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Threatened plant translocation in Australia: a review

Abstract

Translocation of plants has become a common approach in conservation biology in the past two decades, but it is not clear how successful it is in achieving long-term conservation outcomes. We combined a literature review with extensive consultations with translocation practitioners to compile data on translocations of threatened Australian plants. We documented 1001 translocations involving 376 taxa, concentrated in regions and habitats with high numbers of threatened species. Only 109 translocation attempts encompassing 71 taxa are documented in peer-reviewed literature. Over 85% of translocations have occurred since 2000 and half since 2010, with an especially rapid increase in development mitigation translocations, which account for 30% of all translocations documented. Many translocations involved extremely small numbers of propagules, with 45% using <50 propagules and only 16% >250. Of the 724 translocations with sufficient data to assess performance, 42% have <10 plants surviving, and 13% have at least 50 plants surviving and some second-generation recruitment into the population. Translocation performance, measured by number of plants surviving and second-generation recruitment, was highly variable between plant lifeforms, habitats and propagule type. However, species was more variable than all of these, suggesting that some species are more conducive to translocation than others. Use of at least 500 founder individuals increased the chances of creating a viable population. Four decades after the first conservation translocations, our evaluation highlights the need to consider translocation in the broad context of conservation actions for species recovery and the need for long-term commitment to monitoring, site maintenance and documentation.

Keywords: reintroduction; threatened plants; ex-situ conservation; development mitigation; offsets; translocation success

1. Introduction

The practice of translocation has become widespread in biodiversity conservation globally as anthropogenic pressures on ecosystems and species accelerate (Maunder 1992; Muller and Eriksson 2013). As a deliberate transfer of plants or regenerative plant material from an *ex-situ* collection or natural population to a new location, translocation can cover a range of techniques and this will depend on the extinction risk, the threats impacting on the species and requirements under legislation. Translocations are becoming a standard mitigation approach where development projects have impacts on populations of rare and threatened species (Allen 1994) and are increasingly considered as part of a mitigation hierarchy (Arlidge et al. 2018).The prevalence and imperatives for translocations will continue to grow under projected climate scenarios (Hancock and Gallagher 2014; Webber et al. 2011). However, very few translocation studies are published (Godefroid et al. 2011), with the result that little is known about the practice of translocation, rates of success, and whether translocation should be viewed as a viable long-term conservation strategy.

Reviews of plant translocations have been conducted with a global focus (Dalrymple et al. 2012; Godefroid et al. 2011; Menges 2008), and for regions, countries, vegetation communities and plant groups (Albrecht et al. 2019; Brichieri-Colombi and Moehrenschlager 2016; Liu et al. 2015; McDougall and Morgan 2005; Milton et al. 1999; Morgan 1999; Reiter et al. 2016). The emerging consensus highlights translocation as relatively high-risk, high-cost and challenging (Drayton and Primack 2012; Holl and Hayes 2006). Survival, flowering and fruiting rates are generally low and sometimes show a downward trend with time, where monitoring data is available (Godefroid et al. 2011). This is often due to poor understanding of the biology, ecology and habitat requirements of rare and threatened plants (Fiedler and Laven 1996; Reiter et al. 2017; Reiter et al. 2016), short timeframes and funding constraints of projects meaning a lack of long-term management and monitoring (Falk et al. 1996), and the small size of many introduced populations (Krauss et al. 2002). Sometimes the reasons for translocation failures are unknown (Drayton and Primack 2012). Nevertheless, translocation has proven a highly successful tool for threatened species conservation in some instances (Colas et al. 2008; Maschinski and Duquesnel 2007; Milton et al. 1999; Munt et al. 2016), and some plants now only exist in translocated populations (Maunder et al. 2000; Rich et al. 1999).

Australia has a long but poorly documented history of threatened plant translocation. When vegetation clearing and habitat degradation accelerated across Australia’s agricultural and urban regions in the 1940s and 1950s, concerned local residents in some areas rescued plants from sites that were about to be cleared and replanted them in their gardens or safe patches of bush (Australian National Herbarium 2015). These acts of private citizens can be regarded as Australia’s first modern conservation translocations, but today it is unknown what species were involved or whether plantings were successful.

The first documented conservation translocations were carried out in the grasslands of Melbourne in 1950 by plant-lovers in the Victorian Field Naturalists Club, led by Miss Winifred Waddell (Willis 1951). Sods of native vegetation taken from nearby remnant grasslands were planted within a fenced sanctuary, with special emphasis placed on moving several large clumps of the threatened orchid *Diuris fragrantissima*. The next documented translocations occurred in the late 1970s, also in Victoria (Stuwe 1980). Anecdotal and limited published evidence (Dillon et al. 2018; Jusaitis et al. 2004; Morgan 1999; Reiter et al. 2016) suggests that the practice of translocation has expanded over the past four decades to become common practice for conservation of imperilled species, and for mitigation of the impacts of development. While the vast majority of data on these translocations are undocumented, or occur in internal reports that are not publically accessible, a recent study that reviewed approaches to species relocations in Australia based on published studies documented ‘at least 14’ species of threatened plants that had been translocated (Sheean et al. 2012). It is therefore difficult to reliably gauge the nature and extent of plant translocations in Australia, examine their performance or synthesise knowledge to improve future translocations.

We compiled data on as many translocations in Australia of plants of conservation concern as we were able to access through an extensive process of practitioner interviews and literature review, to bring together the most up-to-date information on this increasingly prominent but poorly documented practice. We sought background information on: how many plant translocations for conservation have occurred in Australia, and how many of these have been reported in the published literature; where have these translocations been concentrated; what species and lifeforms have been involved and who has undertaken translocations and why? We used this information to address the following questions: (1) What techniques and methods are commonly used in Australian plant translocations?; (2) How have these translocations performed?; and (3) What are the key biological or management factors that are correlated with success? We aim to improve translocation science and practice in Australia and globally, by enabling more informed decisions to be made on when and where translocation is likely to be an effective management tool, and providing practical guidance on improving outcomes for translocations.

