale and, at the landscape scale, connection between local clusters by more dispersed wetlands that act as aquatic stepping stones between clusters [105].

Landscape-Level Restoration

Many studies investigating the outcome of restoration treatment on amphibians occurred with the context of broader landscape restoration initiatives. This is particularly true in the United States, where many wetlands and surrounding terrestrial matrices have been restored under a variety of U.S. Department of Agriculture programs (e.g., Wetland Reserve Program). These programs aim to transition marginal arable land from production and into conservation for multiple goals, including clean water and wildlife habitat. Within former agricultural landscapes, restoration often focused primarily on restoring hydrological function through combining within pond and broader landscape treatments (e.g., drainage removal, upland revegetation) [54,62,87,88,106]. Many landscape-level restoration projects also occurred within historically disturbance driven systems where disturbance prevention led to widespread seral succession [48,83,84,98]. Often, these projects focused on restoring ecosystem processes (e.g., prescribed fire, grazing) site-wide across habitat types, but also included directed wetland treatments (e.g., vegetation removal). Habitat restoration for wildlife conservation was an explicit goal. Landscape-scale restoration also occurred on degraded land. These sites required a suite of methods to restore site-wide structure and function [32,51,56,57,62,107]. Some projects discussed goals or design considerations beyond individual wetlands, but did not actively manage habitat beyond the wetland [51,86,106]. For example, Rannap et al. [52] paired wetland restoration with creation across multiple protected areas in Estonia. The authors spatially clustered wetlands explicitly to achieve landscape-level goals including dispersal, variation in hydroperiods, and availability of suitable upland habitat.

4. Evidence That Restoration Benefits Amphibian Populations/Amphibian Conservation

Restoration projects occur in a variety of contexts worldwide, though the literature is skewed towards temperate wetlands within North America. Geographically isolated wetland types included prairie potholes, playas, dewponds, vernal pools, Carolina bays, and ephemeral wetlands in hardwood, flatwoods, and longleaf pine forests, as well as in dune and heath habitats. The majority of amphibian-centric restoration projects in geographically isolated wetlands have reported positive outcomes. There is no indication that restoration outcomes depend on wetland type or location.

The most common conclusion of amphibian-centric restoration projects is that restoration can play an important role in amphibian conservation. The metrics used to evaluate success vary greatly, but restoration can lead to an increase in amphibian occupancy [52,54,55,87,88,106], abundance [58,99], and (or) species richness [17,58,59,84,87,88]. Successful restoration was often associated with restoring both hydrology and vegetation [51,52,54,55,58,87,88]. Below, we address outcomes of restoration methods used alone, and then in combination.

4.1. Hydrology

Hydrological restoration was rarely performed in isolation and yielded mixed results. Typically, the goal is to restore longer, but nonpermanent, hydroperiods by plugging ditches [54,55], removing drainage tiles [54,57,106], installing liners [62,63], or dredging sediment [51,52,64]. Plugging ditches or removing tiles was never done in isolation. Plugging ditches and removing berms, in conjunction with removal of invasive species, led to increased wetland depth and a longer hydroperiod [55]. Though not quantitative, call surveys suggest that frogs were more likely to be heard in restored wetlands. A suite of restoration treatments, including removing drainage tiles, prescribed fire, invasive plant removal, and canopy thinning, were applied to wetlands in Illinois, USA [46]. The authors did not report data on changes in wetland hydrology, but did demonstrate that levels of dissolved oxygen were higher in restored ponds and this improved hatching success of salamander larvae. Three studies involved installing liners to improve breeding habitats for conservation of target species [49,62,63]. In one study, lined wetlands recharged earlier and held water longer than unlined ponds. Repatriated aquatic larval striped newts (*Notophthalmus perstriatus*) were able to develop to the eft stage in these wetlands, but no newt breeding was observed [49]. Despite the potential for upland management to influence wetland hydrology, no studies explicitly linked upland management (e.g., grazing, burning, planting) with changes in pool hydrology. Creating a specific hydroperiod can be challenging and lined wetlands can become more permanent, allowing predators to become established and limiting recruitment of target species [63]. While lining wetlands can alter hydrology for the long term, some studies used single season efforts to extend wetland hydroperiod [47,64,65]. For example, in a successful attempt to avoid complete larval mortality, Seigel et al. [47] added over 350,000 L of well water to one wetland. This effort resulted in successful production of metamorphs of the endangered dusky gopher frog (*Rana sevosa*). In general, water supplementation does not restore wetlands, but can be used as an emergency measure.

