Environmental Reviews

Review

The effects of roadways on lakes and ponds: a systematic review and assessment of knowledge gaps

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Abstract

As the global population increases, the expansion of road networks has led to the destruction and disturbance of terrestrial and aquatic habitats. Road-related stressors have significant effects on both lotic and lentic habitats. While there are several systematic reviews that evaluate the effects of roads on lotic environments, there are none that consider their effects on lentic habitats only. We conducted a literature review to achieve two objectives: (1) to summarize the effects of roads on the physical, chemical, and biological properties of lentic environments; and (2) to identify biases and gaps in our current knowledge of the effects of roads on lentic habitats, so that we could find promising areas for future research.

Our review found 172 papers published between 1970 and 2020. The most frequently studied stressors associated with roads included road salt and heavy metal contamination (67 and 43 papers, respectively), habitat fragmentation (37 papers), and landscape change (14 papers). These stressors can lead to alterations in conductivity and chloride levels, changes in lake stratification patterns, increases in heavy metal concentrations in water and organisms, and significant mortality as amphibians disperse across roadways. We also identified a variety of other stressors that may be understudied based on their frequency of appearance in our search results, including polycyclic aromatic hydrocarbons, road dust, increased accessibility, hydrological changes, noise pollution, dust suppressants, sedimentation, invasive species introductions, and water withdrawal.

Our review indicated that there are strong geographic biases in published studies, with 57.0% examining North American sites and 30.2% examining European sites. Furthermore, there were taxonomic biases in the published literature, with most studies focusing on amphibians (41.7%), fish (15.6%), and macroinvertebrates (14.6%), while few considered zooplankton (8.3%), diatoms (7.3%), amoebas (5.2%), water birds (3.1%), reptiles (2.1%), and macrophytes (1.0%). Based on our review, we have identified promising areas for future research for each of the major stressors related to roadways. However, we speculate that rectifying the geographic and taxonomic bias of our current knowledge could significantly advance our understanding of the impacts of roads on lentic environments, thereby better informing environmental management of these important habitats.

Key words: lakes, ponds, roads, lentic, habitat, anthropogenic stress

Résumé

Avec l'augmentation de la population mondiale, l'expansion des réseaux routiers a entraîné la destruction et la perturbation des habitats terrestres et aquatiques. Les facteurs de stress liés aux routes ont des effets importants sur les habitats lotiques et lentiques. Alors que plusieurs revues systématiques évaluent les effets des routes sur les environnements lotiques, aucune ne considère leurs effets sur les habitats lentiques uniquement. Les auteurs ont effectué une revue de la littérature pour atteindre deux objectifs : (1) résumer les effets des routes sur les propriétés physiques, chimiques et biologiques des milieux lentiques ; et (2) identifier les biais et les lacunes des connaissances actuelles quant aux effets des routes sur les habitats lentiques afin de trouver des domaines prometteurs pour les recherches futures.

Leur examen a permis de répertorier 172 articles publiés entre 1970 et 2020. Les facteurs de stress associés aux routes les plus fréquemment étudiés sont le sel de déneigement et la contamination par les métaux lourds (67 et 43 articles respectivement), la fragmentation de l'habitat (37 articles) et la modification du paysage (14 articles). Ces facteurs de stress peuvent entraîner des modifications de la conductivité et des niveaux de chlorure, des changements dans les patrons de stratification des lacs, des augmentations des concentrations de métaux lourds dans l'eau et les organismes, et une mortalité significative lorsque les amphibiens se dispersent sur les routes. Ils ont également identifié une variété d'autres facteurs de stress qui peuvent être sous-étudiés en fonction de leur fréquence d'apparition dans leurs résultats de recherche, notamment les hydrocarbures aromatiques polycycliques, la poussière des routes, l'accessibilité accrue, les changements hydrologiques, la pollution sonore, les dépoussiérants, la sédimentation, l'introduction d'espèces envahissantes et le retrait de l'eau.

Leur examen a indiqué qu'il existe de forts biais géographiques dans les études publiées, 57,0 % d'entre elles portant sur des sites nord-américains et 30,2 % sur des sites européens. De plus, il existe des biais taxonomiques dans la littérature publiée, la plupart des études se concentrant sur les amphibiens (41,7 %), les poissons (15,6 %) et les macroinvertébrés (14,6 %), tandis que peu d'entre elles considéraient le zooplancton (8,3 %), les diatomées (7,3 %), les amibes (5,2 %), les oiseaux aquatiques (3,1 %), les reptiles (2,1 %) et les macrophytes (1,0 %). Sur la base de cet examen, ils ont identifié des domaines prometteurs pour la recherche future pour chacun des principaux facteurs de stress liés aux routes. Cependant, ils supposent que la rectification des biais géographiques et taxonomiques des connaissances actuelles pourrait faire progresser de manière significative notre compréhension des impacts des routes sur les environnements lentiques, et ainsi mieux éclairer les décision en matière de gestion environnementale de ces habitats importants. [Traduit par la Rédaction]

Mots-clés : lacs, étangs, routes, lentique, habitat, stress anthropique

1 Introduction

The Earth currently contains over 21 million km of roads, and models predict that several million more km will be constructed by the year 2050 (Meijer et al. 2018). While roads are vital for transportation, several studies suggest that their presence on landscapes can cause dramatic changes to both terrestrial and aquatic ecosystems. Roads are a source of physical, chemical, biological, and noise pollution for nearby natural environments (Novotny et al. 2008; Eigenbrod et al. 2009; Gavel et al. 2018). In addition, they play an important role in habitat fragmentation by acting as a barrier for the movement of organisms across the landscape (Cott et al. 2015; Hamer 2018). Given the inevitable increase in road construction over the next 30 years, understanding the detrimental effects of these structures on natural environments has become critically important.

There are a multitude of effects that roadways can have on aquatic environments. At mid-latitudes, the use of road salt has been identified as a major threat to freshwater ecosystems, particularly in urban settings (Tiwari and Rachlin 2018; Hintz and Relyea 2019). Dust originating from road surfaces can carry pollutants such as heavy metals from roads to nearby habitats, and also more remote environments via atmospheric transport (Gunter 2017; Corella et al. 2018). Stormwater that washes off roads and other impervious surfaces picks up dust, debris, metal deposits from tire wear, engine oil, and other anthropogenic materials that pollute roadside streams, rivers, and lakes (Durand et al. 2004; Ioannides et al. 2015; Zhu et al. 2019). Heavy metals tend to sorb to suspended particles as metals are weakly soluble in water, and eventually settle as sediment in and around water resources (Algül and Beyhan 2020). Both dust and metal particles can have detrimental effects on water quality, causing changes in pH, alkalinity, dissolved oxygen, and turbidity (Zhu et al. 2009; Jeong et al. 2020). In addition, metal transfer pathways in aquatic food webs allow metals to move from algae and invertebrates to larger animals such as fish, affecting ecosystems as a whole (Chen et al. 2000). Fragmentation and landscape change created by road construction, as well as the urbanization that often accompanies this, can have detrimental effects on freshwater ecosystems by creating barriers to migration, destroying habitat, causing direct mortality to organisms, and increasing the probability of the introduction of invasive or non-native species (Cott et al. 2015).

Despite the rich literature on the effects of roads on aquatic habitats, past studies have focused primarily on lotic environments (i.e., streams and rivers), while fewer studies have explored the potential effects on lentic environments (lakes and ponds). Lentic environments represent key habitats for many species, are important sources of drinking water, and are valuable cultural, aesthetic, economic, educational, and scientific resources (Downing et al. 2006; Dudgeon et al. 2006). Lentic environments are also likely to respond differently than lotic environments to stressors due to differences in physical characteristics such as water volume and residence time between these two types of habitats (Hilton et al. 2006). To our knowledge, a current systematic review synthesizing what has been learned about the effects of the many roadway-induced stressors on lakes and ponds does not exist. An up-to-date systematic review would assist with prioritizing research efforts and could provide valuable insights relevant to the management of roadside lakes and ponds.

For this study, we performed a literature review on the impacts of roadways on lentic environments. From the literature, we were able to identify 172 field studies which investigated the effects of roads on lakes and ponds and identified gaps in our knowledge about how roadways affect water quality and organisms. Specifically, we investigated: (*i*) stressors associated with roads that affect lakes and ponds, (*ii*) spatial variation in these stressors, and (*iii*) the aquatic organisms affected by these stressors. Based on this review, we provide information that can be used to prioritize research and better predict the potential environmental impacts of future road projects on lentic environments.

2 Approach

We performed a literature review to identify field studies that investigated the impacts of road development, road maintenance, and road activity on water quality and aquatic organisms in lakes or ponds using Google Scholar and Web of Science (Web of Science Core Collection). The search terms used can be found in the Supplementary material. For Google Scholar, we reviewed the first 200 results for each search, and we reviewed all 1393 references returned by the Web of Science searches. We screened the titles, abstracts, and, if necessary, the full text of these papers, and irrelevant publications were discarded. Relevant theses or government reports returned by Google Scholar were included. Those kept were solely papers detailing field studies, investigating the effects of roads on at least one lake or pond published between 1970 and 2020. This left us with 72 papers from Google Scholar, and 143 from Web of Science. As 43 of these papers were duplicated by the two search engines, that left us with 172 papers in total. These papers were assessed to determine which road-induced stressor they investigated, with some papers considering multiple stressors (Supplementary Table S1), and which aquatic organisms were involved in the study, if any (Supplementary Table S2). Aquatic organisms were assessed according to higher taxonomic groupings (e.g., fish, birds) rather than at the individual species level.

3 Description of research to date on the effects of road stressors on lentic environments

Our review of the literature showed that road construction, road use, runoff from roads or road maintenance were linked to, or were suggested to be impacting water quality, sediments, and aquatic organisms in lentic environments. There were only nine relevant studies published between 1970 and 1998, after which the number of publications began to increase, with 66 studies published between 1999 and 2010, and 97 studies published between 2011 and 2020 (Fig. 1). Of these studies, 67 (31.5%) of studies investigated road salt, 43 (20.2%) investigated heavy metals, 37 (17.4%) investigated habitat fragmentation, and 14 (6.6%) investigated changes in the landscape surrounding lentic habitats (Fig. 2). Other stressors identified included road dust, polycyclic aromatic hydrocarbons (PAHs), accessibility, hydrology, dust suppressants, noise, sedimentation, invasive species, and water withdrawal for construction of ice roads in northern environments.