2. Material and methods

2.1 Assembling the Australian plant translocation database

We collated data on translocations of plants of conservation concern that have occurred in Australia. We define translocation as the intentional movement or introduction of plant material to a natural or managed area with the aim of establishing a resilient, self-sustaining population to increase geographic range, population size and/or genetic diversity, thus reducing risk of extinction (IUCNSSC 2013). This includes both reinforcement of existing populations and establishment of new ones, either within (introductions or reintroductions) or beyond (assisted migrations) the known range of a species (Table 1). Tree orchards established to protect genetic diversity (Harris et al. 2009) were not included unless they were also aiming to establish a viable self-sustaining population. Revegetation and restoration efforts focusing on entire communities were only included where threatened species were involved and monitored (McDougall and Morgan 2005). Only threatened or locally rare or threatened species were included in the database.

Between October and December 2016, we searched the Web of Science database and Google Scholar using a query modified from Godefroid et al. (2011) and Liu et al. (2015): reintroduc* OR translocat* OR outplant* OR re-establish* OR transplant OR reinforce* AND plant AND Australia. We also searched the relevant Australian journals – *Ecological Management and Restoration*, *Australian Journal of Botany*, *Austral Ecology* and *Australasian Plant Conservation* – and Conference Abstracts and the IUCN Reintroduction Specialist Group case studies (available online at http://www.iucnsscrsg.org/) by scanning titles of each issue.

The vast majority of translocations are not published in the scientific literature (Godefroid et al. 2011), and even those that had been published in some form usually did not contain sufficient or the most up-to-date information for inclusion in the database. To overcome this, between July 2016 and August 2017 we interviewed more than 130 botanists, researchers, Natural Resource Management (NRM) group representatives and environmental consultants about translocations they had been involved in or had knowledge of, and as much information as possible was collected on each translocation attempt. This process involved telephone and face-to-face interviews, emails and accessing filed reports. Despite our efforts at comprehensiveness, it is certain that some translocations have been missed. There is likely to be a bias towards larger, more recent and more successful translocations, as well as those done by government agencies and conservation groups rather than consultants. An expert workshop was held to compile fields for inclusion in the database, while previous translocation studies and reviews suggested other relevant fields (Dalrymple et al. 2012; Guerrant and Kaye 2007). The database fields and explanations are provided in Appendix 1.

Some translocations had multiple experimental treatments applied at the same site, for example use of different propagule types, and watering, fertiliser and fencing regimes. These were included as one translocation with the treatments numbered. Where plantings were done in separate years, these were combined (and subsequent plantings noted) unless there were substantial differences in survival between years or different experimental treatments were applied in different years. In some cases, different propagule types were planted but not monitored separately; these are also combined. Management actions were grouped into pre-planting preparation of site (soil surface preparation and weeding/slashing), protection from herbivores (fencing, cages or guards), watering, post-planting weeding and planned burns.

2.2 Assessing performance

The ultimate goal of translocation is for translocated individuals to become established, produce seedlings of their own, and create or contribute to viable, self-sustaining populations, but this can be determined only after many years of monitoring – up to several decades or even centuries depending upon generation time of the species (Albrecht et al. 2019; Menges 2008; Pavlik 1996). Defining success remains problematic, especially for long-lived species, and each translocation will have its own success criteria based on relevant objectives (Monks et al. 2012; Reiter et al. 2016). Given that it is too early to assess the ultimate success of many translocations, we defined success criteria as short (% of plants that survived first year), medium (sufficient plants established to be considered a viable number for a population, evidence of flowering and/or fruit set, population disease-free and site secure) and long-term (self-sustaining population established, with recruitment into the translocated population and dynamics comparable to natural populations).

In relation to medium-term success criteria, defining the minimum number of plants that can be considered a viable population remains subject to debate (Frankham et al. 2014; Traill et al. 2010). The lowest estimates put the minimum number to prevent inbreeding depression at 50 plants (Jamieson and Allendorf 2012); however, most authors agree that it is likely to be a substantially larger number. Hence, we use 50 plants surviving at last monitoring as the threshold for medium-term success here, but this was relaxed for (i) salvage translocations of those rainforest plants that naturally occur sparsely as part of larger meta-populations (minimum number surviving 25), and (ii) augmentations where translocated individuals number at least 25 and constitute at least 20% of the total population. The timeframes required for plants to set seed and recruit are dependent upon species life history and prevailing site conditions, and practitioners nominated whether they considered it too soon for recruitment to have occurred.

We used Generalised Linear Mixed Models (GLMM) to model the variation in translocation performance (response variables were number of plants extant and whether recruitment had occurred). Our main numeric variables were the number of founder propagules and the time between translocation and last census. We had several categorical variables: taxonomic families, lifeforms, habitats, translocation types, translocation purpose (conservation or development mitigation), and propagule types. Certain lifeforms are only found in particular habitats and some propagule types are used for particular lifeforms and not others, and particular translocation types were only used for some habitat types and lifeforms within them. For this reason, we did not deeply explore combinations of categorical covariates. Early exploration revealed that habitat and propagule type had very small effects, so we chose to focus on lifeforms. We present two models, one for the probability of recruitment, which used a binomial response and a logit link. The model included fixed effects of log(time) and log(number of propagules) and mitigation (yes/no), with random effects of species nested in lifeforms. The model for number of plants extant was a Poisson response and a log link, with fixed effects of log(time), log(number of propagules) and recruitment (yes/no) plus all one way interactions, and random effects of habitat and species nested in lifeforms. All analyses were performed using package RStanArm v2.17.4 (Stan Development Team 2018) in the R software environment (R Development Core Team 2015). Effect sizes were calculated as the coefficient multiplied by the range of the predictor variable for fixed effects, and four times the standard deviation for the random effects.