Another method used to restore wetland hydroperiod involves removing sediment buildup. While four studies included removing sediment [51,52,64,85] as part of a larger restoration effort, there were two [58,59] that removed sediment as the only restoration treatment. In both studies, sediment was removed from wetlands impacted by agricultural practices [58,59]. Based on call surveys, Stevens et al. [58] detected more species in restored wetlands and more individuals of some species (spring peepers [*Pseudacris crucifer*], northern leopard frogs [*Rana pipiens*], and green frogs [*Rana clamitans*]). Beas and Smith [59], on the other hand, used more extensive sampling methods across two years of surveying and found less obvious success. In a wet year, there was no difference in species richness across reference, restored, and cropland wetlands. However, in a dry year, more species bred in the restored than cropland wetlands. Thus, the restored wetlands may provide the most reliable breeding habitat [59]. Importantly, neither study indicated negative impacts of removing sediment with heavy machinery [58,59]. By necessity, dredging sediment removes the standing vegetation and, qualitatively, it did appear that the herbaceous community was altered in restored wetlands and that the dredge piles themselves can sustain unique vegetative communities [58].

4.2. Vegetation

All wetland restoration can influence the vegetation, making it challenging to directly assess the impacts of targeted vegetation removal or revegetation. Restoration efforts rarely included only vegetation, but many attempted to restore hydrology and vegetation [48,52,55,57]. Often the goal is to create a more open-canopy, herbaceous wetland by removal of woody vegetation [81]. Thus, many studies included tree removal as one of several components of the restoration effort [17,83–85]. Removal of woody vegetation was the only treatment in three studies [17,83,84], although in two of these, ecological processes were also reestablished because fire was used to remove vegetation [83,84]. Restoration of wetlands by felling trees to remove the forested overstory resulted in higher species richness in restored wetlands and in higher prevalence of species considered intolerant of closed-canopy conditions [17]. Similarly, species richness was higher in wetlands where the midstory was removed via a combination of mulching and burning, but not when using only fire or mulching [84]. In a separate study, reduction in wetland midstory failed to yield differences in amphibian species richness, regardless of methodology used [83]. That study's goal was to reduce the woody midstory of 21 wetlands in Florida to benefit the federally endangered reticulated flatwood salamander (*Ambystoma bishopi*) [83]. Canopy cover was reduced more effectively with a combination of mechanical removal and herbicide application than by burning, but no treatments led to a recovery of the herbaceous layer [81] thought to be critical for reticulated flatwood salamanders [108,109]. In this study, and several others, the herbaceous layer was expected to respond passively [59,83,84]. However, within the time frame of the study, treatments did not influence the percent herbaceous ground cover [83,84] or emergent cover [59]. Klaus and Noss [84] did find that mulching and burning reduced leaf litter depth and that this, in combination with canopy reduction, was associated with richness of amphibian species considered to be longleaf pine specialists. There were several studies that involved active revegetation, but this was done in the uplands as part of landscape level restoration, rather than in the wetland basins e.g., [51,52,54,86–88]. Terrestrial habitat restoration can be an important component, as seen in Rannap et al. [52], where colonization was more than twice as likely in wetlands surrounded by forests than meadows.

4.3. Ecological Processes

Wetland restoration efforts often included reestablishment of disturbance [48,57,83,84,98] or removal of predators [52,64,99]. As mentioned above, fire was reintroduced as a method to remove woody vegetation, open the canopy, and restore the herbaceous layer of vegetation in wetlands that had experienced fire suppression [83,84]. In two studies, the use of fire alone was inadequate. It appears that after extensive fire suppression, it may be necessary to use mechanical means to initially reduce the encroached woody vegetation [83,84]. Fire is not the only disturbance that historically prevented seral succession in wetlands. In some areas, grazing by ungulates influences the structure and function of plant communities and ecosystems [110]. In terms of wetlands, there has been considerable research examining the impacts of livestock grazing [111–114]. Grazing can affect many aspects of the wetland ecosystem, including aboveground biomass, plant community composition, nutrient conditions, and litter accumulation [115,116]. From a restoration standpoint, we are not aware of efforts to reestablish grazing within wetland basins specifically to improve habitat for amphibians. This is surprising, given that grazing can impact wetlands in ways that are beneficial to local amphibians [111,117]. Denton et al. [48] did use grazing to restore uplands around natterjack toad breeding areas. Their approach was multipronged, with upland restoration, reintroductions, pond creation, introduction of grazing, and removal of competitors. Even with this holistic approach, there was strong evidence that using grazing to prevent encroachment of scrub and trees was a critical component of ecosystem restoration [48]. However, in some contexts, grazing within wetland basins can be detrimental to amphibians and wetland health [118]. It would be advantageous to explore the potential of grazing to restore aquatic habitats, especially given the similar role of fire and herbivory in shaping ecosystems [119].