Studies were found in all continents except Antarctica (Fig. 3), with the majority of studies (98; 57.0%) conducted in North America, and studies from Europe and Asia making up most of those remaining (52; 30.2% and 16; 9.3%, respectively; Fig. 4). In North America, there was a similar number of studies conducted in the USA and Canada (52 and 45, respectively), with one study investigating the Great Lakes straddling both countries. Eighteen European countries were represented in the literature, with the majority of studies taking place in France and Norway (ten studies each), Poland, the UK, Spain, and Germany (four studies each), and Greece (three studies). Six Asian countries were featured in the literature review, with most of the studies taking place in China (seven studies), India (three studies), and Iran and Japan (two studies each). The types of road-induced stressors investigated varied between continents (Fig. 5). In Asia, heavy metals made up the majority of studies, while in North America most of the studies focused on road salt, and in Oceania the focus was on habitat fragmentation (Fig. 5). In Europe, three stressors were the focus of a similar number of studies: habitat fragmentation, heavy metals, and road salt (Fig. 5). South America and Africa had only one study apiece, and so were excluded from this breakdown.

Of the 172 studies found in the literature review, 95 investigated the effects of road-induced stressors on aquatic organisms. The most studied taxon was amphibians (40; 42.1%), while fish and macroinvertebrates were next (15; 15.8% and 14; 14.7%, respectively; Fig. 6). The road-induced stressors investigated in each study varied with the aquatic taxon studied. For semiaquatic organisms (i.e., amphibians, reptiles, and water birds), fragmentation and landscape change were the most prevalent stressors studied (70.2%–100% of studies for each taxa; Fig. 7). For the remaining taxa, road salt was the most studied stressor (33.3%–50.0% of studies for each taxa; Fig. 7) except for fish, where road-induced accessibility was the most studied stressor (33.3% of studies; Fig. 7).

3.1 Road salt

Though now seen as an obvious pollutant, it was not until the 21st century that road salt was seen as a major environmental issue, as investigators in past studies found it difficult to establish road salt as the point source contaminant (Judd 1970; Kattner et al. 2000). There is very little doubt now that road salts are eventually flushed into lentic environments, where they cause geochemical changes to water and sediment quality, which in turn affects aquatic organisms (Roe and Patterson 2014; Roinas et al. 2014). Our literature review found that road salt was the most investigated stressor on lakes and ponds (Fig. 2), due to the large number of studies conducted in Canada, the northern USA, and northern Europe (Fig. 3), where the high latitude and harsh winters deemed necessary by policy makers the use of de-icing salts on roads to maintain road safety.

3.1.1 Effects of road salt in lentic environments on water and sediment

A common pattern found in lentic environments affected by road salt are increases in conductivity and changes in water density. Conductivity increases were strongly correlated with sodium and chloride ions rather than a balance of salts (Meriano et al. 2009; Kelting et al. 2012; Tixier et al. 2012; Roe and Patterson 2014). This almost 1:1 molar relationship between chloride and sodium in lakes suggests that NaCl, used as a de-icer, is likely the point source pollutant for conductivity increases in urban lakes (Novotny et al. 2008; Palmer et al. 2011). Increases in dissolved salts, salt ions, and conductivity have been linked to the increasing application of road salts, road density, road proximity/distance, runoff systems, and % impervious surface in the surrounding area (Rosenberry et al. 1999; Novotny et al. 2008; Kohli et al. 2017; Bunbury et al. 2020). Identifying the linkage between increasing conductivity and dissolved salt concentrations in lentic environments with road salt application in the surrounding area has been facilitated by long-term monitoring of water quality (Molot and Dillon 2008; Yao et al. 2016; Scott et al. 2019; Nava et al. 2020) and analysis of sediment cores (Siver et al. 1999;

Fig. 1. Number of published studies investigating the effects of roads on lakes and ponds (gray bars, left axis), and the cumulative number of studies published (black circles, right axis).

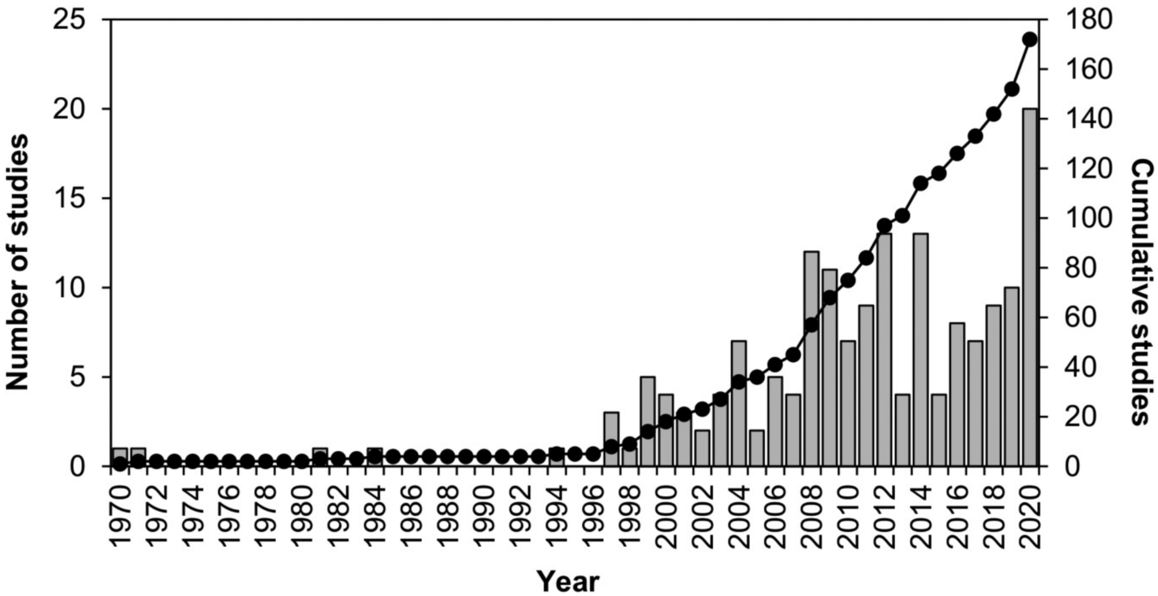
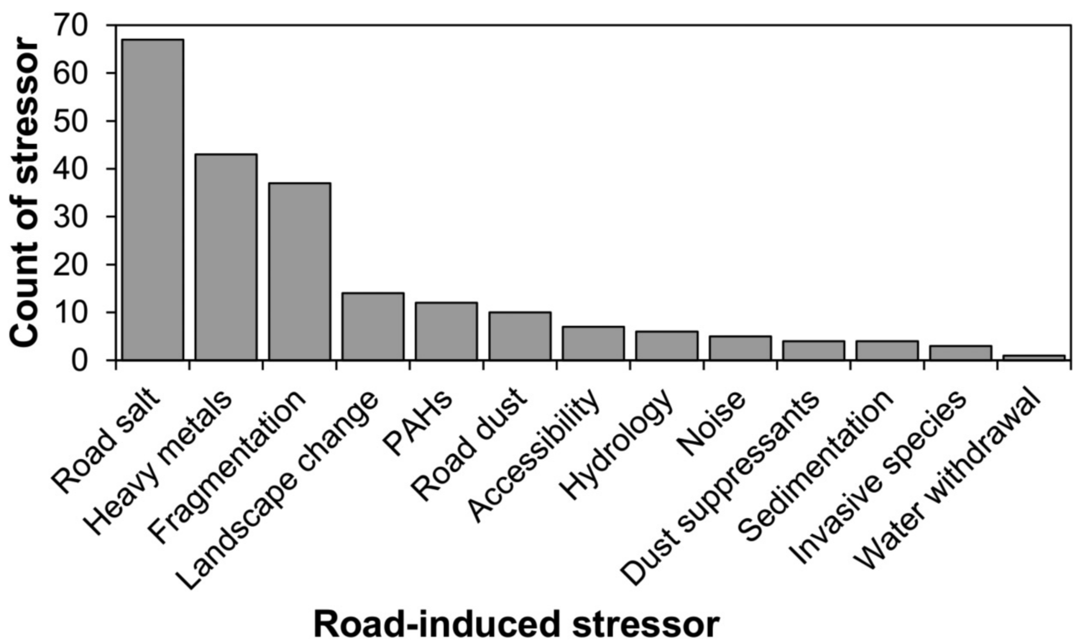


Fig. 2. Number of studies focused on a given road-induced stressor on lakes and ponds.



Ramstack et al. 2004). Seasonality in conductivity and salt ions has been noted by multiple studies, reflecting the use of road salt in the winter months (Murphy and Stefan 2006; Novotny et al. 2008; Tixier et al. 2012; Rogora et al. 2015), with winter snowmelt at the end of the season or during thawing events producing a peak in inputs of road salt (Palmer et al. 2011; Fournier et al. 2022). In North America alone, 14 million tonnes of road salt are applied annually (Environment Canada 2001), and some studies have shown that ~50% of the road salt applied to roads is present in nearby waterbodies due to surface runoff (Meriano et al. 2009; Mueller and Gaechter 2012).

Chloride concentration has been found to be up to 300% higher than in natural conditions in lentic environments affected by road salt, particularly in urban areas (Valleau et al. 2020). This is demonstrated in comparisons between lakes in rural and urban areas, with striking differences in salt ion concentrations and conductivity found between the two regions. Lakes in residential areas were found to have significant increases in specific conductivity, compared with lakes in forested or rural areas (Siver et al. 1999; MacLeod et al. 2011), while similar increases in sodium and chloride concentrations were found to have occurred in lakes affected by development and urbanization, with less developed lakes in the

Fig. 3. Map of sites from field studies investigating the effects of roads-induced stressors on lentic environments by continent [Africa (white circles), Asia (gray circles), Europe (white diamonds), North America (gray diamonds), Oceania (gray triangles), South America (white triangles)]. Country shape file data from Natural Earth (2018). Map projection WGS84-EPSG 4326. Latitude and longitude coordinate system in decimal degrees.