3. Results

3.1 Distribution and habitats of translocations

We documented 1001 translocations involving 376 taxa, spanning all Australian States and Territories except the Northern Territory (Appendix 2). Translocations have been concentrated in regions with high numbers of threatened species, particularly south-western Australia, the south-eastern corner of Australia, and the east coast (Figure 1). New South Wales has the most documented translocations (258), followed by Victoria (243), South Australia (209) and Western Australia (148). Translocations have mostly occurred in highly modified habitats, notably temperate grasslands and grassy woodlands (253), southern Australian heathlands and shrublands on infertile soils (224), rainforest and wet sclerophyll margins (213), wetlands (82), dry sclerophyll forests (64), coastal shrubland and heathland (57), and mallee communities (52) (Figure 2).

3.2 Aims and practitioners

Three-quarters of translocated taxa are listed as Critically Endangered, Endangered, Vulnerable or Near Threatened under State and/or Federal legislation; the other quarter are considered regionally threatened or of conservation significance. Seventy percent of translocations documented are conservation translocations, conducted with the aim of decreasing extinction risk by creating new populations or augmenting existing ones. The remaining 30% are mitigation translocations, which also aimed to create new populations and decrease extinction risk but were undertaken as a requirement for the loss of individuals or populations because of development approval to clear natural vegetation.

Most mitigation translocations (80%) have occurred in coastal and sub-coastal areas of Queensland and New South Wales (Figure 1), as part of road construction and widening, urban infrastructure developments, and mining or gas activities. The majority have involved rainforest taxa, with dry sclerophyll, wetland, coastal heathland and grassy woodland mitigation translocations also well-represented (Figure 2). Almost 15% have occurred in Victoria, mostly in temperate grasslands in the greater Melbourne area. The remaining 5% have occurred in Western Australia, as part of development approvals for mining (banded ironstone and winter-wet ironstone habitats) and urban infrastructure (airport and roads), with one mitigation translocation documented for a road widening project in Tasmania.

Over half of all documented translocations have been led and managed by Government agencies, with not-for-profit conservation groups, universities, Catchment and regional Natural Resource Management groups, Shire Councils and private landholders (often working in conjunction with other groups) also contributing to and/or leading numerous translocations. The 295 mitigation translocations have generally been undertaken by environmental consultants on behalf of resource companies, road and public works authorities and property developers. Two-thirds of these have been salvage translocations, where whole plants are removed and transplanted to another site of similar habitat.

3.3 Timeline and reporting of translocations

The first documented plant translocations in Australia occurred in the early 1950s, when members of the Victorian Field Naturalists Club transplanted threatened grassland species, notably *Diuris fragrantissima*, into a grassland sanctuary near Melbourne. The practice of translocation expanded slowly through the late 1970s and 1980s with numerous translocations in Victoria led by researchers from La Trobe University, while the 1990s saw increased numbers of translocations, particularly in South Australia. Since 2000, the practice has expanded rapidly (Figure 3). Over 85% of all translocations documented have occurred since 2000, and over half since 2010. The first mitigation translocation (of terrestrial orchid *Caladenia hastata* in Victoria) occurred in 1980 (Figure 3). Most mitigation translocations (97%) have occurred since 2000 and 30% in the past five years.

3.4 Lifeform and taxonomic patterns

Shrubs account for almost half of all documented translocations (482 translocations involving 174 taxa), followed by perennial forbs (187 translocations/71 taxa), trees (163/57) and terrestrial orchids (94/44). This is roughly proportional to the number of taxa of each life form listed as Endangered or Critically Endangered at Federal and/or State level, although trees are slightly over-represented in translocations (comprising 16% of translocations but only 9% of the total Endangered or Critically Endangered flora), while terrestrial orchids are under-represented (9% of translocations but 20% of Endangered or Critically Endangered flora). The few translocations of perennial grasses (25 translocations/6 taxa), annual herbs (21/12), sedges (8/4) and annual grasses (3/1) reflects their relatively low representation in threatened species lists.

Just over half the taxa (52%, 194) have been translocated a single time, 90 twice and 53 three or four times. Sixteen taxa have been the subject of 10 or more translocations at different sites, and together these account for nearly 30% of all translocations documented. The most translocated taxa are *Allocasuarina robusta* (n=32), *Gossia gonoclada* (n=27), *Fontainea oraria* (n=24), *Acanthocladium dockeri* (n=23), *Dianella amoena* (n=23), *Pimelea spinescens* subsp. *spinescens* (n=23) and *Olearia pannosa* (n=20).

3.5 Types and practice of translocations

Nearly 80% of translocations have been introductions to new sites within the known range of the subject taxon, with the remainder mostly reinforcements of existing populations. Only 3% have been reintroductions to sites where a taxon was formerly known to occur, while there are two examples of assisted migration outside a species' known range: *Grevillea maxwellii* in south-western Australia and *Wollemia nobilis* in New South Wales. Most translocations were close to a former or current natural population: 27% within 1 km and almost three-quarters within 10 km. Only 14 translocations were introduced >50 km from a natural population.

Over 82% of translocations were planted into remnant or long-term regrowth vegetation, although half of these were roadside or small urban remnants and often in poor ecological condition. The other 18% of sites were non-remnant and often highly disturbed (e.g. gravel pits, farm paddocks, grader scrapes). Mitigation translocations were more likely to be placed in non-remnant sites with only 2% of mitigation translocations planted into large intact protected areas. Smaller translocations tended to be placed in non-remnant habitat, with 62% of translocations using <50 propagules planted into non-remnant sites. Some 30% of translocation sites were in moderately-sized remnants or regrowth (>10 ha), while only 10% were in large protected areas (including National Parks, Nature Reserves, and privately-owned land set aside for conservation). The relatively small proportion of translocations into protected areas reflects the fragmented and modified habitats of most translocated species.

Types of propagules used in translocations are summarised in Figure 4. While more than a quarter of translocations have used multiple propagule types, seedlings propagated *ex-situ* (including orchids once tubers have developed) were the most common, used in 59% of translocations, followed by cuttings (26%). Twenty percent of translocations moved whole plants (including adults and seedlings) and all except two of these were salvage translocations. Nine per cent of translocations used direct seeding (either sown or broadcast by hand), and 5% involved the translocation of topsoil assumed to contain a seedbank of the target taxon. Notably, 61% of translocations involving direct seeding or seedbanks occurred in conjunction with other propagule types.

