Review

Recreational watercraft decontamination: can current recommendations reduce aquatic invasive species spread?

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Abstract

Decontaminating recreational watercraft, and fishing, sailing or watersports equipment after use can reduce the overland dispersal of aquatic invasive species (AIS) among lakes. Recommended methods include pressure-washing, rinsing with hot water, using cleaning agents, or air-drying, but the extent of their efficacy is unknown. The aim of this review is to assess the effectiveness of current decontamination measures for recreational watercraft against various AIS. Web of Science, Greenfile, Environment Complete and Geobase were searched for articles published through September 2019. Studies on preventing overland AIS spread, and plant and invertebrate AIS response to hot water, pressure-washing, desiccation or cleaning agents, were selected. Of 37 studies included in the review, the majority (70.3%) assessed air-drying, followed by hot water (32.4%), household chemicals (16.2%), and pressure-washing (2.7%). The recommended air-drying duration of up to one week produced high mortality ($\geq$ 90%) among several invertebrate and macrophyte species, although survival was high for certain aquatic snails. Larger and/or older invertebrates were more resistant to desiccation. Aquatic plant survival and growth were inversely related to water loss (a function of drying time and relative humidity), and short or single fragments were less resistant to air-drying than larger or clustered fragments. Immersion in water $\geq$ 50 °C for 15 minutes resulted in 100% mortality among mussels, small invertebrates and some plant species. A higher temperature of 60 °C was required for hot water spray applications lasting $\geq$ 5 seconds to achieve the same mortality rate among dreissenid mussels. High pressure-washing eliminated significantly more entangled plants, and small organisms and seeds than low pressure. Household chemicals such as salt or bleach required specific doses and immersion durations to be lethal to small organisms. This review reveals that current decontamination methods may be effective, but their efficacy against a diversity of AIS, including those on watch lists, are not yet well-understood. As the literature is currently skewed towards studies on air-drying, which has limited efficacy, further research is required to evaluate practical, and alternate or combined measures to best inform management practices.

Key words: aquatic invertebrates, macrophytes, secondary spread, cleaning, efficacy

Introduction

Overcoming geographical barriers is a crucial early step in the colonisation of new environments by invasive species, and human-mediated transport has facilitated this stage in the invasion pathway (Blackburn et al. 2011).

There is strong evidence that anthropogenic activities have amplified the frequency of long-distance dispersal, the number of species transported, and propagule size, while diversifying the means of spread and greatly reducing the effect of geographical barriers (Mack et al. 2000; Ricciardi 2007), especially with regards to aquatic ecosystems. The establishment of aquatic invasive species (AIS) outside of their native range is accompanied by a multitude of ecological (Ricciardi and Rasmussen 1998; Ricciardi et al. 2013; Gallardo et al. 2016) and economic impacts (Pimentel 2005; Krantzberg and de Boer 2008). These impacts are further exacerbated as invaded sites become the source for propagules implicated in the secondary spread of AIS to disconnected, inland water bodies (Vander Zanden and Olden 2008), where the vulnerability of the site to invasions and the influx of propagules via natural or human-related vectors can allow for the establishment of new AIS populations (Leung and Mandrak 2007; Vander Zanden and Olden 2008).

Empirical research and models have determined recreational boating activities to be an important vector of AIS spread (Johnson et al. 2001; Leung et al. 2006; De Ventura et al. 2016). Several studies have shown that invertebrate and plant AIS of various life stages are capable of becoming attached to or caught on recreational watercraft and equipment used in invaded waterbodies (Johnson et al. 2001; Rothlisberger et al. 2010; Kelly et al. 2013). Moreover, AIS can survive overland transport (Alonso et al. 2016; Collas et al. 2018) aboard trailered vessels, in bilge and live wells, engines, and as or in macrophytes caught on boats and trailers (Ricciardi et al. 1995; Johnson et al. 2001; Havel 2011; Kelly et al. 2013; Snider et al. 2014). Overland spread is amplified as a result of AIS physiological or metabolic tolerance to abiotic stress (Brooks and Storey 1997; Evans et al. 2011; Havel 2011; Wada and Matsukura 2011; Gechev et al. 2012; Gaff and Oliver 2013) and adaptations such as resting eggs and dormancy (Bailey et al. 2004; Muirhead and Macisaac 2005; Wada and Matsukura 2011). High boat traffic among lakes during peak seasons can potentially increase the number of events where AIS are transported and introduced to non-colonised sites (Rothlisberger et al. 2010; Chivers and Leung 2012; Kelly et al. 2013). Thus, it is important to reduce the quantity of living or viable individuals arriving given the role of propagule size in successful AIS colonisation (Blackburn et al. 2015; Sinclair and Arnott 2016). Preventing AIS spread to novel ecosystems is the most effective control strategy (Puth and Post 2005; Drury and Rothlisberger 2008). Hence, to reduce the risk of AIS dispersal related to boat traffic, several biosecurity and management programs aimed at recreational boaters have been proposed or implemented worldwide, including campaigns in the USA (US Aquatic Nuisance Species Task Force 2017), Canada (Ontario Ministry of Natural Resources and Forestry 2017; Ministère des Forêts, de la Faune et des Parcs 2018; Manitoba Government Wildlife and Fisheries Branch 2020; Invasive Species Council