Rather than reestablishing disturbance, some wetlands were restored by attempting to reverse ecological disturbances. For example, fish can establish in wetlands via human introduction [94,97], connectivity from ditches [120] or flooding [96]. We found three restoration efforts that included removal of fish [52,64,99]. In all three studies, data were collected pre- and posttreatment, making for stronger conclusions. Fish were successfully removed by draining [52,64] or application of rotenone [99]. When fish removal was the sole restoration treatment, it resulted in increased recruitment in four of five target amphibian species [99]. When combined with numerous other restoration treatments, there was a clear, and positive, relationship between occurrence of target amphibian species and elimination of fish [52]. In fact, landscape-level restoration efforts using multiple approaches were consistently the most successful.

4.4. Landscape Considerations

Overall, most restoration efforts recognized that hydrology, vegetation, and (or) ecological processes operate at local and landscape scales and addressed a combination of these factors among suites of wetlands across landscapes [48,51,54,56,62,83,84,86–88,106]. Most of these studies reported at least some successful outcomes for amphibians [48,51,54,56,62,84,86,87,106]. In fact, the only unsuccessful landscape level restoration also had the shortest time frame (2 years) for evaluating the response [83]. Some of the most successful results were found when some [54], or all [87,88] of the restored wetlands were part of the United States Department of Agriculture's Natural Resources Conservation Service's Wetlands Reserve Program (WRP). The wetlands restored under the WRP occurred on private lands in agricultural landscapes, and restoration typically included cessation of agricultural use, lengthening the hydroperiod, and revegetating the surrounding uplands. All three studies found higher occupancy and species richness in WRP wetlands compared to unrestored agricultural wetlands [54,87,88], but when compared to reference wetlands, occupancy was lower [54].

Another approach at the landscape level included creation of new wetlands [51,52,106]. For example, Rannap et al. [52] undertook a large-scale effort to restore and construct wetlands for two target species: the crested newt (*Triturus cristatus*) and common spadefoot (*Pelobates fuscus*). They constructed 208 new ponds and restored 22. Restoration included removing sediment until the mineral soil was exposed, but when needed they also removed vegetation, pumped some wetlands dry to eliminate fish, and in some cases enlarged the ponds. It is very challenging to evaluate the success of wetland restoration per se in this context. However, they did demonstrate that restoration of the entire landscape (including adding wetlands) can have rapid and positive conservation outcomes. Similarly, Petranka et al. [51] evaluated the success of a landscape-scale wetland mitigation effort. In this case, some wetlands were created, surrounding streams were restored, and uplands were reforested. While no existing wetlands were directly restored, restoration in the surrounding landscape would alter wetland hydrology and vegetation dynamics. A critical component of this work was long-term population monitoring of two species: wood frogs (*Lithobates sylvaticus*) and spotted salamanders (*Ambystoma maculatum*). By monitoring breeding efforts and juvenile production for 13 seasons, they were able to demonstrate spatial and temporal fluctuations in breeding success due to factors such as drought and disease. Overall, populations of both species appear to be resilient, and the authors point to the importance of having many diverse breeding habitats for long-term persistence [51]. Mushet et al. [86] draw similar conclusions by evaluating the habitat suitability for five amphibian species across a landscape (~200 km^2) where croplands were restored to grasslands. In this case, wetlands were not directly restored or amphibians monitored, but the habitat suitability analysis results demonstrated that grassland restoration efforts worked and that conservation of the amphibian community requires an ecosystem approach to maintain diverse upland and wetland habitats [51].

4.5. Limitations

As can be seen above, there have been numerous efforts to restore geographically isolated wetlands and evaluate the impact on pond-breeding amphibians. However, it is challenging to evaluate the overall level of success these efforts have achieved toward amphibian conservation. This is due, in part, to several limitations of study designs and approaches, including variation in metrics of success, spatial scale, and temporal scale, as well as stochasticity of amphibian populations. We found a lot of variation in the types of data collected to evaluate success. This variation included how the amphibian response was measured, as well as what the postrestoration data were compared to. For example, surveys of amphibians ranged widely and included call surveys [55,58], estimates of habitat suitability [86], various measures of community metrics, e.g., [17,52,56,84,87], successful development e.g., [47,63], and long-term population analyses [108]. In addition, these measures could then be compared to data from the same wetlands pre-restoration, e.g., [63,64,83], unrestored but degraded wetlands, e.g., [86–88], and (or) reference wetlands deemed to be in good condition, e.g., [17,58,83,84]. Variation in data and "reference" types can influence the overall determination of success or failure. For example, in Balas et al. [54], hydrology was restored by a combination of ditch plugging or tile destruction, and uplands were reseeded to perennial grasslands. While the restored wetlands had higher occupancy than agricultural wetlands, they did not achieve the occupancy levels of reference wetlands.