Data on number of propagules translocated were available for 859 (607 conservation and 252 mitigation translocations) of the 1001 translocations (Figure 5). Around 45% of all translocations used <50 founder propagules. Over three-quarters of rainforest translocations and over half of mallee, montane and wetland translocations involved <50 propagules. Only 16% of translocations used >250 propagules and 3% used >1000 propagules. The majority

(70%) of these relatively large-scale translocations were conservation translocations of forbs, grasses and terrestrial orchids in south-eastern Australia, and of shrubs in south-western Australia. There were 117 translocations (14%) that involved <10 propagules, encompassing 29% of all mitigation translocations. The majority of these were the salvage digging up and replanting of rainforest shrubs and trees as part of road widening and development in eastern Australia. Despite the small number of propagules used in the majority of mitigation translocations, a few have been done on a very large scale, including eleven that transplanted >250 whole plants. Over 2700 cycads were dug up and moved from the path of gas pipeline developments in central Queensland, and several thousand propagated seedlings are to be planted at these translocation sites in the near future.

Planting techniques and treatments were detailed for 884 translocations. These are summarised in Table 2 and cover site preparation, grazing protection, watering, weeding and burning in a range of different habitats across Australia. An experimental approach was applied in 11% of these translocations, involving between two and 15 experimental treatments. These included use of different propagule types (89 translocations), experimental grazing (14 translocations), weeding or slashing (7 translocations), investigating different microhabitats (4 translocations), testing the effect of fertiliser application (4 translocations) investigating different watering regimes (2 translocations), and one involved burning part of the translocation.

Although practitioners indicated that research was conducted to support 552 translocations, only 109 translocation attempts encompassing 71 taxa are documented in peer-reviewed literature (Figure 3). Over half of all published translocations are documented in three papers: two reviewing terrestrial orchid translocations (Reiter et al. 2016; Wright et al. 2009), which together document 33 translocations, and one reviewing planting of forbs into grasslands in Victoria (Morgan 1999), which includes 22 translocations of threatened taxa. There are 14 South Australian and seven Western Australian translocations documented in IUCN Case Studies (*Global Re-introduction Perspectives*, available online at http://www.iucnsscrsg.org/), and four of these are also published in peer-reviewed literature. The most common types of research to support translocations were translocation experiments and trials (n=69), germination and propagation trials (n=35), pollination biology (n=30) and seed or seedbank biology (n=24). Thirty-eight translocations were informed by previous translocations, including experimental trials, while 195 were informed by the results of genetic studies on the subject taxon.

3.6 Performance of translocations

Of the 1001 translocations documented, 214 had no available data on survival. A further 46 had been in the ground for <12 months when the database was compiled, and were excluded from performance analysis, as were 17 translocations that were explicitly and solely experimental, designed to test techniques and enhance understanding of the target species' ecology prior to larger-scale translocations. The remaining 724 translocations comprised 507 conservation and 218 mitigation translocations.

Of the 724 translocations evaluated for performance, 135 (19%) have no plants surviving, while 166 (23%) have <10 plants surviving. Without further plantings, these translocations will not result in the creation of viable populations, or the meaningful augmentation of existing populations, and together account for 42% of all translocation attempts, including half the mitigation translocations. A further 149 (21%) translocations have fewer plants surviving than is considered necessary to establish self-sustaining populations (see Methods), meaning that 62% of translocation attempts analysed (59% of conservation and 70% of mitigation translocations) are extremely unlikely to result in viable populations without further plantings (Figure 6).

The remaining 274 translocations (38%) have at least 50 plants surviving at the time of reporting (at least 25 for some augmentations and rainforest translocations; see Methods), encompassing 208 conservation and 66 mitigation translocations. Two-thirds of these have no recruitment into the population, although in nearly 70% of cases practitioners considered it was too early for plants to have produced viable seed and recruited. This time period varied between life histories, but most translocations in this category had been in the ground 1-3 years for perennial forbs and 8-10 years for shrubs and trees.

Only 93 translocations, or 13% of all attempts documented in Australia for which data are available, have sufficient plants surviving and some recruitment into the population, although for 15 of these <10 recruits have been observed. Vegetative reproduction only was recorded in 10 translocations, and the number of second generation plants was not recorded for 17 translocations where recruitment was reported by practitioners. For translocations where recruitment was documented, 28 are in semi-arid grasslands in south-eastern Australia and 19 are in southern Australian shrublands, heathlands and woodlands. All other habitat types have <10 translocations with ≥50 plants surviving and recruitment observed. Translocations have especially low performance in temperate grasslands and rainforest, with >60% of translocation attempts in both habitats having <10 plants surviving, and 80% with <50 plants extant.

Short-term success of translocations is generally high, with 72% of translocations (excluding annual herbs) having at least 50% survival of propagules after one year and 41% with at least three-quarters of propagules surviving this period. There was no correlation between number of propagules used and % survival ($R^2 = 0.0024$); however only 36% of translocations had at least 50 plants surviving after one year, reflecting the small number of propagules used in many translocations. The majority of these (83%) have become healthy established populations with flowering and fruiting observed, although relatively few have second generation recruitment.

3.7 Factors influencing translocation performance

Translocation performance, in terms of number of plants surviving at last monitoring and second generation recruitment, was highly variable between plant lifeforms, habitats, propagule type and types of translocation. Species were more variable than all of these, highlighting that some species seem more conducive to translocation than others, and this was only partly predictable by lifeform or habitat. In our chosen model for the number of surviving plants, the number of propagules had the largest effect size (9.6), followed by species within lifeforms (6.0), lifeforms (3.4), habitat (2.9), recruitment (2.0) and time in recruiting populations (0.7) (Figure 6).