Table 1. Examples of recommended recreational watercraft and equipment decontamination measures, with set conditions where specified by the agency.

Agency	Hot water use	Air-drying conditions	Pressure-washing
Ministry of Natural Resources and Forestry, Ontario, Canada	> 50 °C	2–7 days	> 250 psi
Manitoba Government Wildlife and Fisheries Branch, Canada	> 60 °C for ≥ 10 s to 70 s	Yes, duration not specified	Yes, pressure not specified
Ministère des Forêts, de la Faune et des Parcs, Quebec, Canada	60 °C for 10 s	≥ 5 days (when relative humidity ≤ 65%)	2600 psi
Invasive Species Council of British Columbia, Canada	Not included	Yes, duration not specified	Yes, pressure not specified
Minnesota Department of Natural Resources, USA	~ 48.9 °C for ≥ 2 min, or 60 °C for ≥ 10 s	≥ 5 days	Not included
Wisconsin Department of Natural Resources, USA	Not included	Yes, duration not specified	Not included
US Aquatic Nuisance Task Force	~ 48.9 °C (2 minutes for motors)	≥ 5 days	Not included
Ministry for Primary Industries, New Zealand	> 60 °C for ≥ 1 min, or > 45 °C for ≥ 20 min	> 48 h after equipment has dried	Not included
Great Britain Non-Native Species Secretariat	Yes, temperature/duration not specified	Yes, duration not specified	Not included

of British Columbia 2020), Great Britain (Great Britain Non-Native Species Secretariat 2020), and New Zealand (Biosecurity New Zealand 2018), to state laws in the USA (Wisconsin Department of Natural Resources 2017; Minnesota Department of Natural Resources 2020). In general, these programs include recommendations for lake users to decontaminate watercraft, and fishing, sailing or watersports gear by washing with high water pressure, rinsing with hot water at temperatures from 50 °C to 60 °C, or allowing all parts to air-dry for durations from two to greater than five days, before use at another site (Table 1). However, surveys in the US and Canada have found that many boaters did not implement recommended cleaning techniques such as rinsing, pressure-washing or drying between trips when the watercraft was used on more than one lake (Rothlisberger et al. 2010; Kelly et al. 2013). Boaters were also less likely to clean their boats if they perceived the related effort to be difficult or costly in terms of time and money (De Ventura et al. 2017).

As such, in order to identify decontamination measures that would be both effective and easy to implement, we reviewed the scientific literature for studies testing the efficacy of commonly recommended methods geared towards recreational watercraft. We also sought to determine if there was any consensus across studies, or if there were gaps in our current knowledge of effective decontamination.

Materials and methods

We conducted a search of journal articles published in English or French from 1900 to September 2019, from four databases: Web of Science, Green file, Environment Complete and Geobase. Web of Science has an extensive coverage dating back to 1900 for scientific disciplines, while the other three also cover journals that include environmental aspects and applications in the fields of ecology, natural resources, aquatic environments, public policies and social impacts. The search terms are shown in Table 2.

Table 2. Search terms and strategy

1	(decontaminat* OR "hot water" OR steam* OR clean* OR disinfect* OR spray* OR heat* OR dry* OR prevent* OR manage* OR antifoul* OR biofoul* OR sun* OR hot OR inspect* OR interven* OR airdry* OR rins* OR pressure* OR desiccat* OR expos* OR control OR biosecurity OR biocontrol OR "biological control")
2	(invasive OR non-native OR exotic OR foreign OR alien OR spread* OR invad*)
3	(aquatic OR freshwater OR lake* OR pond* OR river* OR stream*)
4	(species OR organism* OR animal* OR plant* OR invertebrate* OR arthropod* OR mollusc* OR bivalve* OR mussel* OR pest)
5	(viability OR viable OR mortality OR death OR surviv* OR reproduc* OR dispersal OR "overland transport" OR tolerance OR maxim* OR lethal OR "acute upper lethal temperature" OR temperature OR heat OR hot OR "critical maximum temperature")
6	1 AND 2 AND 3 AND 4 AND 5

Eligibility criteria

Studies were included if they (i) assessed cleaning and decontamination using hot water, air-drying, pressure-washing, or commercially available/household products, (ii) evaluated their efficacy on recreational watercraft and equipment, (iii) included aquatic invasive invertebrates or plants, and (iv) determined AIS viability, survival or growth after treatment. We excluded studies on boater surveys about cleaning practices or knowledge, decontamination of ballast, ocean-going ships and industrial equipment, eradication of invasive species, invasion models, other vectors of AIS spread, and experiments where the same group of test organisms were exposed to gradual changes in treatment (e.g. increasing salt concentration or water temperature over a fixed time period).