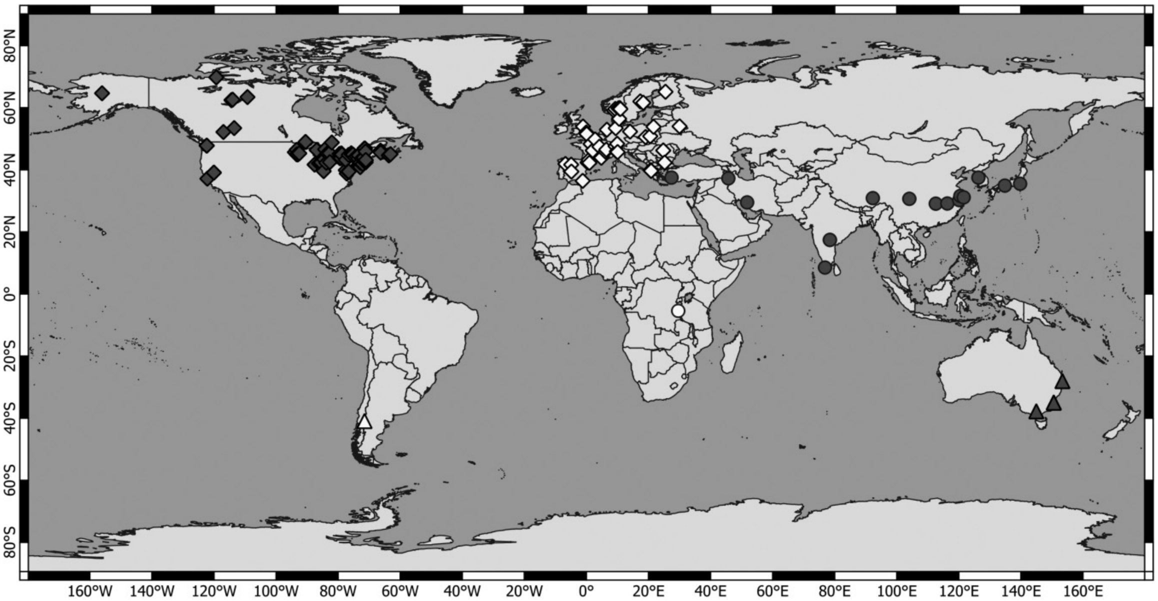


Fig. 4. Proportion of studies investigating the effects of road-induced stressors on lentic environments conducted on each continent [Africa (black), Asia (dots), Europe (dark gray), North America (vertical stripes), Oceania (light gray), South America (white)].

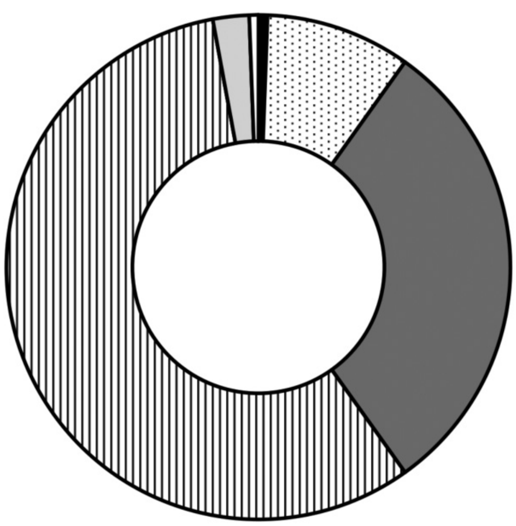
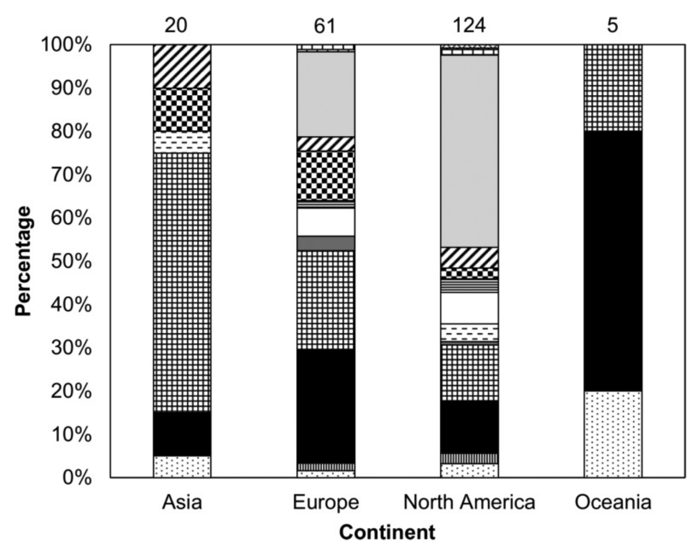


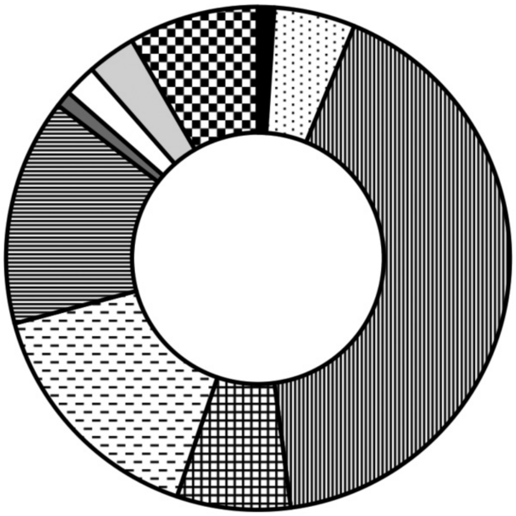
Fig. 5. Percentage of studies focusing on a particular road-induced stressor [accessibility (dots), dust suppressants (vertical lines), fragmentation (black), heavy metals (grid), invasive species (dark gray), landscape change (white), hydrology (dashed lines), noise (horizontal lines), PAHs (checkerboard), road dust (diagonal lines), road salt (light gray), sedimentation (brick), and water withdrawal (zigzag)] on lentic environments across continents with $n \geq 3$ stressors. Total number of stressors per continent is given at the top of each column.



area showing neutral or negative chloride trends (MacLeod et al. 2011; Hintz et al. 2020; Yao et al. 2020).

Road salt has been linked in the transformation of lentic environments from holomictic to meromictic. Lakes in the USA (Judd 1970; Bubeck et al. 1971; Hoffman et al. 1981; Novotny et al. 2008; Novotny and Stefan 2012; Wyman and Koretsky 2018; Dupuis et al. 2019; Wiltse et al. 2020) and Norway (Kjensmo 1997) have moved toward monomixis or meromixis, where previously they had been dimictic. This move toward meromixis could have significant impacts on affected lentic environments. The persistence of high salinity in the hypolimnion of lentic environments can signifi-

Fig. 6. Proportion of studies investigating the effects of road-induced stressors on different aquatic taxa [algal palynomorphs (black), amoebas (dots), amphibians (vertical stripes), diatoms (grid), fish (dashed lines), macroinvertebrates (horizontal stripes), macrophytes (dark gray), reptiles (white), water birds (light gray), zooplankton (checkerboard)] that inhabit lentic environments.



cantly affect biogeochemical cycles in affected lakes, because it prevents dissolved oxygen from reaching lake sediments, resulting in consequences for benthic communities, phosphorus recycling, and fish and their habitat (Novotny and Stefan 2012; Sibert et al. 2015; Wyman and Koretsky 2018; Wiltse et al. 2020). Methane concentrations in lakes can accumulate due to increases in the spatial and temporal extent of hypolimnetic anoxia, and there is a growing concern that permanently stratified urban lakes could increase global greenhouse gas emissions by increasing methane release (Sibert et al. 2015; Wyman and Koretsky 2018; Dupuis et al. 2019).

Lakes with slower discharge rates are more susceptible to road salt-induced changes in water quality, resulting in a greater salinity over time compared with lakes with higher discharge times (Koretsky et al. 2012). Increased chloride concentration due to road salt application has been linked with freezing point depression in urban stormwater ponds, although this depression was not large enough to significantly affect ice formation or thawing (She et al. 2016).

Road salt application can affect both small and large lakes, across wide gradients of land usage and road density in their catchments. Mueller and Gaechter (2012) investigated the chloride concentration in Lake Constance, the second largest lake in Europe, draining watersheds in Germany, Austria, and Switzerland. Chloride concentrations in Lake Constance have increased by a factor of 2.4 over the last 40 years, with about 45% of that chloride coming from road salt alone (Mueller and Gaechter 2012). In the Laurentian Great Lakes, sodium sediment concentrations were found to have increased since the 1940s, when road salt applications began (Aliff et al. 2020). Previous to the introduction of road salts, some of the Laurentian Great Lakes had sodium sediment concentrations below detection limits (Aliff et al. 2020). Despite its large size and low percentage of urban lands and roads within its watershed (12%), Lake Simcoe, Canada, is still experiencing increasing chloride concentration due to road salt application (Winter et al. 2011).

3.1.2 Effects of road salt in lentic environments on aquatic organisms

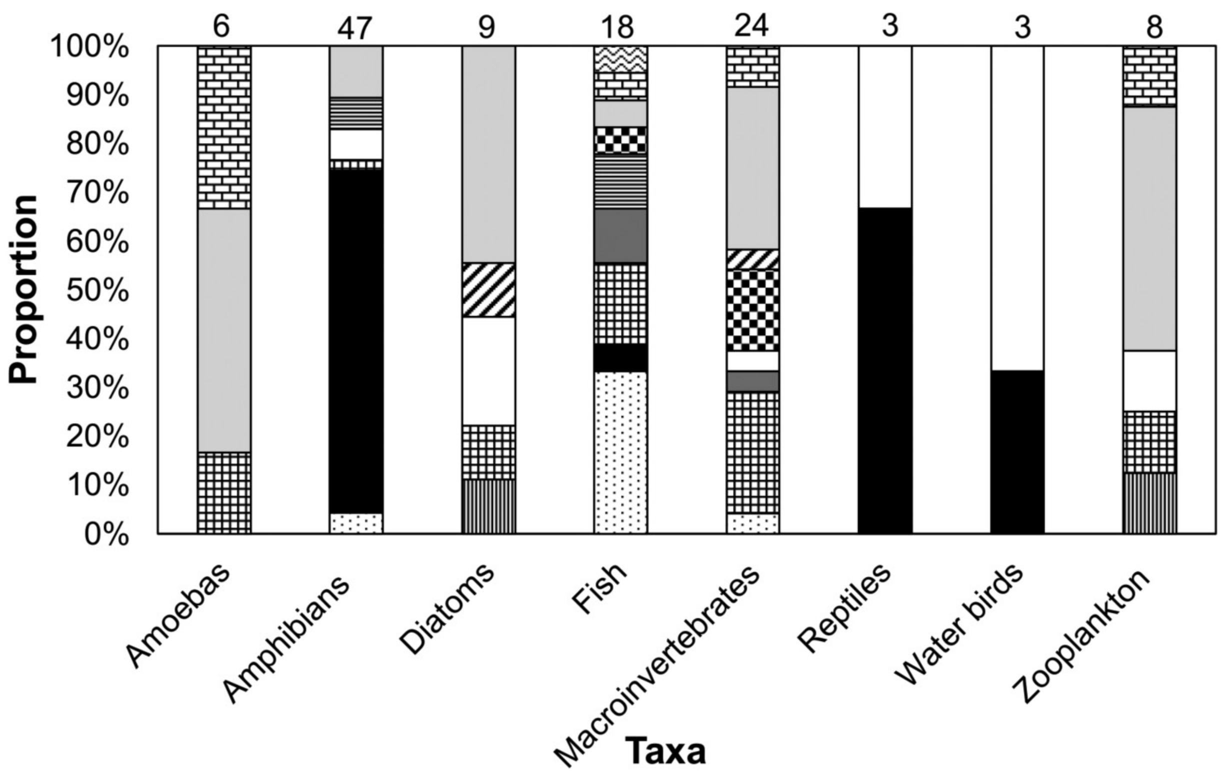
Road salt has numerous impacts on aquatic organisms, from single-celled organisms through to vertebrates. While different countries have their own guidelines for the concentration of chloride that will lead to chronic impairment of aquatic organisms (e.g., 120 mg/L in Canada, 230 mg/L in the USA, and 250 mg/L in Europe), it is clear that many urban lakes and ponds have already exceeded these, and also that these guidelines may be too high to protect aquatic organisms from the effects of road salt (Novotny and Stefan 2010; Arnott et al. 2020; Perron and Pick 2020).

