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Review

Improving invasive ant eradication as a conservation tool: A review

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ABSTRACT

While invasive species eradications are at the forefront of biodiversity conservation, ant eradication failures are common. We reviewed ant eradications worldwide to assess the practice and identify knowledge gaps and challenges. We documented 316 eradication campaigns targeting 11 species, with most occurring in Australia covering small areas (<10 ha). Yellow crazy ant was targeted most frequently, while the bigheaded ant has been eradicated most often. Of the eradications with known outcomes, 144 campaigns were successful, totaling approximately 9500 ha, of which 8300 ha were from a single campaign that has since been partially re-invaded. Three active ingredients, often in combination, are most commonly used: fipronil, hydramethylnon, and juvenile hormone mimics. Active ingredient, bait, and method varied considerably with respect to species targeted, which made assessing factors of eradication success challenging. We did, however, detect effects by active ingredient, number of treatments, and method on eradication success. Implementation costs increased with treatment area, and median costs were high compared to invasive mammal eradications. Ant eradications are in a phase of increased research and development, and a logical next step for practitioners is to develop best practices. A number of research themes that seek to integrate natural history with eradication strategies and methodologies would improve the ability to eradicate ants: increasing natural history and taxonomic knowledge, increasing the efficacy of active ingredients and baits, minimizing and mitigating non-target risks, developing better tools to declare eradication success, and developing alternative eradication methodologies. Invasive ant eradications are rapidly increasing in both size and frequency, and we envisage that eradicating invasive ants will increase in focus in coming decades given the increasing dispersal and subsequent impacts.

Contents

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1. Introduction

Invasive alien species continue to impact species, ecosystems, and human welfare (Simberloff, 2013). Ants are one of the most cosmopolitan invasive taxa: dozens of species have invaded islands and continental areas around the globe (Suarez et al., 2010). Certain ant species exhibit a suite of characteristics that result in anthropophilic tendencies. Consequently, invasive ants continue to spread globally (Ascunce et al., 2011; McGlynn, 1999). These tramp species are having direct and indirect negative impacts on natural and managed ecosystems (Holway et al., 2002; Lach and Hooper-Bui, 2010). In some cases, those impacts can be complex and dramatic (O'Dowd et al., 2003). In a few cases, the biodiversity benefits of removing invasive ants have been documented (Gaigher et al., 2012; Hoffmann, 2010).

Invasive species eradications have been at the forefront of biodiversity conservation gains over the past two decades (Veitch et al., 2011). Over 1200 invasive mammal eradications have been attempted on over 800 islands worldwide (DIISE, 2014). The conservation benefits of such conservation actions are increasingly well documented (Donlan et al., 2007; Lavers et al., 2010). Despite a long history of invasive ant management, methods and approaches vary widely and eradication failures are common (Hoffmann et al., 2011a). Social insects, like invasive ants, complicate management actions due to their complex interactions with each other and the environment. For example, a caste system can prevent reproductive members of a colony from getting sufficient exposure to bait with an active ingredient that is targeted at foragers (Moller, 1996). Thus, many popular approaches to insect management (e.g., integrated pest management) are inappropriate for social insects because of a failure to expose reproductively active individuals (Gentz, 2009). These characteristics present unique challenges for eradication, or even effective control, of invasive ants (Silverman and Brightwell, 2008). However, new developments in insecticides and other active ingredients (collectively referred to hereafter as AI) and management methodologies have improved practitioners' ability to eradicate invasive ant populations (Hoffmann et al., 2011a).

Over the past decade, taxa-specific reviews of invasive species eradications have helped clarify the benefits, costs, and risks of eradication as a biodiversity conservation tool, as well as identify important research needs (Campbell et al., 2011; Howald et al., 2007; Nogales et al., 2004). Here, we review ant eradication attempts worldwide. In particular, we assess the status of ant eradication as a conservation practice and explore what factors influence success or failure. We characterize the approaches and outcomes of ant eradication campaigns, and identify knowledge gaps and challenges to be addressed by research and other activities that will likely improve the ability to safely eradicate invasive ant populations.

2. Methods

We compiled data from publications, gray literature (e.g., government reports), and personal communications on ant eradications. We only included efforts that explicitly targeted a spatially discrete ant population for eradication. For example, programs that targeted a subset of a population for eradication, which is common in efficacy trails, were not included in our review. Further, we did not include historical eradications that used organochlorine sprays because those insecticides are now widely banned, and insecticide spraying is no longer advocated in most situations for ant eradications (Hoffmann et al., 2011a). For each eradication effort, we collected information on location, species, area treated, methods used, AI, cost, and outcome. We judged failure or success based on the outcome and evidence reported by those that conducted the eradication. For the purposes of our review, an eradication attempt was considered successful if two years of monitoring occurred with no detection (FAO, 1998; Howald et al., 2007). We treated the year of the final treatment as the eradication date. In some instances, multiple attempts were made to eradicate a single population. In these cases, each attempt followed by a monitoring assessment was considered an independent eradication attempt, and all but the final attempt were counted as failures. Our unit of analysis was the area of each spatially discrete population in which eradication was attempted (referred to hereafter as a campaign), which in the case of islands is often a fraction of an island as opposed to the entire island as occurs for other invasive species eradications (e.g., rodents). Data from the Database of Islands and Invasive Species Eradications (DIISE, 2014) was accessed 10 March 2016, and we used events only for invasive mammals (excluding domestic animal populations), whole island eradications, and events that were classified as good or satisfactory data quality. For determining success rates, we considered only successful or failed projects, and excluded reinvasion as these can also include misdiagnosed operational failures. Statistical analyses were conducted using R (R Development Core Team, 2011) with an alpha-level of $p = 0.05$, and details are described below.

3. Results

3.1. The state of invasive ant eradication

The history of ant eradications began with multiple, large unsuccessful campaigns. Starting in the 1950s, the red imported fire ant program (*Solenopsis invicta*) in the southeast United States was one of the first eradication programs, and one of the largest eradication programs ever attempted for any species. For 16 years, more than 56 million hectares were treated with a myriad of liquid-based compounds (Williams et al., 2001). Eradication was not achieved. Over the same time period in Australia, programs covering tens of thousands of hectares targeted the Argentine ant (*Linepithema humile*) (Van Schagen et al., 1994). With the banning of organochlorine compounds, these programs ended without achieving eradication. When the limitations of liquid sprays were widely recognized, practitioners developed solid granular baits (Lofgren et al., 1975; Williams et al., 2001). While these bait developments improved invasive ant management, large campaigns initiated in the 2000s in China and Australia continue to struggle to achieve eradication (Vanderwoude et al., 2003; Zhang et al., 2007).

Overall, we documented 316 eradication campaigns targeting 11 ant species (Fig. 1). Most campaigns have occurred on continents ($n = 236$, 75%). Slightly less than half of all campaigns were successful ($n = 144$), and the remaining were either failures (74) or of unknown outcome (98), with 92 of the latter being in progress (Fig. 2). Over 50% of the campaigns were unpublished (Supplementary Materials). Most successful eradications were in Australia and targeted an area less than 10 ha (Fig. 3). The total area that invasive ants have been eradicated from worldwide is approximately 9500 ha (Fig. 2).

We identified only five successful eradications prior to 2000, totaling 7 ha (Fig. 2). These campaigns targeted yellow crazy ant (*Anoplolepis gracilipes*) from a small area of unknown size on Praslin Island