Data extraction and analysis

As the aim of this review was to identify the conditions under which a low survival rate was achieved for the principal decontamination methods described above, we recorded those that produced a minimum mortality of 90%. These were either reported as percentages of survival after the application of specific treatments, or as estimates such as lethal concentrations and values derived from regressions in the studies included. When 100% mortality was reported, we produced scatterplots of the corresponding conditions to appraise those that had the highest efficacy. Using the statistical software R (R Core Team 2020), we applied a quasi-Poisson regression (generalised linear models) to this data to determine the relationship between conditions (for instance, hot water temperature and exposure durations) required for 100% mortality. For experiments with air-drying conditions producing 100% mortality, we calculated the overall Pearson's correlation coefficient to determine the strength of the relationship between relative humidity and air temperature.

Results

The search returned a total of 12,290 results from the four databases. Due to overlap among the databases, we eliminated 5,163 duplicates and the remaining unique records were screened by title. We retained 267 articles

which were next screened by abstract. Finally, we assessed the eligibility of 92 full articles, of which 37 were included in the review. The majority of studies were from the USA (56.8%), with the remaining from Europe and the United Kingdom (27.0%), Australia and New Zealand (5.4%), Argentina (5.4%), Canada (2.7%), and Japan (2.7%).

The majority (70.3%) evaluated air-drying as a decontamination method, and only five studies assessed the efficacy of more than one method simultaneously (Supplementary material Tables S1 to S4). Species such as zebra mussels (*Dreissena polymorpha* [Pallas, 1771]) or quagga mussels (*Dreissena bugensis* Andrusov, 1897), and various aquatic snails featured in 11 (29.7%) and 8 (21.6%) studies respectively, whereas cumulatively, 16 different species of aquatic plants were included in 11 studies with experiments on macrophytes.

Air-drying

Twenty-six studies (Tables S1 and S2) assessed the effects of air-drying on the survival or viability of AIS. Only two included experiments conducted outdoors or in field settings (Montalto and de Drago 2003; Havel 2011) whereas the remaining were laboratory experiments. Overall, air-drying resulted in significantly higher and faster mortality than controls (Montalto and de Drago 2003; Evans et al. 2011; Havel 2011; Anderson et al. 2015; Piersanti et al. 2018) and increasing air-drying duration was significantly associated with decreased AIS survival (Barnes et al. 2013; Collas et al. 2018; Coughlan et al. 2018). Collas et al. (2018) demonstrated that increased exposure to air decreased the percentage of sessile zebra and quagga mussels that were alive upon detaching from surfaces when the latter were returned to water (Table S2); furthermore, 66% and 58% of these surviving zebra and quagga mussels remained alive 24 hours later. There were mixed results regarding the importance of air temperature on survivorship: while Snider et al (2014) showed that temperatures above 25 °C were required for no quagga mussel veliger survival at high humidity, Ricciardi et al. (1995) found that mortality among zebra mussels was significantly higher with increasing temperature and air-drying duration, as well as with decreasing relative humidity, but not among quagga mussels. Similarly, Bickel (2015) and Havel (2011) showed that temperature did not affect survivorship among macrophytes (Carolina fanwort, *Cabomba caroliniana* A. Gray, temperature range: 20 to 30 °C) and Chinese mystery snails (*Cipangopaludina chinensis* [Gray, 1834], temperature range: 15 to 25 °C) respectively (Havel 2011; Bickel 2015). Instead, relative humidity predicted mortality, with higher relative humidity allowing various AIS to tolerate air-drying for longer (McMahon et al. 1993; Ricciardi et al. 1995; Havel 2011; Coughlan et al. 2018). Moreover, other studies found no significant difference in survivorship after treatment between test groups subjected to air-drying at high humidity (70% to 89%), and control groups which remained in an
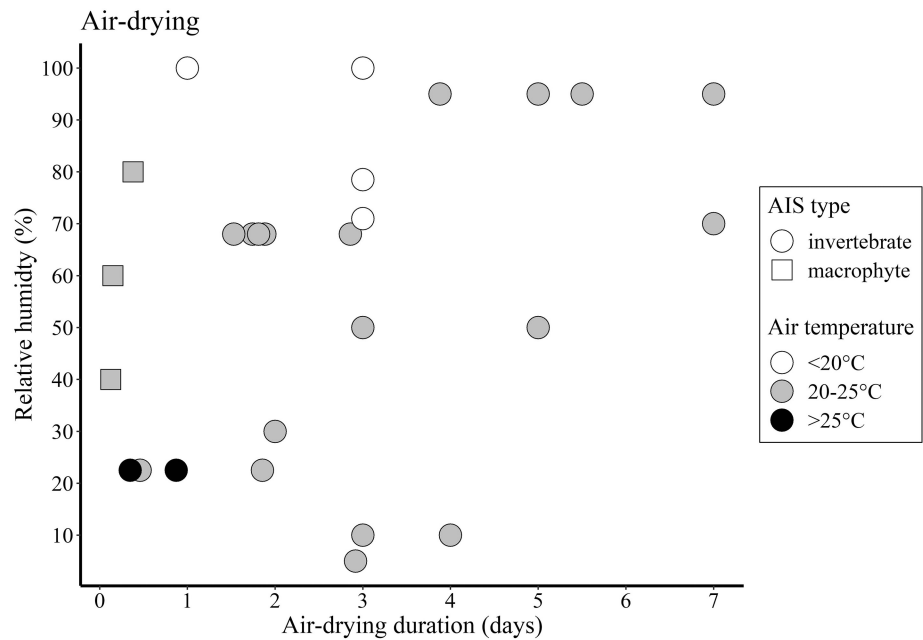
Figure 1. Air-drying conditions within recommended durations, producing 100% mortality.