Community composition of single-celled aquatic organisms can vary in lentic environments impacted by road salt. The diversity and abundances of Arcellacea (testate amoebae) communities in lentic environments have been affected by changes in conductivity and sodium concentrations caused by road salt input, with increases in these variables leading to lower diversity and the presence of more salt-tolerant species (Roe and Patterson 2014; Cockburn et al. 2020). Amoeba assemblages have strong local association with elevated conductivity (Roe et al. 2010). Similarly, impacts of road salt on diatom communities can be seen through both historical studies examining sediment cores, and present-day studies looking at freshly sampled diatoms. Ions from road salt application influence water chemistry resulting in alterations to diatom community composition, with diatom species associated with brackish waters becoming more dominant with increasing road salt application over time (Hammer and Stoermer 1997; Siver et al. 1999; Pienitz et al. 2006; Ginn et al. 2015; MacDougall et al. 2017).

Zooplankton density, abundance, and diversity have been affected by road salt. Zooplankton density has been observed decreasing along a chloride gradient across a series of stormwater ponds (Van Meter et al. 2011; Van Meter and Swan 2014). Changes in lake stratification patterns caused by increasing chloride concentration facilitate shifts in zooplankton community composition, and can be exacerbated by climate change (Jensen et al. 2014). Cladoceran assemblage composition in lentic environments as assessed from sediment cores shows changes that coincide with the start of road salt applications in those areas, with an increase in more salt-tolerant species in affected lakes (Arnott et al. 2020; Valleau et al. 2020). There is also evidence that current water quality guidelines are not sufficient to protect zooplankton from the effects of road salt. Current water quality guidelines across Canada, the USA, and the EU have levels set between 120 and 250 mg/L of chloride for chronic exposure, but *Daphnia* species have decreased reproduction and increased mortality at between 5 and 40 mg/L (Arnott et al. 2020).

Macroinvertebrates in stormwater ponds were found to be significantly impacted by road salt. In stormwater ponds

Fig. 7. Percentage of papers focusing on a particular road-induced stressor [accessibility (dots), dust suppressants (vertical lines), fragmentation (black), heavy metals (grid), invasive species (dark gray), landscape change (white), noise (horizontal lines), PAHs (checkerboard), road dust (diagonal lines), road salt (light gray), sedimentation (brick), and water withdrawal (zigzag)] on lentic environments across aquatic organism taxa with $n \geq 3$ stressors. Total number of stressors per taxa is given at the top of each column.



in Canada, a decrease in the survival of the amphipod *Hyalella azteca* was linked primarily to chloride toxicity, despite elevated levels of other pollutants like heavy metals and PAHs (Bartlett et al. 2012), while oligochaete taxonomic richness declined from the seasonal effects of chloride and heavy metals (Tixier et al. 2012). Mayfly larvae in stormwater ponds were found to express a stress protein in their chloride cells and gill insertions, indicative of osmotic shock from salty pond water (De Jong et al. 2006). Macroinvertebrate communities have been found to be significantly different between stormwater ponds and natural ponds, with the larger stormwater ponds with high conductivity having a slightly higher number of taxa than the smaller natural ponds (Meland et al. 2020). Individual taxa have been negatively associated with water and sediment pollutants, including chloride (Sun et al. 2019). Dragonfly and damselfly nymphs were found to be less abundant in stormwater ponds in comparison to natural ponds, with dragonfly community structure significantly influenced by chloride concentrations (Perron and Pick 2020). Damselfly community structure was found to be similar between stormwater ponds and natural ponds, suggesting less susceptibility to road salt in damselfly communities than dragonfly communities (Perron and Pick 2020). The distribution of gastropod species has been affected by conductivity, with salt-tolerant invasive species associated with the higher conductivity found in roadside ponds (Krodkiewska et al. 2018).

Amphibians are known to be highly affected by road salt, as all life-stages of amphibians are sensitive to osmotic changes in their environments (Karraker et al. 2008). Some species, such as wood frogs (*Rana sylvatica*) and spotted salamanders (*Ambystoma maculatum*), are more sensitive to the effects of road salt than others (Collins and Russell 2009). Wood frogs were more likely to breed in stormwater ponds with lower chloride concentrations, with wood frog and spotted salamander larvae exhibiting significantly reduced survival and growth rates and more variable developmental rates in higher conductivities and chloride concentrations (Karraker et al. 2008; Gallagher et al. 2014; Hall et al. 2017). Adult male wood frogs in roadside populations experience increased water retention and resting plasma corticosterone levels due to elevated salinity (Hall et al. 2017). Demographic modelling has found that road-salt induced egg and larval mortality can decrease wood frog and spotted salamander populations sizes, potentially leading to local extinction, although this decrease is dependent on the concentration of road salt and the distance of the pond to the roadside (Karraker et al. 2008). In natural ponds, field surveys found that high chloride ponds contained no wood frogs or spotted salamanders, although amphibian species with higher salt tolerances were present, indicating that road salt application affects amphibian community structure (Collins and Russell 2009).

While most of the effects of road salt on amphibians are negative, some studies found potential positive effects. Adult frogs from salty roadside pools were more fecund, had superior jumping performance, and were larger than those from less polluted woodland pools (Brady et al. 2019). Brady et al. (2019) suggested that these positive responses to salinity could be related to protection against disease agents such as fungal outbreaks and parasites.

3.1.3 Interaction of road salt with other stressors

Road salt can interact with other road-induced stressors on lentic environments to produce compounding effects. Road salt that reaches sediments and groundwater can mobilize metals, leading to contamination (Meriano et al. 2009). Jay et al. (2005) found that salt runoff into a small lake was slightly increasing the solubility of As minerals, Mayer et al. (2008) found that road salt-derived chloride increased chloride complexation of cadmium in pore-water, and Meriano et al. (2009) found a strong positive correlation between strontium and chloride in Frenchman's Bay in Lake Ontario, Canada. Conversely, increased additions of cations like sodium from road salting have been found to offer *Daphnia* some protection from heavy metal toxicity (Celis-Salgado et al. 2016).

Additionally, road salt effects can compound with non-road-induced stressors. Increasing chloride concentrations likely contribute to the delay in and the complication of the recovery of lentic environments from acidification (Rosfjord et al. 2007; Jensen et al. 2014). Furthermore, the effects of road salt on water chemistry in lakes and ponds interferes with the ability of monitoring programs to detect changes in water chemistry due to other stressors such as acidification and climate change by altering the direction and magnitude of change of major cations in lakes (Rosfjord et al. 2007).

3.1.4 Remediation of road salt

Efforts to reduce and remediate the effects of road salt have met with variable success. For example, when an interstate highway was constructed near Mirror Lake (NH, USA), a diversion berm was also constructed to divert salt runoff away from the lake basin (Rosenberry et al. 1999). Despite this berm, chloride concentration in the lake tripled in the 23 years following the opening of the interstate (Rosenberry et al. 1999). In an effort to mitigate this, further structural modifications to divert salt from the interstate away from the lake were completed (Likens and Buso 2010). However, another road servicing a newly constructed housing development became a new source of road salt for Mirror Lake, providing more than three times as much salt to the lake as the interstate, leading to the continuous increase in salt concentration in the lake (Likens and Buso 2010). If successful diversion of road salt away from lakes can be achieved, or, alternatively, reduction or cessation of road salt use is instigated, modeling has suggested that chloride concentrations in lakes could be reduced to predevelopment concentrations within 10–30 years (Novotny and Stefan 2010). This is the case in Lake Champlain, USA, where reductions in road salt application in the state of Vermont have led to reduced chloride concentrations since 1992 in the section of this lake that borders this state, versus a 30% rise in the main lake over the same time period (Smeltzer et al. 2012).

Another method to mitigate the impacts of road salt on surrounding freshwater systems is through the construction of stormwater management ponds. Stormwater management ponds are designed to lessen the impacts of roads on the local environment by sequestering excess run-off and pollutants (Van Meter et al. 2011). However, some retention ponds are designed better than others, as poorly designed ponds can still leach pollutants into surrounding freshwater environments, albeit more gradually compared with the pulsed exposure caused by direct discharge of runoff (Casey et al. 2013). For example, chloride ions from stormwater ponds may pass through soil to nearby groundwater and surface waters, causing these ponds to act as year-round sources of salt ions to local waters (Casey et al. 2013; Lam et al. 2020). Stormwater pond construction and design is therefore a key factor driving ion transport through these freshwater systems (Lam et al. 2020).

A key positive of stormwater pond construction as a pollutant mitigation technique is the development of additional habitat for aquatic organisms (Van Meter et al. 2011; Meland et al. 2020). Meland et al. (2020) found that the number of taxa in macroinvertebrate communities in stormwater ponds was slightly higher than in natural ponds, despite having conductivity levels five times higher. Amphibians have been found to utilize stormwater ponds; however, species that are highly sensitive to salt such as wood frogs will be excluded from the more polluted ponds (Gallagher et al. 2014). While pollutant levels such as road salt, heavy metals, and PAHs can be quite high, limiting diversity and abundance of the aquatic community, they can still provide important habitat, particularly to more pollutant-tolerant species, and therefore factors such as pond size should be considered during planning to maximize aquatic community diversity and abundance (Sun et al. 2018, 2019; Meland et al. 2020).

3.1.5 Areas of future study for road salt

While evidence for changes in the vertical stratification and mixing patterns of lakes has been identified as a consequence of salt pollution, it is unclear how many lakes may be affected. Changes in stratification can have significant ecological effects, and salt-induced meromixis could lead to increased methane release (Wyman and Koretsky 2018; Dupuis et al. 2019). Therefore, understanding how widespread salt-induced meromixis may become will be important for understanding lake ecology and the potential role of affected lakes in greenhouse gas emissions. In addition, research on the potential changes in habitat size for fish and benthos within individual lakes due to salt-induced meromixis would be helpful. Groundwater near lakes was also reported as understudied even though high amounts of chloride can travel into groundwater (Murphy and Stefan 2006; Meriano et al. 2009). Future studies should focus on the movement of salts into

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groundwater near lakes, and whether road salts can mobilize heavy metals into groundwater. The interaction between climate change and road salt is understudied, and would be an important area for future study. Continued research into salt alternatives for road de-icing should obviously continue, but we encourage researchers to consider how those alternatives (e.g., beet juice, sand), may affect aquatic organisms (Schuler et al. 2017). Finally, further research into the design of stormwater ponds to reduce pulses of chloride to urban waters may also be helpful for regions where salt reduction is difficult due to safety considerations.