Number of founder propagules was the major determinant of the number of extant plants (Figure 6). Using at least 500 founder individuals (either established in a single planting or in multiple successive plantings) increased the chances of sufficient plants surviving to create viable populations, if recruitment occurred. The probability of recruitment was also increased by the number of propagules, but species was a stronger determinant of recruitment probability than the fixed effects and the lifeforms (Figure 7). Effect sizes in decreasing order were: species within lifeforms (9.6); lifeforms (8.4), time (5.9) and number of propagules (4.3). Translocation purpose (conservation vs mitigation) effects were small (1.4). Using 500 founders had, on average, just over 50% chance of resulting in recruitment at 20 years in conservation translocations, but about 80% chance in mitigation translocations (Figure 7). The mean number of propagules planted in translocations that achieved medium-term success (excluding those for which it was too soon to judge) was 346, compared to 179 for unsuccessful translocations.

When only translocations that use ≥50 founder individuals were considered (n = 437), 60% have sufficient plants (see Methods) surviving to potentially result in viable self-sustaining populations, and one-third of these have some recruitment into the population. Substantial recruitment was typically observed between five and ten years post-translocation. Before this, it is generally too early to expect recruitment except for annual and short-lived perennial forbs. Annual forbs are the only lifeform with more than one-quarter of translocations with some recruitment occurring, reflecting the shorter time required for recruitment and the generally higher numbers of propagules used. By 20 years, many translocations that would have been considered ‘too soon’ in earlier translocations became ‘no recruitment’ (Figure 8).

Practitioners nominated factors contributing to good performance for 281 translocations and failure for 417. This included 123 translocations where factors were nominated as contributing to both elements of failure and success within the same translocation. Lack of recruitment (often perceived to be due to lack of a disturbance event such as fire) was the most commonly nominated factor for failure of translocations. This was closely followed by climate, with 84 failures attributed to drought/dry conditions and 34 to flooding or waterlogging (some translocations suffered from both in different planting years). There were 86 translocations where poor site and/or microhabitat selection contributed to low performance. High seedling mortality, sometimes due to herbivory or dry conditions but often unexplained, led to the failure of 58 translocations. Lack of maintenance and long-term commitment was a factor in the failure of 42 translocations, although this is probably an underestimate (as many translocations for which no data was provided, or no reasons nominated, may have suffered from this). Grazing/trampling (mostly by macropods), weeds and disease also affected a substantial number of translocations (Figure 9). Inherent biological factors (taxon difficult to germinate or transplant) were perceived to have contributed to the failure of 42 translocations, while lack of biological or ecological knowledge was noted in 43 cases. Propagule type, planting age/size, nursery or planting techniques, and low germination of seed each affected between 10 and 25 translocations.

Conversely, an experimental approach was identified as underpinning success in 72 translocations (including those that had failed to establish a viable population), followed by correct choice of propagule, good habitat or microsite selection, long-term maintenance, monitoring and commitment to the project, climate (good rains following planting), protection from grazing/trampling, inherent species biology (good to work with), sound biological and ecological knowledge, watering, weeding and nursery and/or planting techniques.

4. Discussion

Our extensive evaluation of plant translocations in Australia has identified key factors that are important for achieving the long-term objective of establishing viable populations of threatened species. The major factor contributing to translocation success is the use of a sufficient number of individuals at planting, with the strongest predictor of translocation performance being the number of propagules used. The problem of limited number of propagules is not confined to Australia (Deredec and Courchamp 2007; Godefroid et al. 2011) and is to some extent understandable because of limitations on number of propagules able to be sourced from threatened species, and the fact that growing and translocating them is often a lengthy and labour-intensive process. Thus, implementation of treatments that improve plant survival and translocation shock are important areas for improvement for meeting short and medium-term success criteria. While there is no specific population size that guarantees population persistence (Flather et al. 2011), only 35% of translocations have greater than what is generally considered to be the lowest estimate of minimum viable population size (50 plants; Jamieson and Allendorf 2012). The majority have population sizes substantially lower than estimates of >1,000 individuals frequently advocated (e.g. McGlaughlin et al. 2002; Reed 2005; Whitlock 2000). Translocation programs that use very low numbers of individuals are not likely to lead to establishment of viable populations (Albrecht and Maschinski 2012; Traill et al. 2010).

If a suitably large number of propagules is not available for a particular species, then consideration should be given as to whether translocation is the best conservation action to be undertaken for that species. In such instances the best use of scarce conservation resources may be to build *ex-situ* collections and seed banks, which will sometimes entail the use of seed orcharding, and to consider *in-situ* conservation actions such as habitat restoration. Exceptions to this principle may occur where translocations represent the only effective recovery action to reverse local extinction, such as the few small introductions and augmentations, mostly of shrubs in Western Australia, that represent high proportions of the global population of the target species. These translocations are extremely important to the conservation of these species, and future augmentation can be undertaken to build larger populations over successive plantings. Small-scale experimental translocations can also be valuable to test factors that may contribute to success, prior to large-scale translocations.

Recent studies suggest that better long-term population viability is likely to be achieved when translocations, particularly for slow-growing and long-lived species, are conducted as reinforcements into existing reproductive plant populations, where genetic, plant breeding and site security factors are considered (Encinas-Viso and Schmidt-Lebuhn 2018).

Where at least 50 propagules were planted, medium-term success (defined as the establishment of sufficient plants to be considered a viable number for a population and evidence of flowering and/or fruit set) was achieved in 60% of translocations. However, translocation performance is highly variable and difficult to predict using variables examined here (lifeform, habitat type, propagule type and translocation type). Certain species performed better than others, highlighting that some have inherent traits that may influence whether species make good or poor candidates for translocations. The factors influencing performance, as identified by practitioners, are similar to the findings of other reviews (e.g. Dalrymple et al. 2012; Godefroid et al. 2011; Guerrant 2012; Menges 2008) and many are common across habitats and lifeforms, notably climatic conditions, microsite selection and long-term project commitment. Others are idiosyncratic and unpredictable even within the same habitat, for example the impacts of mites, moths and slugs on grassland seedlings in south-eastern Australia (Neville Scarlett, pers.comm., November 2016). Sometimes results are perverse, for example the shrub *Prostanthera eurybioides*, where unfenced translocated plants were grazed and much less healthy than those protected from grazing, but these grazed plants had much better survival during a period of drought than fenced plants (Jusaitis 2012). Decadal-scale studies examining translocations are uncommon globally, but numerous examples suggest that early plant performance may not reflect longer-term performance (Drayton and Primack 2012; Guerrant 2012; Jusaitis 2012), further underscoring the importance of long-term monitoring.