aquatic environment for the test duration (Bernatis et al. 2016; Piersanti et al. 2018). Our analysis on air-drying conditions for 100% mortality resulted in a significant Pearson's correlation coefficient of 0.317 (p = 0.041) between air-drying duration and relative humidity, supporting the observation that longer air-drying durations are required for maximum mortality as relative humidity increases.

Table S1 shows the air-drying conditions and durations which led to a minimum mortality rate of 90% among various AIS, with Figure 1 specifically illustrating those resulting in no survival (data drawn from Tables S1 and S2). Nine studies recorded near-complete or complete mortality (99% to 100%) after air-drying among invertebrates, namely red swamp crayfish (*Procambarus clarkii* [Girard, 1852]) and signal crayfish (*Pacifastacus leniusculus* [Dana, 1852]) (Banha and Anastácio 2014; Piersanti et al. 2018), molluscs including dreissenid mussels, New Zealand mudsnails (*Potamopyrgus antipodarum* [J. E. Gray, 1843]) and juvenile golden mussels (*Limnoperna fortunei* [Dunker, 1857]) (McMahon et al. 1993; Ricciardi et al. 1995; Montalto and de Drago 2003; Richards et al. 2004; Collas et al. 2014), and planktonic organisms such as a non-native *Daphnia*, calanoid copepod (Tremblay et al. 2019) and bloody-red shrimps (*Hemimysis anomala* G.O. Sars, 1907) (De Stasio et al. 2019). However, only two of seven studies on aquatic plants reported 100% mortality among specific species (Jerde et al. 2012; Barnes et al. 2013). Although others observed that durations of 3 h to 18 h led to at least 90% mortality among various macrophyte species at temperatures ranging from 21 °C to 26 °C and relative humidity from 40% to 80% (Evans et al. 2011; Bickel 2015; Baniszewski et al. 2016; Coughlan et al. 2018) (Table S1), one study found that 4 to 9 days were required for the same effect among other macrophytes such as curly water-thyme (*Lagarosiphon*

major [Ridl.] Moss), floating pennywort (*Hydrocotyle ranunculoides* L. f.) and parrot's feather (*Myriophyllum aquaticum* [Vell.] Verdc.) (Anderson et al. 2015).