The spatial and temporal scales of wetland restoration also differed greatly. In the Balas et al. [54] example above, data were collected 10 years after restoration, for two seasons, in 36 wetlands spanning three states in the U.S. It is hard to know, without long-term continuous monitoring, how long it took for the amphibian community in the restored wetlands to rebound. In other studies, data were collected within just a few years. Restoration may be deemed a failure in the short term, but could be successful long term, especially when using passive revegetation, e.g., [83]. In general, restoration of hydrology can occur quite rapidly, e.g., [36,121]. For example, installing pond liners should immediately affect wetland hydrology, but the recovery of desired structure and function can be much slower, especially for inland depression wetlands [36]. Even after 50 years, the biological and biogeochemical properties of restored inland depression wetlands may not be recovered [36]. Once wetlands recover, the amphibian response will still vary depending upon many variables. Climatic conditions play a critical role in amphibian population dynamics [122] and the breeding population of amphibians can be highly variable among years [123,124]. For restorations that focus on target taxa, the likelihood of success will be affected by numerous factors, including generation time, population status before restoration, availability of source populations, and whether reintroductions are included. Success of these targeted efforts is hard to compare to community-level analyses where the goal may be overall richness. Long-term monitoring is recommended in either case, but Greenberg et al. [34] demonstrated that monitoring amphibians at wetlands, even for long time periods, is not sufficient for evaluating population trends at the landscape level. Consequently, it is difficult enough to assess whether a specific wetland restoration endeavor was successful, let alone to compare across studies and make broad conclusions about which methods are most effective.

5. Recommendations and Future Research Directions

5.1. Recommendations

(1) Integrate landscape-scale factors during the planning stages. Stable populations require suitable aquatic and terrestrial habitats within migration and dispersal distances. Evaluate upland habitat and, if necessary, consider explicit terrestrial restoration goals. When feasible, restore wetlands in clusters with multiple clusters dispersed across the broader landscape. Wetlands should represent a range of hydroperiods: including very long and very short hydroperiods may increase population persistence during extreme weather years and promote resilience under global change.

(2) Incorporate multiple restoration methods or targets. Achieving the greatest success when applying multiple approaches was a consistent outcome. In practice, if hydrological restoration is the primary method, evaluate the current plant community and seedbank to determine if additional restoration goals/objectives related to vegetation are warranted. Multiple methods are particularly important for wetlands at advanced seral stages due to the reduction or elimination of disturbance. Removing vegetative overgrowth or accumulated sediment without reinstating disturbance processes (or surrogates) is unlikely to benefit amphibians in the long term.

(3) Utilize adaptive management when feasible. Adaptive management seeks to both increase our knowledge of how systems respond to management actions, thereby reducing uncertainty, and apply knowledge gains to improve management outcomes [125,126]. Because adaptive management utilizes formalized structured decision-making, following an adaptive management framework can also enhance project planning. This is particularly true for projects with multiple stakeholders and (or) objectives that must be considered and evaluated holistically. In addition to the references above, interested readers should refer to Williams [127] and Williams et al. [128] for background and technical guidance on adaptive management.

(4) Report amphibian outcomes for restoration projects and research. Improved reporting will enhance our ability to successfully restore geographically isolated wetlands and support amphibian populations. Projects with explicit goals for amphibians should clearly define the methods, time frames, and metrics used to define success. Other projects, e.g., those focused on hydrological restoration goals, should consider involving a collaborator to robustly monitor the amphibian response or minimally include basic amphibian monitoring (e.g., call surveys). Modern remote sensing or citizen science approaches can reduce the data collection burden while adding significantly to the ability to monitor amphibians. Consider collecting data utilizing a common framework to facilitate data sharing, e.g., SER Restoration Project Information Sharing Framework [129].

(5) When possible, include metrics that assess recruitment success and (or) population persistence. The presence of calling adults, eggs, and (or) tadpoles may indicate suitable habitat for breeding. However, these metrics alone do not reflect the ability of a wetland or wetlandscape to sustain amphibian populations. Metamorph abundance is a good first step. However, increased usage of robust methods for estimating population parameters (e.g., capture–mark–recapture) can contribute to assessing population persistence following restoration.