3.2 Heavy metals

Heavy metals were the second most investigated road-induced stressor. Most studies investigated heavy metal contamination in urban lakes. Road traffic was presumed to be responsible for many different trace elements transported into lakes such as As, Cd, Cr, Ni, Pb, Cu, Fe, Mn, Se, Ba, Zn, Mo, V, Co, Ag, Sb, Sr, Rb, Li, Na, Mg, K, Ca, B, Al, and Si (Reddy et al. 2012). However, these are considered nonpoint source pollutants as road traffic is among many other suspected mechanisms for the introduction of trace elements into water bodies (Bai et al. 2011; Wang et al. 2020). Other sources include industrial facilities, inorganic and organic chemicals, agricultural fields, and urban construction (Bai et al. 2011; Watchorn et al. 2013; Weiss et al. 2018; Wang et al. 2020). The most common heavy metals correlated with road traffic included Cd, Cu, Ni, Pb, Zn, Pt, and Cr (Rice et al. 2002; Rauch and Hemond 2003; Rabajczyk et al. 2011; Mohammadi et al. 2018). Among these parameters, Zn was specifically linked to tire wear (Thapalia et al. 2010; Hwang et al. 2016), and was the metal with the highest reported concentration in a study that looked at 19 roadside stormwater detention ponds in Sweden (Wik et al. 2008). Many studies found that metal concentrations, particularly of those mentioned above as heavily correlated with road traffic, were highest in the areas of lentic environments closest to roads (Kleebergetal. 1999; Bai et al. 2011; Ioannides et al. 2015; Algül and Beyhan 2020; Torghabeh et al. 2020). Metal concentrations in multiple lakes often varies according to road density (Yang et al. 2014).

3.2.1 Effects of heavy metals in lentic environments on water and sediment

The distribution and movement of metals into lakes was often via stormwater runoff, surrounding streams, or particles being captured in the atmosphere through road dust (Barbosa and Hvitved-Jacobsen 1999; Camponelli et al. 2010; Jeong et al. 2020). Concentrations of metals varied spatially within lakes (Rabajczyk et al. 2011; Roinas et al. 2014; Xu et al. 2019). Zn and Cu accumulated in the inlet sediments of a pond, while Ni and Cr accumulated at the outlet (Roinas et al. 2014). Lake sediments are typically a sink for heavy metals but can act as a source if mobilized by salinity, pH changes, or redox condition changes, and impact the overall status of the lake (Gjessing et al. 1984; Mayer et al. 2008; Meriano et al. 2009; Roinas et al. 2014).

Heavy metals associated with roads (Cd, Cu, Ni, Pb, Zn, Pt, and Cr) often occurred in high concentrations in lentic environments due to road runoff (Rabajczyk et al. 2011; Ioannides et al. 2015; Mohammadi et al. 2018). Runoff-induced increases in Cu and Cd concentrations in lakes and ponds have been linked to dissolution of these metals from brake pads (Rice et al. 2002; Camponelli et al. 2010; Torghabeh et al. 2020). Pb from leaded gasoline (finally phased out globally for use in cars and trucks in July 2021, but still used in motor racing and aviation) and car parts such as wheel weights, wheel rims, and batteries is commonly found in runoff (Hwang et al. 2016), and accumulates in high concentrations in the water and sediment of lentic environments near roads (Kleeberg et al. 1999; Eskola and Peuraniemi 2008; Reddy et al. 2012; Sheela et al. 2014; Algül and Beyhan 2020; Torghabeh et al. 2020). Pt contamination in the sediments of roadside lakes and ponds has been associated with its use in automobile catalysts (Rauch and Hemond 2003; Rauch et al. 2003; Rauch et al. 2004). Zn was frequently reported as having high concentration in the water and sediments of lentic environments near roads (Wik et al. 2008; Thapalia et al. 2010; Torghabeh et al. 2020). While Zn is a common component of runoff, these findings overlapped with studies investigating road dust as a stressor of lentic environments, where Zn was reported as highly available in urban road dust (Camponelli et al. 2010), having been produced from tire wear (Thapalia et al. 2010; Hwang et al. 2016).

3.2.2 Effects of heavy metals in lentic environments on aquatic organisms

In some cases, heavy metal pollution from roads has led to metal concentrations in nearby lentic environments in exceedance of water quality guidelines, which have implications for the aquatic organisms living within these habitats (Camponelli et al. 2010; Waltham et al. 2014; Perron and Pick 2020). Oligochaete taxonomic richness and abundance in stormwater ponds was affected by seasonally varying toxicity (high in spring, low in fall) related to the influx and flushing out of heavy metals and road salt (Tixier et al. 2012). Along with high road salt, Gallagher et al. (2014) found that high metal concentrations in roadside pond sediment decreased the survival of wood frog larvae. In a study of roadside stormwater management ponds, DNA damage in dragonfly nymphs was found to be much higher in these ponds than natural ponds, and was linked to higher pollutant levels in sediment, particularly for Zn from road runoff (Meland et al. 2019). Dragonfly nymph abundance in contaminated stormwater ponds was found to decrease with increasing metal concentrations (Perron and Pick 2020), while Sun et al. (2019) found that macroinvertebrate taxa in stormwater ponds were negatively correlated with levels of pollutants (including metals) in the water and sediment.

Metals can bioaccumulate up the food web, resulting in potentially dangerous levels of contamination at higher trophic levels (Xu et al. 2019). Chen et al. (2000) identified road density as the best predictor of Cd concentration in water, and found it biomagnified at lower trophic levels (from small plankton to macrozooplankton), but not higher ones (macrozooplankton to fish). Zn was found to biomagnify up the food web, but while other studies have linked Zn inputs to lakes to tire wear, this study did not find roads to be a significant predictor of Zn in the system studied (Chen et al. 2000). A study that looked at bioaccumulation and health risk assessment of trace metals found that while bioaccumulation of metals did occur, fish in ponds near roads had sufficiently low levels of metals in muscle tissue that their consumption was safe for humans (Xu et al. 2019).

3.2.3 Interaction of heavy metals with other stressors

Heavy metals can be associated with road dust, which is a major pathway of moving metals from roads into lentic environments, particularly for Zn from tires and brake pads (Gjessing et al. 1984; Camponelli et al. 2010; Wijaya et al. 2012). When being transported by road dust in the atmosphere, heavy metal pollution from roads can travel a considerable distance, before being deposited in remote lakes and increasing heavy metal contamination in those systems (Corella et al. 2018). As mentioned in the previous section, road salt can interact with heavy metals in lentic systems to mobilize them, increasing metal contamination in these environments (Jay et al. 2005; Mayer et al. 2008; Meriano et al. 2009).

3.2.4 Remediation of heavy metals

Stormwater ponds are utilized to filter heavy metals out of road runoff, and ensure ground water protection (Barbosa and Hvitved-Jacobsen 1999). A comparison of the use of natural and constructed wetlands (such as stormwater ponds), found that constructed ponds were the most preferable option for remediation of metal contamination in freshwaters via filtration through pond sediment (Sriyaraj and Shutes 2001). When designing stormwater ponds for remediation of heavy metals, it is important to consider the composition and texture of the soils selected for use in the ponds, with soils which exhibited resistance to desorption at low pH and a high sorption capacity performing the best at removal of heavy metals (Barbosa and Hvitved-Jacobsen 1999). Stormwater ponds can be very effective in removing heavy metals from water passing through them, with Färm (2002) noting a 26%–84% reduction rate for total metal content, and Tixier et al. (2012) showing a strong decrease in sediment metal concentrations from outflow to inflow. However, as metals in runoff can be lost to roadside soils prior to reaching these ponds, attention must be paid to pond design to maximize their effectiveness as a trap for metal (Lee et al. 1997). Construction of these stormwater ponds for the remediation of metal contamination should be considered when new roads and urban development are being designed, as retrofitting these afterward when pollution has become a problem is limited by cost and the availability of suitable locations (Waltham et al. 2014). In urban areas, oil and grit separators can be used to trap heavy metals associated with sediments in runoff before it can reach storm sewer systems.

3.2.5 Areas of future study for heavy metals

Further research is needed to track the source of metals to lakes, as confounding factors such as sewage discharge or runoff from agricultural practices may limit our knowledge on cause of heavy metal distribution and may lead to erroneous conclusions about the contributions of roadways. This work could further improve management and control plans to reduce heavy metal runoff pollution from their sources. Methods to remediate sediments contaminated with heavy metals due to road contamination and other sources deserves continued research (Mayer et al. 2008; Algül and Beyhan 2020). As mentioned above, studies that examine how heavy metals interact with road salt contamination will be important to fully discern how the mobilization of metals by salt may affect aquatic organisms (Chen et al. 2000).

3.3 Fragmentation, landscape change, and accessibility

Fragmentation and landscape change were frequently studied road-induced stressors on lentic environments (Fig. 2). They are combined here with accessibility due to their similar mechanics and interconnectedness as stressors. Fragmentation, defined here as the building of roads between neighboring lentic habitats, and landscape change often overlap, and these two stressors give rise to increased habitat accessibility, this being increased access for people, invasive species, and contaminated equipment such as boats and fishing gear. These combined effects have detrimental impacts on aquatic organisms experiencing habitat loss and alteration, and changes in water quality due to modifications of hydrological pathways of rivers and streams to lentic environments, and also to the environments themselves (Williams et al. 2016; Gavel et al. 2018). Aquatic organisms that migrate between different habitats, particularly amphibians, are disproportionally affected by these stressors.

3.3.1 Effects of fragmentation, landscape change, and accessibility on water and sediment

Road-induced fragmentation, landscape change, and accessibility tend to act more on aquatic organisms than on the sediments or water of lentic environments. However, this does not mean that water and sediments are unaffected by these stressors. For example, hydrological changes caused by road construction can affect water residence time in a lake, causing changes in sedimentation rate, nutrient retention, and dissolved oxygen concentrations in the water column (Gavel et al. 2018).

3.3.2 Effects of fragmentation, landscape change, and accessibility on amphibians

Amphibians are particularly affected by fragmentation, landscape change, and accessibility. Their habitat requirements vary seasonally, with distinct habitats for refuge, mating, and feeding that are patchily distributed (Jochimsen et al. 2004). Additionally, amphibians undergo mass migrations at

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certain times of year between terrestrial habitats and breeding ponds, and if the land between these habitats has been intersected by a road, there is the potential for mass mortality events during these migrations (Jochimsen et al. 2004).