As various agencies recommend air-drying watercraft and equipment for at least two to greater than five days (Table 1), it is noteworthy that 18 studies found that air-drying for up to seven days was sufficient to result in at least 90% mortality among zebra and quagga mussels, crayfish, specific snails, planktonic organisms as well as certain macrophytes (Tables S1 and S2, Figure 1). Although air-drying for a week therefore seems to be a rather effective means of decontamination, other species – notably Asian clams, adult golden mussels, applesnails, Chinese mystery snails, killer shrimps, and plants such as parrot's feather and New Zealand pygmyweed – required much longer air-drying durations ranging from greater than a week to several months for complete mortality (Montalto and de Drago 2003; Havel 2011; Collas et al. 2014; Anderson et al. 2015; Collas et al. 2018), or as shown in Table S2, still had high survivorship within the study duration. Among invertebrates, larger or older individuals were also more resistant to desiccation than smaller ones or juveniles (Ricciardi et al. 1995; Montalto and de Drago 2003; Richards et al. 2004; Havel 2011; Collas et al. 2014; Havel et al. 2014; Snider et al. 2014; Bernatis et al. 2016), often with drastic differences such as among Chinese mystery snail (*Cipangopaludina chinensis* [Gray, 1834]) where air-drying for 14 days resulted in at least 90% mortality among small juveniles (6–8 mm), compared to only 10% among larger juveniles (25 mm), regardless of humidity level (Havel 2011) (Table S2). Similarly, as a species with different life stages, the planktonic veligers of zebra mussels had high mortality after air-drying for a few hours (Banha et al. 2016) compared to sessile adults, which required several days in other studies (McMahon et al. 1993; Ricciardi et al. 1995; Collas et al. 2014; Anderson et al. 2015) (Table S1). Havel et al. (2014), Wood et al. (2011) and Bernatis et al. (2016) further showed that certain aquatic snails were especially capable of surviving extended periods of desiccation, whereas among plants, New Zealand pygmyweed (*Crassula helmsii* [Kirk] Cockayne) required up to 23 days of air-drying for 90% mortality (Anderson et al. 2015). The configuration or shape of plant fragments also affected their survival, with Jerde et al. (2012) achieving 100% mortality among uncoiled fragments of Eurasian watermilfoil (*Myriophyllum spicatum* L.) compared to 76% for coiled fragments subjected to the same treatment conditions. Similarly, coiled fragments remained viable for longer after air-drying than single or uncoiled fragments (Bickel 2015; Bruckerhoff et al. 2015). Finally, two studies assessed the probability of Eurasian watermilfoil fragments being viable after desiccation as a function of water loss (Evans et al. 2011; Barnes et al. 2013). Both found that water loss was positively correlated to both air-drying time and plant mortality. Moreover, the ability for plant fragments to generate new growth following desiccation

Hot water immersion
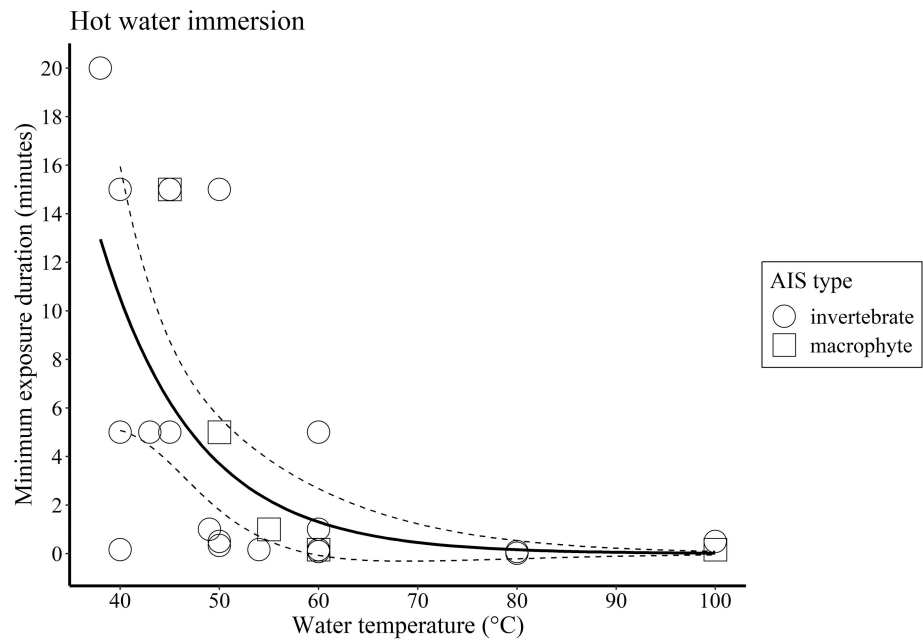
Figure 2. Water temperature and exposure duration resulting in 100% mortality. The regression line shows the relationship between water temperature and exposure duration among all AIS types collectively. Dashed lines represent the 95% confidence bands.

was inversely proportional to drying time (Evans et al. 2011). Although Barnes et al. (2013) found that water mass loss ranging from 64% to 100% was required for 90% (empirical) to 98% (modelled) mortality among nine plant species, the corresponding air-drying times were not reported.