(6) Extend monitoring timelines beyond 5 years. High annual variation in amphibian breeding and success at a single wetland makes inferences regarding population persistence difficult [34,130]. Monitoring wetlands beyond the standard 5-year time point may improve statistical power [34,130]. When possible, monitoring multiple wetlands simultaneously can reduce the monitoring time required to evaluate trends and may be a better gauge of amphibian persistence at the landscape level [34]. Longer monitoring times are also essential for detecting and responding to the potential impacts of global change. In all cases, ensure that demographic units are clearly defined and independent [131]. Independent units may be ponds or clusters of ponds,

depending on several factors, including the distance between ponds and the species' dispersal distance [131].

5.2. Future Research Directions

(1) Increase research focused on the response of pond-breeding amphibians to restoration treatments. Given the long history of wetland restoration and ongoing amphibian declines, there are relatively few studies specifically investigating the outcomes of restoration on amphibian populations. Research that includes the full range of abiotic and biotic responses, including amphibians, will be most useful for sustaining biodiversity. Interdisciplinary or collaborative studies could bring valuable insight and perspectives. Special consideration should be given to less studied amphibian species, geographically isolated wetland types, and localities.

(2) Expand research questions and restoration outcomes to incorporate the broader landscape. Geographically isolated wetlands are an integral part of the broader landscape. Upland condition and management, the density and distribution of wetlands, and watershed and regional effects all influence restoration outcomes for amphibians. For most studies, it is easy to incorporate landscape variables into data analysis. When feasible, studies and projects should be designed to test factors within the broader landscape (e.g., upland management, wetland spatial distribution). Funding for restoration research needs to match these larger scales, as significantly more resources and funding will be required compared to pond-based research.

(3) Link restoration treatments to mechanisms. Early work linking restoration treatments to mechanisms includes the effects of hydrology via predation, canopy removal on resource availability, and disturbance on competition, among others. While some mechanisms are readily apparent (e.g., failed development due to insufficient hydroperiod), others are less so (e.g., resource availability, structure effects on predation). Understanding the mechanisms driving responses to restoration treatments will help improve outcomes, minimize failures, and enable us to target specific aspects of the amphibian's environment.

(4) Supporting self-sustaining systems. The paradigm of restoration has shifted away from returning systems to a prior or even reference state. Rightly so, restoration now often focuses on an ecosystem's function, resilience, and ability to self-regulate. For geographically isolated wetlands, crucial topics include reinstating disturbance regimes, surrogates for disturbance in a disturbance-limited world, and resilience in the face of global change. These topics are also important for pond-breeding amphibians, but perhaps even less tractable. Pond-breeding amphibians, and amphibian populations generally, are stochastic. Determining the stability of stochastic populations, predicting their future persistence, and promoting resilience are areas of ongoing research need.

(5) Determining and predicting long-term trends in amphibian populations. Current monitoring and statistical analysis methods require decadal-scale data to determine the population persistence of most amphibian species with any reasonable confidence. Addressing this difficulty should be a high priority in light of ongoing global amphibian declines. Recent work is illuminating some of the practical limitations and addressing methods for reducing them [34]. However, improved methods that reduce monitoring time or effort will increase our ability to determine restoration successes and failures, manage at-risk species, and recognize new declines sooner.

6. Conclusions

Restoration and preservation of geographically isolated wetlands is critical for the conservation of pond-breeding amphibians [6,8,9]. In our review of amphibian-centric wetland restoration studies, we found that common restoration practices fell into the broad categories of hydrology, vegetation, and ecological processes. While most studies reported some positive outcomes, those that incorporated a combination of efforts at the landscape scale were the most consistently successful [48,51,54,56,62,84,86,87]. There was a lack of consistency in types of data collected, metrics of success, and the spatial and temporal scales of data collection. This variation, in conjunction with the stochasticity of amphibian populations, makes it challenging to draw conclusions on which restoration methods are more likely to benefit amphibian conservation. To that end, we suggest several recommendations for restoration efforts that not only make use of prior successes but also address the need for increased standardization of data collection and dissemination for robust comparisons in the future. In addition, we outline research needs to fill gaps in our understanding of how restoration of geographically isolated wetlands impacts amphibian populations. These much-needed data will inform future restoration research and projects to maximize the benefits to pond-breeding amphibians.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/d14100879/s1, File S1: Supplementary Methods, Table S1: List of published (n = 31) and unpublished (n = 1) accounts of restoration outcomes for amphibians in geographically isolated wetlands considered in this review.

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