As noted in other studies, second generation recruitment is a key issue in long term success of plant translocations. However, we find that with the notable exception of semi-arid grassland forbs and species that reproduce vegetatively, second generation recruitment is generally lacking and is the major factor inhibiting success in translocations with adequate numbers of founder individuals and good survival rates. In some habitats, notably southern Australian heathlands and shrublands, this is due to lack of appropriate disturbance, usually fire, to stimulate germination (Shedley et al. 2018). In habitats with high levels of biomass, such as temperate grasslands, lack of inter-tussock spaces inhibits germination (Kirkpatrick and Gilfedder 1998; Morgan 1997), and translocations planted into highly-disturbed sites with lower competition have succeeded while plantings into more natural areas have failed. Recruitment is a sporadic and poorly-understood event even in many natural populations of threatened plants (Clarke 2002; Yates and Broadhurst 2002), as well as in some common species (Morgan 1999).

After four decades, translocation of threatened plants in Australia remains largely at the experimental stage, and our results show that, so far, only a small proportion of translocations have reached the ultimate objective of becoming self-sustaining populations. This suggests that caution should be exercised in relying on the use of translocation to mitigate impacts of development on threatened species. It also highlights the value of experimental approaches whereby information learnt about plant life history, habitat requirements and translocation methods can improve future translocations as well as *in-situ* conservation actions. Well-documented experimental translocations can also inform protocols and contribute to knowledge of this emerging science beyond individual species and sites (Guerrant and Kaye 2007; Menges 2008). The low rates of publishing in translocation science, despite over half of translocations documented having a reported research component, indicates that there are large amounts of unpublished data that are not able to be accessed by translocation practitioners to improve future performance.

Documenting translocation activity, processes and success is important for development of this field of science. The sheer number of translocations documented here dwarfs previous estimates (Sheean et al. 2012), and is also higher than the numbers documented in existing global reviews, including those that covered Australia (Dalrymple et al. 2012; Godefroid et al. 2011). This highlights the fact that reviews tend to rely heavily on published literature, sometimes supplemented by postal or email surveys. If we had relied solely on published literature, only 109 translocations (11% of those documented here) would have been included, demonstrating the importance of extensive consultation with practitioners for reviews such as these. The number of plant translocations that have already occurred in Australia, together with the rapidly increasing trend over time, underscores the importance and timeliness of this review.

While the debate about the ethics and practice of assisted colonisation continues in academic spheres (e.g. Albrecht et al. 2013; Harris et al. 2013; Ricciardi and Simberloff 2009; Webber et al. 2011), the practice has been uncommon in Australia, with documentation of only two translocations of species outside their natural range. The low success rates of introductions, reintroductions and augmentations suggest that further research is required before assisted migration may become a useful technique for biodiversity conservation. The limited long-term success of translocations to date emphasises the importance of a balance between translocation, *ex-situ* conservation in seedbanks and Botanic Gardens living collections, and *in-situ* conservation actions, including comprehensive surveys, targeted management and studies on ecological processes and threats to natural populations. Improved costing of translocation projects is required to assess their utility compared to other conservation actions. When considered in the context of a range of conservation actions required to secure species recovery, translocation can be an effective conservation tool for some of our most imperilled species. Using sufficient numbers of founder propagules, ensuring good early survival, and a commitment to long-term maintenance, monitoring and documentation will all underpin success into an uncertain future.

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More than 150 botanists, ecologists and land managers shared their knowledge of translocations past and ongoing. Special thanks to the Victorian pioneers Neville Scarlett, Bob Parsons and John Morgan, who discussed ideas borne of decades of experience, and to

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Table 1. Definition of types of translocation compiled for this review; definitions are based on recipient site and translocation objectives and are adapted from IUCNSSC 2013 and Vallee et al. 2004.

Translocation type	Definition
Recipient site	
Reinforcement	Adding individuals of a species into an existing population with the aim of enhancing population viability by increasing population size, genetic diversity and/or representation of specific demographic groups or stages. Also referred to as enhancement, re-stocking, enrichment, supplementation or augmentation.
Reintroduction	An attempt to establish a population in a site where it formerly occurred, but where it is now locally extinct. Also known as re-establishment.
Introduction	An attempt to establish a population in a site where it has not previously occurred but is within the known range of the species and provides similar habitat to known occurrences.
Assisted migration	An attempt to establish a taxon, for the purpose of conservation, outside its indigenous range in what is considered to provide appropriate habitat for the taxon based on climate change predictions. Also known as assisted colonisation or managed relocation.
Objectives	
Conservation translocation	Translocations to assist in the management and conservation of threatened plant species.
Mitigation translocation	Translocations to mitigate the impacts of development on a threatened species; also known as development translocations, and are often done to offset the impacts of development. Includes ‘salvage translocations’, where entire plants are moved from a site prior to development.