Hot water

We identified 12 studies assessing the effect of heat treatment on AIS survival or viability, by means of hot water immersion, sprays, or steam (Table S3). While certain invertebrate species such as zebra mussels, bloody-red shrimps, and killer shrimps (*Dikerogammarus villosus* [Sowinsky, 1894]) appeared in at least two separate studies, few studies included aquatic plants. The methodology or mode of hot water application differed based on the management strategies that the authors sought to evaluate, and only three studies consisted of outdoors experiments (Comeau et al. 2011; Havel et al. 2014; Bruckerhoff et al. 2015). Nonetheless, all reported very high mortality rates for at least one of the treatment groups and most species tested, and compared to controls, hot water was an effective tool that significantly increased mortality among organisms (Blumer et al. 2009; Morse 2009; Comeau et al. 2011; Anderson et al. 2015; Coughlan et al. 2019; Crane et al. 2019). Figure 2 shows the water temperature and exposure durations that produced 100% mortality among both invertebrates and macrophytes, and consists of a subset of studies presented in Table S3. Regarding the relationship between water temperature and exposure duration for all AIS and hot water application methods resulting in no survival, our quasi-Poisson regression showed that the required exposure

duration decreased by 9.9% for every 1 °C increase in water temperature (regression coefficient = −0.104, standard error [SE] = 0.033, p = 0.004).

Overall, exposure to water at temperatures of at least 40 °C for up to 15 minutes was required for complete mortality among small invertebrates such as bloody-red shrimps, spiny waterfleas (*Bythotrephes longimanus* Leydig, 1860), killer shrimps, and dreissenid mussels (Table S3). For aquatic plants, increasing temperature reduced time to mortality: 90% mortality after 15 minutes at 45 °C (Anderson et al. 2015) *vs* 100% after 1 minute at 55 °C (Shannon et al. 2018). More generally, species (both plant and invertebrate) was not a good predictor of mortality when several species were subjected to the same treatment conditions (Anderson et al. 2015), and temperature was a better predictor of mortality than immersion time (Blumer et al. 2009; Beyer et al. 2011). There was no significant difference in mortality rates when hot water use was followed by air-drying, compared to hot water only, implying that air-drying had no added benefit (Anderson et al. 2015). Although most of the studies on heat treatment tested immersion as a means of decontamination, spraying with hot water would be more feasible for boats and large equipment. Higher temperatures (≥ 54 °C to 80 °C) are required with sprays to produce comparable results to immersion (Table S3) (Morse 2009; Comeau et al. 2011). Steam (100 °C) was highly efficient on invertebrates and macrophytes, resulting in complete mortality or degradation among species tested (Coughlan et al. 2019; Crane et al. 2019) (Table S3).

Pressure-washing

Only one study (Rothlisberger et al. 2010) evaluated the efficacy of pressure-washing, comparing high pressure (1800 psi), low pressure (40 psi), and visual inspection combined with manual removal. Known amounts of large plant fragments or small organisms (spiny waterfleas and aquatic plant seeds) were attached to boats and the amount removed after pressure-washing or manual removal was determined. Rothlisberger et al. (2010) found that high pressure or visual inspection plus manual removal eliminated significantly greater quantities of large fragments (83%, SE = 4% and 88%, SE = 5%, respectively) than low pressure (62%, SE = 3%, p < 0.001). High pressure was also significantly more effective at removing small-bodied organisms (91%, SE = 2%) than low pressure (74%, SE = 6%) and visual inspection plus manual removal (65%, SE = 4%, p < 0.001). Cleaning for either 90 s or 180 s did not affect the amount of either large fragments (p = 0.37) or small organisms (p = 0.20) removed.

Other cleaning agents

Salt

Five studies (Hofius et al. 2015; Sebire et al. 2018; Coughlan et al. 2019; Tremblay et al. 2019; Underwood et al. 2019) assessed the efficacy of salt as

a cleaning agent. Table S4 shows the concentrations and immersion durations that produced complete mortality. Other studies found high survivorship among different AIS for similar exposure time frames; 60% of killer shrimps survived after 15 minutes in a salt solution of 160 Practical Salinity Units (PSU), the highest concentration tested by Sebire et al. (2018), while Coughlan et al. (2019) found that over 70% of Asian clams survived when exposed to 35 PSU and 70 PSU salt solutions for 1 to 6 hours. Nonetheless, Asian clams immersed in these salt solutions for up to 72 hours had significantly higher mortality (48%) than controls (11%, $\chi^2 = 107.410$, p < 0.001) (Coughlan et al. 2019).