Mortality on roads via impacts with vehicles has been noted for a number of different migratory amphibian species. Bouchard et al. (2009) found that northern leopard frogs (*Rana pipiens*) were more successful at crossing low-traffic roads than high-traffic roads during their spring migration (94% versus 72% successful), potentially due to their slow movement speeds around roads. Other studies have found much poorer probabilities of successful migrations. Hels and Buchwald (2001) found that probability of amphibians of six different species successfully crossing a road varied from 39% to 66% on a two-laned road, and 2%–11% on a motorway. Annually, about 10% of the adult populations of spadefoot toads (*Pelobates fuscus*), common frogs (*Rana temporaria*), and moor frogs (*Rana arvalis*) in the study area were killed by the traffic (Hels and Buchwald 2001).

The more vagile (or more likely to move between different habitats) an amphibian species is, the more likely it is to experience high road mortality. Carr and Fahrig (2001) found that the population density of the more vagile northern leopard frog was negatively affected by traffic density with a radius of 1.5 km, while the population density of the less vagile green frog (*Rana clamitans*) was not greatly affected by the presence of traffic. Other studies, however, have found that green frog abundance decreased as traffic intensity increased (Gravel et al. 2012). The common toad (*Bufo bufo*) has the highest rate of road mortality of any amphibian in many European countries, which was found to be associated with traffic density, quality of water bodies for breeding, and toad abundance (Santos et al. 2007). It was found that common toads use streams, which flow into breeding ponds as their main migration route between these ponds and terrestrial hibernation sites, and where these streams cross roads is where the highest rate of toad mortality occurs (Santos et al. 2007). Other studies investigating rates of road mortality in multiple amphibian species found that the common toad had the highest road mortality out of all species studied, with estimates of mortality positively correlated with the mean body mass of the species (Brzeziński et al. 2012).

Habitat fragmentation causes reductions in population persistence and distribution of amphibians. The probability of moor frogs inhabiting a moorland pond is negatively affected by road density, with areas adjacent to a motorway found to have an occupation probability of <30% (Vos and Chardon 1998). Similarly, the probability of California red-legged frogs' (*Rana draytonii*) presence in a pond increased with increasing distance to the nearest dirt road or trail (Anderson 2019). Amphibian species richness in general has been found to be higher in ponds with low to intermediate road density (Bounas et al. 2020). The negative effects of traffic density on amphibian species richness were found to be stronger than the positive association between forest cover and species richness (Eigenbrod et al. 2008*a*). Gravel et al. (2012) found that the ability of juvenile amphibians to successfully disperse from natal ponds can be decreased by the presence of road-induced habitat fragmentation, which may lead to inhibited population persistence. Pond occupancy of agile frogs (*Rana dalmatina*), as determined by egg mass number, was negatively related to the extent of high-traffic roads nearby (Hartel et al. 2009).

The effects of fragmentation and landscape change can be identified in amphibian genetics. Gravel roads were one of the landscape features that reduced landscape permeability and increased genetic differentiation between northern crested newt (*Triturus cristatus*) populations from different breeding ponds (Haugen et al. 2020). Single nucleotide polymorphisms (SNPs) were used to detect the effects of fragmentation in easter tiger salamanders (*Ambystoma tigrinum*), and uncovered that over a small spatial scale (~40 km^2), the population was highly structured, and the presence of roads was a strong predictor of genetic divergence (McCartney-Melstad et al. 2018). In Blanchard's cricket frogs (*Acris blanchardi*), the presence of highways was predictive of increased genetic distance by impeding movement among populations (Youngquist et al. 2016). Differences in dispersal behavior of two syntopic newt species meant that only the species which undertook overland dispersal rather than aquatic dispersal suffered from roads acting as a potential barrier to gene flow (Sotiropoulos et al. 2013). However, roads did not always produce genetic divergence in amphibians. An alpine newt (*Ichthyosaura alpestris*) population had no evidence of reduced gene flow, despite the presence of a 40-year-old divided highway (Prunier et al. 2014).

Fitness disadvantages and maladaptations can occur in amphibians from roadside ponds. Wood frog tadpoles from roadside ponds survived at lower rates in comparison to tadpole from woodland populations transplanted to these natal ponds, suggesting a local maladaptation (Brady 2017). However, some roadside populations have elevated fitness when compared with more rural populations. Brady et al. (2019) found that adult frogs in roadside ponds were more fecund, larger, and had elevated jumping performance, potentially due to roadside ponds being warmer due to the open canopy and having higher dissolved oxygen than woodland ponds, increasing growth. Palmate newts (*Lissotriton helveticus*) in had difference in hindlimb lengths in different environments, with selection toward less mobile short-legged newts in populations in areas with high road densities and mortalities due to higher mortality of more mobile long-legged newts, while populations in forests or from ponds close to other water bodies were long-legged (Trochet et al. 2016).

The effects that roads have on amphibian mortality, behavior, and genetics can depend on the distance of the road from their ponds. In one study, amphibian species richness was negatively correlated with road density within 50 m (Couto et al. 2017). However, the distance between roads and lentic environments that causes negative effects can vary between species. When seven species of amphibians were studied in ponds along a major highway, road-effect zones were found for four species at distances of 250–1000 m, while two other species had road-effect zones that extended well beyond 1000 m (Eigenbrod et al. 2009). The four species with smaller road-effect zones had decreased breeding habitat use near the highway during high night-time truck traffic (Eigenbrod et al. 2009). Similarly, Hartel et al. (2010) investigated the effects of roads on multiple amphibian species, and found that four species were negatively associated with high traffic roads at varying spatial scales (400, 600, and 800 m), while the *Rana esculenta* complex showed a positive association with low-traffic roads in the 400 m spatial scale. Chambers (2008) found that newts and salamanders had a significant correlative effect of distance from logging roads on their selection of breeding sites, with the more sensitive species breeding farther from roads than more generalist species. Among other land-use variables, proportion of roads was negatively correlated with amphibian species richness, with land-use effects peaking at 180 m from ponds (Jacobs and Houlahan 2011). The presence of road surfaces had a strong negative effect on the presence of European tree frogs (*Hyla arboea*) at distances from 100 m up to 1 km, with this negative effect increasing when considering traffic instead of road surfaces (Pellet et al. 2004). Amphibian species richness, particularly richness of infrequently encountered species, was found to strongly decrease with increasing road length within 1 km of breeding ponds (Villaseñor et al. 2017).

3.3.3 Effects of fragmentation, landscape change, and accessibility on other vertebrates

Reptiles tend to experience similar issues with road mortality as those described above for amphibians, due to their similar use of divergent habitats for different life stages, and migrations to breed. Baldwin et al. (2004) found that adult female painted turtles (*Chrysemys picta*) that had to cross roads to reach nesting habitat suffered mortality on roads, with distance travelled negatively correlated with how much nesting habitat was available near a pond. Dense road networks, along with other parameters, can alter the structure of painted turtle populations, potentially causing a reduction in recruitment (Marchand and Litvaitis 2004). Ponds with greater road densities nearby had painted turtle populations with a greater proportion of males, as females crossing roads in search of nesting sites were subject to higher mortality (Marchand and Litvaitis 2004).

For water birds, landscape change produced by roads has an effect on habitat choice and abundance. Water bird species richness, abundance, and probability of patch-use significantly decreased in road-impacted areas (Riffell et al. 2003). Black storks (*Ciconia nigra*) use of ponds for feeding was negatively affected by proximity to roads, limiting their foraging ability in areas with higher development (Moreno-Opo et al. 2011). Increasing distance from lakes to roads had a positive influence on populations of three different crane species, while another crane species had less of a tendency to avoid roads (Huang et al. 2018).

Fish species are particularly vulnerable to the effects of increased habitat accessibility, which is produced by road construction. Increased accessibility can lead to increases in fishing pressure, as these lakes and ponds are now more convenient to access. Gunn and Sein (2000) found that loss of reproductive habitat through increased siltation from new roads did not significantly affect lake trout (*Salvelinus namaycush*) populations, but the rapid and severe effects of fishing pressure did. Likewise, Kaufman et al. (2009) found that lake trout abundance decreased in lakes with road access, partially due to increased fishing pressure as well as the introduction of invasive fish species. Bull trout (*Salvelinus confluentus*) abundance in a road-accessible lake did not show the same patterns of change in as a remote lake, likely due to illegal fishing activity limiting abundance response (Parker et al. 2007). Forestry can increase accessibility to formerly isolated lakes via the construction of access roads, and if these lakes contain sport fish species (among other variables) that access is likely to increase (Hunt and Lester 2009).

3.3.4 Effects of fragmentation, landscape change, and accessibility on other aquatic organisms

Fragmentation and landscape change can have a large effect on nonvertebrate aquatic organisms. The degree of urbanization and land-cover disturbance, such as road construction, has been found to affect the zooplankton community in roadside lakes, with different species becoming more prevalent in the face of disturbance-induced stressors (Gélinas and Pinel-Alloul 2008). Landscape metrics including road density strongly influenced the response of indicator diatom species assemblages (Niemi et al. 2011). Emergent macrophyte cover and floating macrophyte cover in northern temperate lakes was found to be negatively affected by road presence, likely because as access and development increases, human removal of these visible macrophytes increases (Cheruvelil and Soranno 2008).

While fragmentation can cause reductions in abundance and diversity of species, this is not always the case. Li et al. (2009) found that fragmentation of lakes on the Yangtze River floodplain by the construction of road embankments, dams, and sluices did not lead to the reduction of helminth parasite communities in yellowhead catfish (*Pelteobagrus fulvidraco*). Construction of a road that isolated Lake Morenito in 1960 induced changed to lake limnology that resulted in associated changes in the chironomid community (Williams et al. 2016). Lake isolation led to increased productivity, which resulted in high abundance and richness values of the chironomid community (Williams et al. 2016).

3.3.5 Interaction of fragmentation, landscape change, and accessibility with other stressors

Landscape change in the form of increased urbanization and impervious surfaces such as roads is a major driver of increased road salt and heavy metal contamination in lakes and ponds. An increase in impervious surfaces and road density has been linked to significantly increased chloride concentration (Bunbury et al. 2020).