Table 2. Details of treatments applied to translocations in Australia, including proportion of translocations with site preparation (including weeding, soil treatments, fertiliser application and pre-planting burns), herbivore protection, watering, post-planting weeding and post-planting burning, by habitat type

	N	Site Preparation (%)	Grazing Protection (%)	Watering (%)	Weeding (%)	Burnt (%)
Banded ironstone	*10*	50	70	60	0	0
Coastal headland or dunes	*11*	45	82	54	36	0
Coastal heath or shrubland	*53*	57	40	60	40	15
Dry sclerophyll	*40*	43	54	83	46	3
Grassland	*146*	44	62	58	50	39
Grassy woodland	*70*	52	83	67	51	10
Mallee	*49*	32	88	38	12	0
Montane	*19*	30	68	60	5	15
Rainforest (including wet sclerophyll)	*197*	84	63	87	86	0
Southern shrublands, heathlands, woodlands	*214*	38	82	53	27	5
Wetland	*75*	38	67	23	29	5
Mean number of sites	*n=884*	*49*	*70*	*61*	*46*	*10*

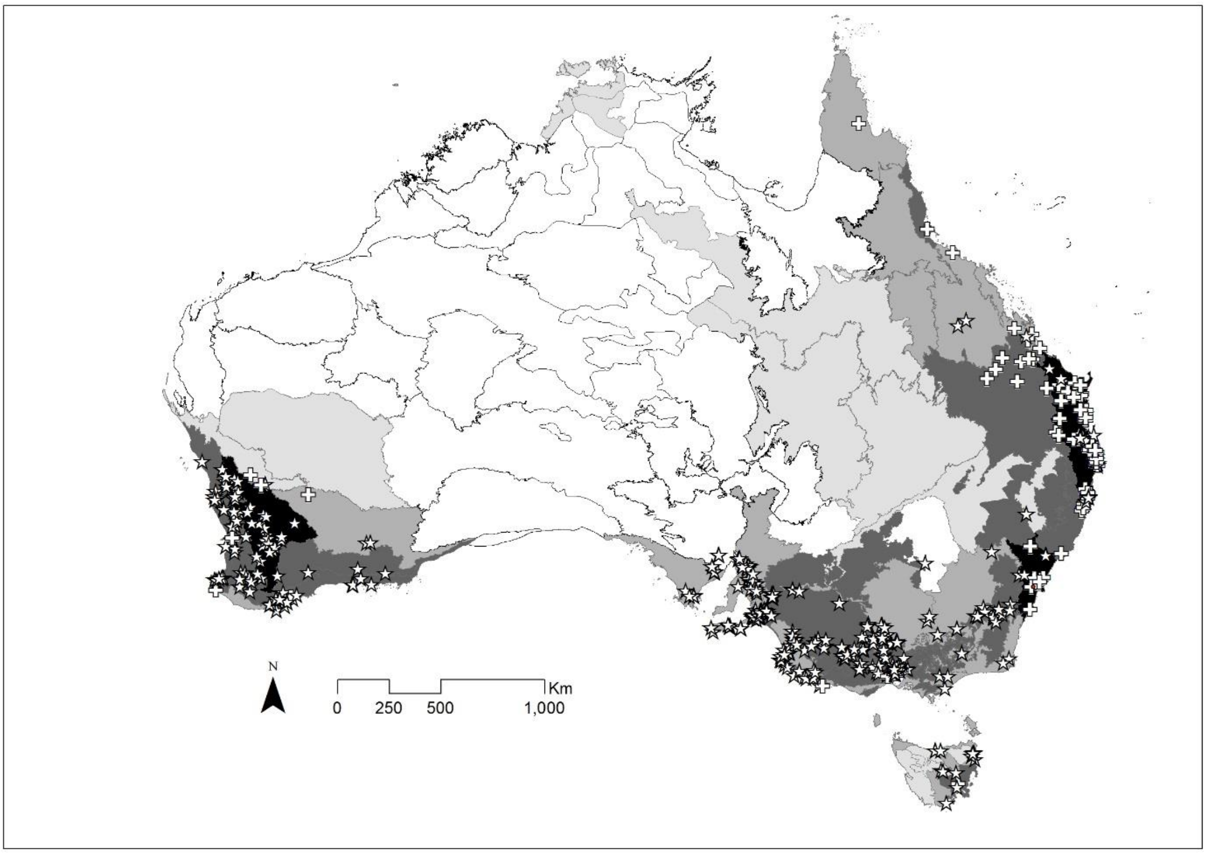

Figure 1. Translocations documented in Australia. Stars represent conservation translocations; crosses represent development mitigation translocations. Australia’s 89 biogeographic regions are shaded according to number of state and federal listed Endangered and Critically Endangered plant taxa: white = 0-2, light-grey = 3-10, medium-grey = 11-30, dark-grey = 31-71, black = 73-119.

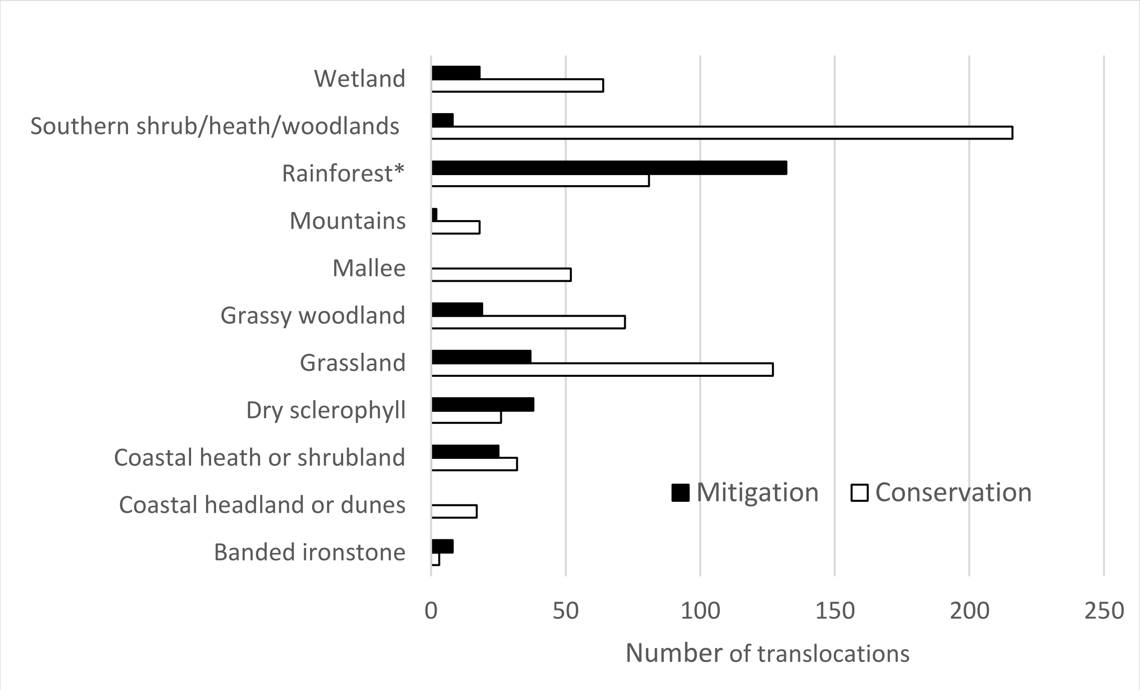

Figure 2. Number of plant translocations by broad habitat groups in Australia. * Rainforest includes wet sclerophyll forests on rainforest margins. Definitions of broad habitat types are provided in Appendix 3.