Bleach

Four studies investigated the effects of bleach solutions for decontamination (Sebire et al. 2018; Coughlan et al. 2019; De Stasio et al. 2019; Tremblay et al. 2019), with three reporting complete mortality (Table S4). Generally, increasing concentration of bleach solutions or exposure time resulted in higher and faster mortality. For instance, complete mortality among killer shrimp was instant at high concentrations of at least 10,000 mg/L (150–200 mL household bleach per litre), but delayed at a lower concentration of 450 mg/L (6.75–9 mL household bleach per litre), whereas survival remained high (40%) at 300 mg/L (4.5–6 mL household bleach per litre) (Sebire et al. 2018). De Stasio et al.'s study including different species showed variable responses to bleach concentrations recommended by the Wisconsin Department of Natural Resources. Despite its efficacy against planktonic AIS, 400 mg/L solution (6–8 mL household bleach per litre) had lower efficacy against New Zealand mudsnails, resulting in 82.7% to 92% mortality when immersed, which was nonetheless more effective than bleach sprays (F = 0.95, p = 0.456) (De Stasio et al. 2019). Finally, Coughlan et al. (2019) showed that mortality in control groups of Asian clam (11%) was not significantly different to that in treatment groups using 50 mg/L (≤ 1 mL household bleach per litre) to 200 mg/L (3–4 mL household bleach per litre) bleach solutions and immersion times of 10 to 80 minutes (21%, $\chi^2 = 1.6879$, p-value not specified).

Virkon

Virkon is a broad-spectrum veterinary disinfectant used on farming, aquaculture and research equipment, with demonstrated efficacy against viral, bacterial and fungal pathogens (Hernandez et al. 2000; McCormick and Maheshwari 2004). Three studies (Sebire et al. 2018; Coughlan et al. 2019; De Stasio et al. 2019) evaluated its efficacy on AIS, including two which revealed that immersion in Virkon solutions (concentrations ranging from 4g/L to 20 g/L) produced complete mortality (Table S4). De Stasio et al. (2019) also showed that immersion performed better than spray application as the latter failed to produce complete mortality among all AIS

tested. Coughlan et al.'s study on Asian clams further revealed that there was no significant difference in mortality rates between 20 g/L and 40 g/L Virkon Aquatic and Virasure Aquatic solutions (p > 0.05). However, exposing Asian clams to either concentration resulted in significantly higher mortality (31–58%) than among non-exposed controls (0–14%, χ^2 = 133.40, p < 0.001) (Coughlan et al. 2019).

Discussion

The studies included in this review show that the prescribed cleaning and drying methods of various decontamination programs have demonstrated efficacy (Figures 1 and 2), especially against species that have been widely studied, such as zebra and quagga mussels. The paucity of studies on spiny waterfleas, bloody-red shrimps, and killer shrimps, as well as the lack of more than one study on the same macrophyte species highlight the need for further research on new or potential AIS. In the absence of other decontamination methods, air-drying is more efficient than no action. Our review and analyses would indicate that air-drying for one week may be adequate and effective to result in no survivorship among various AIS. However, certain species of invasive snails were capable of surviving beyond the recommended time frame of air-drying protocols (Havel 2011; Havel et al. 2014; Bernatis et al. 2016), while desiccated plant fragments may still remain viable (Coughlan et al. 2018). It is also difficult to establish air-drying times required for complete mortality as the latter depends on other environmental factors, especially relative humidity (McMahon et al. 1993; Ricciardi et al. 1995; Havel 2011; Coughlan et al. 2018). Although we found a weak positive correlation between air-drying duration and relative humidity, an important caveat is the considerable variation in experimental design, environmental conditions, and species assessed among the studies included in our analyses. Different studies have assessed air-drying at various temperatures and relative humidity in both laboratory and field settings; while the studies covered a range of environmental conditions occurring over the span of a boating season, they were not all effective at producing complete mortality. Furthermore, the majority of these studies are limited to the response of few species concurrently, or specific life stages and body sizes. In fact, Yoshida et al. (2014) observed that individuals from the same species but different populations differed in their resistance to desiccation, and as such, applying the findings from air-drying studies should be done cautiously and with regards to regional context. As a result, the risk of introduction even after air-drying remains a concern especially in high traffic lakes when mortality remains below 100% (Blackburn et al. 2015; Sinclair and Arnott 2016).

The studies on hot water presented here have shown that for water temperatures of 40 °C and above, immersion for up to 20 minutes results in complete mortality among various species of invertebrates and plants.