The accessibility to new habitats which is facilitated by roads is linked with the introduction of non-native and invasive species into lentic environments. Non-native fish species (particularly goldfish) were more commonly found in ponds, which were closer to roads due to human-facilitated introductions, such that the rate of introduction of ornamental varieties of fish per year was 3.5 in ponds adjacent to roads

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(Copp et al. 2005). At lakes with easy road access, introductions of smallmouth bass (*Micropterus dolomieu*) alongside increased fishing pressure combined to cause a 77% decrease in lake trout abundance in road accessible lakes in comparison to unexploited reference lakes (Kaufman et al. 2009). Kizuka et al. (2014) found that a pond's visibility from roads was an effective predictor of invasive fish species distribution. More visible water bodies are more accessible water bodies, and are more likely to be visited by humans bringing with them contaminated boating gear, nets, and other paraphernalia (Kizuka et al. 2014). Alien snail species more often inhabited roadside ponds than those in forested areas, again, potentially through contaminated fishing equipment (Krodkiewska et al. 2018).

3.3.6 Remediation of fragmentation, landscape change, and accessibility

As amphibian populations are declining, with the construction of roads destroying habitat and leading to vehicular mortality, it is more important than ever to attempt to mitigate the effects of roads on amphibian species (Lesbarrères et al. 2010). Understanding how amphibians respond to changes in the weather and how that affects when and where they migrate can greatly assist in remediating the effects of fragmentation and road mortality on amphibian populations (Gravel et al. 2012).

Mitigation methods like fences and under-road passages have the potential to reduce the effects of roads on amphibian populations. At a multitunnel mitigation site in northern England using both under-road passages and fences, most amphibians successfully entered the tunnels to move around the site, although there was substantial evidence of amphibians refusing to enter the tunnels or making a U-turn once inside (Jarvis et al. 2019).

If ponds or lakes have to be destroyed when roads are created, replacement ponds should be created, and monitored to ensure that native species are re-establishing themselves and to determine if pond design needs to be modified (Lesbarrères et al. 2010; Hamer 2018). Habitat around these new ponds is important, as environmental differences around these ponds influences amphibian communities (Parris 2006). Under-road passages, fences, and terrestrial buffer zones should be implemented around replacement ponds and lakes to ensure maximum remediation success (Lesbarrères et al. 2010). These methods should be used together where possible, as the implementation of one (say, just under-road passages) may not be sufficient to divert amphibians off roads (Santos et al. 2007). Under-road passages, drift fences (short barriers that direct amphibians traveling overland into traps), and the construction of compensatory ponds and terrestrial habitat ensured that the amphibian population at a multitunnel road mitigation site increased rapidly (Jarvis et al. 2019). A population of common toads was successfully diverted from using its traditional breeding ponds across a road to an artificial pond through the use of barrier fences, and trapping and transferring the toads to the new pond (Schlupp and Podloucky 1994). After 4 years, the migration rate to the old pond decreased to ∼15%, and subsequently dropped further to <1% (Schlupp and Podloucky 1994). Without mitigation and management efforts like these, increasing isolation of urban lentic environments by roads may lead to a reduction in the number of amphibian species persisting in these environments, as the likelihood that the ponds or lakes will be recolonized following local extirpation is reduced (Parris 2006).

In some cases, stormwater ponds built alongside roads to mitigate the effects of polluted runoff can become compensatory habitat for aquatic organisms who have suffered from habitat loss via the construction of the road, although their sensitivity to pollutant levels can limit their use. Amphibians were found at stormwater retention ponds at roughly the same proportion as they were found in non-highway ponds, although the abundance of amphibians in stormwater ponds were lower (Le Viol et al. 2012). Similarly, macroinvertebrate communities in stormwater ponds were as diverse and rich at the family level on ponds further from roads, although the taxa within the ponds were different (Le Viol et al. 2009).

Thorough monitoring of amphibian populations is necessary to ensure that the effects of landscape change on them are accurately understood. To effectively mitigate effects on amphibians of habitat loss and roads, which are often intertwined, a metric that combines both was developed. Accessible habitat (defined as the amount of habitat that can be reached from a focal patch without crossing a road), was found to be a better predictor of amphibian species richness than total habitat or distance to roads individually, allowing for a more accurate assessment of the state of amphibian populations, and therefore better population management (Eigenbrod et al. 2008*b*). The metric was applied by Hamer (2018), who found it was better at explaining pond occupancy of the threatened green and golden bell frog (*Litoria aurea*) than individual metrics alone, and was positively correlated with occupancy. When designing urban mitigation schemes, metrics like these should be included in landscape connectivity models alongside barriers like roads, which reduce landscape permeability, as their consideration when planning could substantially improve population-level outcomes for amphibian species (Matos et al. 2019).

Studying which environmental variables trigger mass amphibian migrations allows for better forecasting of when these events will take place. Timm et al. (2007) studied the timing of adult immigration and juvenile emigration in two species of salamander, one species of frog, and one species of newt. A number of environmental variables including Julian date, amount of rainfall in the last 24 h, degree-days, temperature, and droughtiness were all important in modeling these amphibian migrations, and in the future will provide a means to forecast when these migrations are most likely to occur, and therefore when road closure events designed to minimize road mortality should be held (Timm et al. 2007).

For other vertebrates, there are other methods of mitigating road-induced fragmentation, landscape change, and accessibility alongside those listed for amphibians. Like for amphibians, enhancing turtle habitat around their ponds (e.g., by increasing the amount of suitable nesting habitat away from roads) will help lower traffic-related mortality (Baldwin et al. 2004). To combat the effects of increased accessibility and associated increased fishing pressure on fish species, it may be necessary to enforce harvest catch limits to protect fish populations (Gunn and Sein 2000).

3.3.7 Areas of future study for fragmentation, landscape change, and accessibility

Studies that focus on landscape changes should fragmentation of habitats occur, can broaden our understanding of the true extent of road impacts on water birds, amphibians, fish, and aquatic animals alike (Gunn and Sein 2000; Riffell et al. 2003). More efforts to protect aquatic animals from road crossing such as development of improved engineering of hydrological pathways, and further study on the timing of mass migrations can potentially reduce the rates of road mortalities.

3.4 Road dust and dust suppressants

Through our literature search, we found a combined 14 papers (Fig. 2) on the effects of road dust and dust suppressants on freshwater lakes and ponds. Dust has been reported to travel 5–300 m from roads, and no study has reported travel distance greater than 1000 m from roadside lakes (Gjessing et al. 1984; Urban 2006; Gunter 2017; Zhu et al. 2019). However, it is difficult to establish how far dust can travel from roads because wind direction, surrounding vegetation, and urbanized development play a significant role in the movement and deposition of dust particles around ecosystems (Sanders and Addo 1993; Gunter 2017). Dust from unpaved roads can enter houses and cause a nuisance, clouds formed when vehicles drive on these roads can lower visibility, which is hazardous to other vehicles, and the loss of fine material as dust can lead to the degradation of road surfaces (Sanders and Addo 1993). This necessitates the use of dust suppressants, which are themselves a source of pollution (Sanders and Addo 1993).

3.4.1 Effects of road dust and dust suppressants in lentic environments on water and sediment

Dust and debris can cause water quality changes in lakes and ponds (Zhu et al. 2009). Changes in water quality differed depending on whether the road was in a rural or urban area. For example, gravel roads in Northern regions tend to generate large amounts of dust that contain Ca and Mg, rather than Zn deposits that would normally be found in urban road dust (Camponelli et al. 2010; Gunter 2017). Lakes within 1 km of a gravel highway had higher values for alkalinity, conductivity, total dissolved solids, pH, Ca^{2+}, Mg^{2+}, hardness, NO_3-N, $NO_2 + NO_3$-N, $SO4^{2-}$, and Sr^{2+}, which were attributed to the influence of road dust (Gunter 2017). Dust suppressants ($MgCl_2$ and $CaCl_2$) used to inhibit the generation of dust from roads can also contribute to ion loading in lentic environments, being a source of Ca^{2+}, Mg^{2+}, and Cl^- (Kjensmo 1997; Palmer et al. 2011; MacDougall et al. 2017). Road dust can also affect water clarity and the composition of lake sediments. Zhu et al. (2009) found that the clarity of Lake Tahoe has declined over the past 40 years, partly due to road dust inputs, which can scatter light. These road dust inputs are seasonal and increase by a factor of five on average during winter, due in part to sanding of nearby roads to increase traction (Zhu et al. 2009). Camponelli et al. (2010) found that surface sediments from a pond near a busy road were comprised of 27% road dust.

3.4.2 Effects of road dust and dust suppressants in lentic environments on aquatic organisms

Road dust influences aquatic organism species assemblages in a variety of ways. Road dust suppressants have been found to affect the composition of diatom communities in lakes via changes in ion loading (MacDougall et al. 2017). Ca input from dust suppressants was found to alter the cladoceran complex present in a lake, reversing the effects on the community of a decline in water Ca due to acid deposition and tree-harvesting practices (Shapiera et al. 2012). However, road dust does not always affect aquatic organisms. According to diatom records, road dust had little impact on species assemblage in roadside lakes despite changes in ionic loading in lakes closer to the highway, and changes in diatom assemblages were instead influenced by climate warming (Zhu et al. 2019). Gunter (2017) observed a similar result where algal palynomorphs were consistent with changes in temperature, although algal palynomorphs assemblages in one lake showed some response to the addition of road dust during the construction of a gravel highway.

Snails inhabiting ponds near a gravel highway in Alaska had increasing trematode infection with decreasing distance between their pond and the highway (Urban 2006). These infections may be driving reductions in snail density, which was negatively correlated with road distance (Urban 2006). As the distance over which infections occurred was similar to the distance over which road dust settled (~300 m), it was suggested that road dust was facilitating dispersal of the trematode parasite (Urban 2006).

3.4.3 Interaction of road dust and dust suppressants with other stressors

Dust-suppressant salts applied to roads near lentic environments combine with those from de-icing salts causing increases in ion accumulation and changes in salinity, in some cases impacting the meromictic stability of these environments (Kjensmo 1997; Palmer et al. 2011).

Heavy metals and PAHs from roads travel with road dust, both atmospherically and via stormwater runoff into nearby waterbodies, with streams draining into Shihwa Lake heavily contaminated with Cu and Pb from road dust (Gjessing et al. 1984; Corella et al. 2018; Jeong et al. 2020). The observed metals known to travel with road dust include Pb, Cd, Zn, As, Cr, Ni and Cu, and Zn has been reported to be more available than other metals in road dust (Camponelli et al. 2010; Wijaya et al. 2012).

Trace metals and calcareous debris carried by road-side dust can be physically deposited into surface waters and surrounding sediments causing increased sedimentation and turbidity (Sanders and Addo 1993; Gunter 2017).