An important challenge in implementing this method is that it may be feasible only for smaller equipment that can be immersed, and additionally, it would be necessary to maintain the immersion water at the appropriate temperature for the required duration in order for decontamination to be effective. However, since planktonic AIS or those with life stages not readily detected with the naked eye are often found in the standing water of recreational vessels (Johnson et al. 2001; Kelly et al. 2013), flooding parts such as the bilge and live wells with hot water may be an appropriate means of eliminating live AIS; currently, in Canada for instance, established protocols such as Manitoba's Aquatic Invasive Species Regulations are already centred around the use of hot water (60 °C) for the decontamination of watercraft and related equipment (Manitoba Government Wildlife and Fisheries Branch 2020), with specific recommendations regarding its use also given by Ontario's Invading Species Awareness Program (Ontario Ministry of Natural Resources and Forestry 2017) and the province of Quebec (Ministère des Forêts, de la Faune et des Parcs 2018). Although hot water sprays and steam jets have demonstrated efficacy and are more practical for large surfaces, the high temperatures they deliver may damage equipment and be potentially injurious. In addition, steam and even hot water sprayers are not commonly accessible to recreational boaters and homeowners. Overall, comparatively few studies have evaluated the efficacy of hot water as a decontamination method and it is necessary to explore the effects of hot-water on more diverse AIS. In fact, aquatic snails—which often proved to be resistant to other decontamination methods—were not included in any study testing the efficacy of hot water or steam.

Finally, other decontamination methods have been even more scarcely studied. Although Rothlisberger et al. (2010) have demonstrated the efficacy of washing surfaces at high pressure, further studies assessing the range of pressures between 40 and 1800 psi that could yield similar results are necessary. In addition to consolidating the evidence for pressure-washing, identifying other effective pressures would contribute to informed best management practices that can be adopted by a majority of watercraft users without the need for specialised equipment, often not accessible to recreational lake users (De Ventura et al. 2016). Studies conducted so far on the use of popular cleaning products such as salt, bleach, and Virkon have reported mixed results on their efficacy in addition to testing a limited number of AIS (Hofius et al. 2015; Sebire et al. 2018; Coughlan et al. 2019; De Stasio et al. 2019; Tremblay et al. 2019; Underwood et al. 2019). As mortality rates were affected by chemical concentration and exposure duration—both of which varied among studies—a caveat of this method is that the need for specific concentrations and treatment time could present a barrier to effective implementation, as users would be required to prepare precise amounts of solution, and allow equipment to soak in potentially corrosive media for extended periods.

Overall, the differences in experimental design and methodology among the studies included can be attributed to regional context (species, life stage, temperature, relative humidity) and decontamination recommendations being evaluated (species, mortality following desiccation on various material, hot water spray versus immersion versus steam). The criteria to establish invertebrate mortality was common among all studies, but the means of determining plant survivorship and viability differed. These included measuring enzyme activity (Blumer et al. 2009), the ratio of variable to maximal fluorescence of leaves as an indicator of stress (Anderson et al. 2015; Shannon et al. 2018), visual estimation of degradation and colouration (Jerde et al. 2012; Baniszewski et al. 2016; Crane et al. 2019), morphological measurements (e.g. new structure, growth rate, biomass) (Evans et al. 2011; Jerde et al. 2012; Barnes et al. 2013; Bickel 2015; Bruckerhoff et al. 2015; Coughlan et al. 2018), and estimating the probability of fragments remaining viable as a measure of the percentage of water loss following desiccation (Evans et al. 2011; Barnes et al. 2013; Bickel 2015). Such variation in methodology could limit the generalisation of findings among studies, and future research on plant species should include the determination of survival and viability by more than one means in order to ascertain the sensitivity and specificity of the chosen criteria. Nonetheless, all studies specified whether only fragments containing the vegetative part, apical meristems, or turions of plants were included, which is important to consider given the different propagative potential of these structures.

Our review has revealed that although current recommended decontamination methods may be effective, the range of species that they can be confidently used against is limited given the lack of studies including multiple and more diverse organisms simultaneously. Air-drying, although extensively studied, is less effective than hot water, while also being influenced by fluctuating conditions such as air temperature and humidity. In addition to comparing the efficacy of different methods, it will also be important to further explore the efficacy of hot water use and pressure-washing in field studies in order to best inform *in situ* decontamination practices. More knowledge on the demonstrated range of efficacy on various species and ease of use for recreational boaters would allow government and environmental agencies to tailor best management practices adapted to the geography, climate, and existing as well as emergent AIS of threat locally.

Acknowledgements

Funding Declaration

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Supplementary material

The following supplementary material is available for this article:

Table S1. Air-drying conditions for maximum AIS mortality.
Table S2. Studies on air-drying with outcome measures other than maximum mortality.
Table S3. Studies achieving at least 95% AIS mortality with hot water.
Table S4. Concentration and exposure duration of cleaning agents producing ≥ 99% mortality

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