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3.4.4 Remediation of road dust and dust suppressants

Identifying hotspot areas that are impacted by dust emission from roads is necessary to mitigate negative effects (Zhu et al. 2014). Dust loading from roadway emissions to Lake Tahoe was estimated using measured road dust emission factors, meteorological data, GIS analysis, and a traffic demand model to estimate where and how much dust deposition there will be in the lake (Zhu et al. 2014). Such modelling methods can allow for successful mitigation of the effects of road dust on lentic environments. There are several mitigation methods for road dust; however, many of these can cause their own issues. Dust suppressants, as previously mentioned, can cause pollution problems (Sanders and Addo 1993; MacDougall et al. 2017), while road watering could potentially facilitate the dispersal of invasive species to roadside ponds (Urban 2006), and paving gravel and dirt roads leads to a loss of permeability, and increased run-off of pollutants such as heavy metals (Camponelli et al. 2010).

3.4.5 Areas of future study for road dust and dust suppressants

The use of dust suppressants is a common solution to reduce the transport of dust to the surrounding landscape, but these compounds may degrade water quality and alter aquatic food webs (Sanders and Addo 1993). More research into practical environmentally friendly alternatives could help mitigate the effects of dust suppression techniques (Sanders and Addo 1993). Studying the potential interactions between road dust and climate change may also be fruitful. For example, changes in precipitation and wind patterns may alter the transport of road dust to the surrounding environment. Lastly, road dust may facilitate colonization of snails by trematodes and may fuel diseases (Urban 2006); more research is needed to understand how the movement of road dust may affect disease transmission in aquatic food webs.

3.5 Other stressors

We found there were multiple other road-induced stressors that have been studied, although not as extensively as those listed in the previous sections. These include PAHs, hydrology, noise, sedimentation, invasive species, and water withdrawal. As invasive species are so thoroughly interlinked with road-induced accessibility, this stressor has already been covered in that section, and will not be further discussed here.

3.5.1 PAHs

We found 12 studies that examined the effects of PAHs from roads on lentic environments (Fig. 2). PAHs in lentic environments can come from a number of different sources such as soil runoff, agriculture, and industrial wastewater, but a significant source of PAHs in these environments can be sourced to road runoff (Li et al. 2003; Chen et al. 2004; Hijosa-Valsero et al. 2016), with peak concentrations often measured after storm events (Roinas et al. 2014). PAHs can also be transported atmospherically by road dust, and can be found in high concentrations 50 m from the road (Gjessing et al. 1984). PAH concentrations can be particularly high in stormwater ponds, with these sediments sometimes so contaminated that disposal of them once extracted from the ponds has become a major problem (Durand et al. 2004; Tixier et al. 2012). Marshes around the periphery of lakes can offer protection against PAHs of vehicular origin in road runoff, with PAHs binding to humic substances in these stagnant, marshy areas before reaching the lake proper (Naffrechoux et al. 2000).

PAH concentrations in stormwater pond sediments can exceed guidelines, with potentially serious consequences for aquatic organisms (Tixier et al. 2012). High PAH concentrations have been found in urban stormwater ponds in comparison to natural urban ponds, with dragonfly nymphs bioaccumulating these PAHs (Girardin et al. 2020). Exposure of dragonfly nymphs to high sediment concentrations of PAHs in stormwater ponds has been linked to significantly higher DNA damage than that experienced by nymphs living in less polluted natural ponds (Meland et al. 2019). Minnows from a stormwater pond had higher levels of PAH metabolites than those from a lake unaffected by traffic, and were in poorer condition (Grung et al. 2016). High PAH concentrations in lentic environments do not always negatively affect aquatic organisms. PAH concentrations did not drive benthic community structure, despite high sediment concentrations (Bartlett et al. 2012; Tixier et al. 2012).

3.5.2 Hydrology

We found six studies that examined the effects of road-induced hydrological changes on lentic environments (Fig. 2). Interconnectivity between different water bodies can allow the movement of road pollutants. Stormwater ponds can be a source of chloride from road salt to nearby streams due to chloride movement in groundwater, or directly to the streams themselves if connected (Casey et al. 2013; Lam et al. 2020). Similarly, pollutants from roads do not always directly enter lentic environments, but can be introduced via groundwater, or by streams and rivers that flow into these environments (Rosenberry et al. 1999; Kattner et al. 2000; Jeong et al. 2020). Roads can have a direct effect on the hydrology of lakes. For instance, construction of a major road at the outlet of a lake in Yellowknife, Canada, caused a reduction in lake drainage, which exacerbated eutrophication (Gavel et al. 2018).

3.5.3 Noise

We found five studies that examined the effects of noise from roads on lentic environments (Fig. 2). Road noise is a particular problem for amphibians. Noise associated with very high night-time truck traffic has been suggested as a cause of reduced use of breeding ponds near a highway for four species of amphibians, leading to negative effects of roads on species that are comparatively unaffected by traffic mortality (Eigenbrod et al. 2009). Traffic noise can also affect the vocalizations of amphibians. Traffic noise affects various amphibian call parameters, resulting in significant differences in calls between quiet and noisy sites (Lukanov et al. 2014). Amphibian species with the lowest call peak frequency called most often when traffic noise intensity was low, a strategy to enhance their signal-to-noise ration and increase effective communication (Vargas-Salinas et al. 2014).

Traffic noise can also be a problem for fish, particularly when ice roads are used over lentic environments during the winter. Many fish species use calls to communicate with each other (e.g., burbot), and traffic noise could interfere with this by masking sounds for fish with sensitive hearing (Mann et al. 2009; Martin and Cott 2016).

3.5.4 Sedimentation

We found four studies that examined the effects of sedimentation from roads on lentic environments (Fig. 2). Sediments deposited by roads into stormwater ponds can be highly polluted, which may make their disposal difficult (Durand et al. 2004). Erosion from road construction has resulted in increased clay inputs and sedimentation in lakes, resulting in changes to diatom assemblages (Watchorn et al. 2013). Alin et al. (1999) found that fish, mollusc, and ostracod species densities were affected from increased sedimentation caused by disturbances such as road building. However, increased siltation (as simulated using plastic tarps) that destroyed lake trout spawning habitat did not affect lake trout populations, while excessive exploitation caused by road-induced accessibility did (Gunn and Sein 2000).

3.5.5 Water withdrawal

Water withdrawal from northern lakes for the construction of ice roads can have potentially large consequences for fish species within these lakes. The water is used to build ice roads over terrestrial habitat, or to smooth roadways over water bodies. Water withdrawal can decrease oxygen concentration and reduced overwintering habitat in comparison with prewithdrawal conditions (Cott et al. 2008).

4 Conclusions

Our literature review summarizes the impacts roads have on the physical, chemical, and biological aspects of lentic environments. Lentic environments of all sizes, from small ponds to the largest freshwater bodies in the world were found to have been impacted by roads. In some cases, the effects of roads can extend further than 1 km across the landscape. Most studies that compared ponds and lakes near roads with more remote environments found that water quality, sediments, and aquatic organisms in the roadside habitats were all suffering from road-induced stressors. Of the 172 papers examined as part of this review, only three noted positive changes as a result of the effects of road-induced stressors, one relating to road salt, and the other two to fragmentation. Chemical pollutants such as road salt, heavy metals, dust suppressants, and PAHs contaminated the water column and sediments of roadside lakes, and caused problems including DNA damage, reduced growth, increased mortality, changes in species abundance and richness, and increased stress levels in aquatic organisms. Road salt applications are affecting the meromictic stability of lakes, destroying habitats for aquatic organisms, and may be facilitating an increase in the release of greenhouse gases. Landscape changes caused by roads, such as increase in impermeable surfaces, road density, traffic volume, and road proximity, all impacted the abiotic and biotic variables in nearby lakes and ponds. Fragmentation was of particular concern for amphibians and reptiles that move between different environments for mating, feeding, and reproduction, with traffic mortality being a significant concern for some species. Accessibility of lentic environments can lead to introductions of invasive species, and overexploitation of fish. Road dust and sedimentation can increase water turbidity and the destruction of aquatic habitat. Traffic noise from busy roads can alter the behavior of amphibians and fish. These stressors often interact with each other, compounding their effects.

The best mitigation method to reduce the effects of roads on lentic environments would be to build fewer roads, and instead improve mass transit and reduce urban sprawl. However, with road building set to increase over the next 30 years, effective remediation methods must be sought. Remediation methods included the use of stormwater management ponds to remove pollutants, oil and grit separators, runoff diversion techniques, the development of more effective modelling tools, compensatory pond construction, and construction of structures which maintain connectivity in fragmented environments. The construction of stormwater ponds has a supplementary benefit of providing additional habitat for aquatic organisms, although species abundance and richness may be limited by high pollutant concentrations.

4.1 Future directions

Road salt, heavy metals, and fragmentation were the road-induced stressors for which we found the most studies. However, our identification of the "most important" stressors according to the number of published studies is likely skewed by the geographic biases inherent in those studies. Published studies were biased toward North America and Europe, leaving open questions about the effects of roads in other parts of the world. For example, the contamination of lakes and ponds by road salt is likely not a significant concern for most areas in Africa and South America. More research is needed in areas outside of North America and Europe to gain a global picture of the effects of roads on lentic habitats.

Taxonomic bias was also evident in the published studies, with the most effort focused on amphibians, fish, and macroinvertebrates. Fewer studies have been conducted on water birds and zooplankton. This is unfortunate, as water birds are sensitive to many types of disturbance that are associated with roads (e.g., noise pollution; Burton 2007). Zooplankton are also highly sensitive to changes in water quality that are caused by roadways, such as changes in conductivity and pH (Vucic et al. 2020). Further studies on underrepresented taxa would help to provide a more comprehensive understanding of the impacts of roadways on lakes and ponds.

It is also likely that some aspects of the effects of roads and lakes on ponds were missed during our review of the literature. While our search terms were made to be broad and inclusive, we know that some areas were missed, such as the

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impacts of roads on connectivity on fish migration, and mitigation efforts to restore access for fish (Januchowski-Hartley et al. 2013, 2014). This reflects both potential weaknesses in our search terms, as well as limitations of the search engines used for this study.

Finally, we suggest that more research is needed to understand how changes in both land use and climate will interact with roadways to affect lentic habitats. A growing human population combined with urban sprawl will affect both the size of the transportation network and the number of vehicles traveling on roads (van der Ree et al. 2015). It is likely that these changes will further exacerbate the stressors currently affecting our lakes and ponds. It is also likely that the effects of climate change will compound road-induced stressors. For example, rising temperatures and changing precipitation patterns may cause more stress on freshwater habitats that are already suffering from road-induced stressors (Murdoch et al. 2021). In the northern hemisphere, seasonal lake ice coverage is declining (Sharma et al. 2021), and summer temperatures are increasing, changing lake stratification patterns (Woolway et al. 2021). Studying how the contribution of ions from roadways will contribute to changing the vertical structure of water in lentic habitats will be critical for understanding how lakes will change over the next century.

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Competing interests

The authors declare there are no competing interests associated with this work.

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