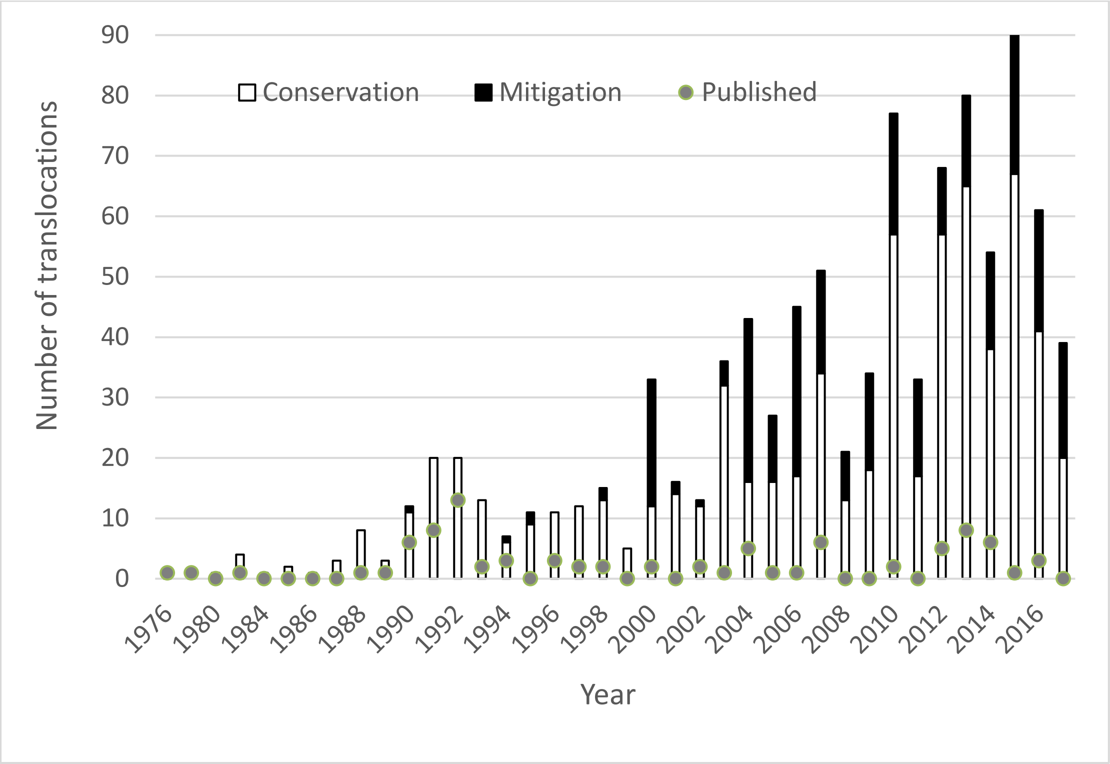

Figure 3. Number of translocations (conservation and mitigation) of threatened Australian plants per year, 1976-2017. The total number published in peer-reviewed literature each year is indicated by circles. The data for 2017 includes 12 mitigation and 7 conservation translocations that were in progress but plants not yet in recipient site at time of data collection, but there are likely to be other translocations that occurred post data collection that were not compiled here.

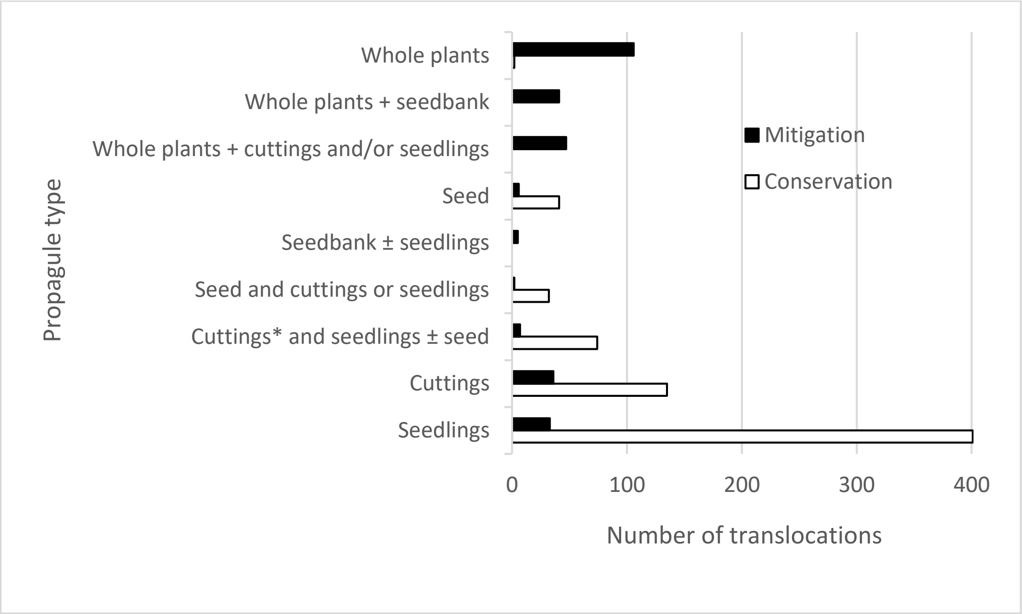

Figure 4. Types of propagules used in translocations in Australia. * Cuttings here includes seven translocations using tissue culture propagules

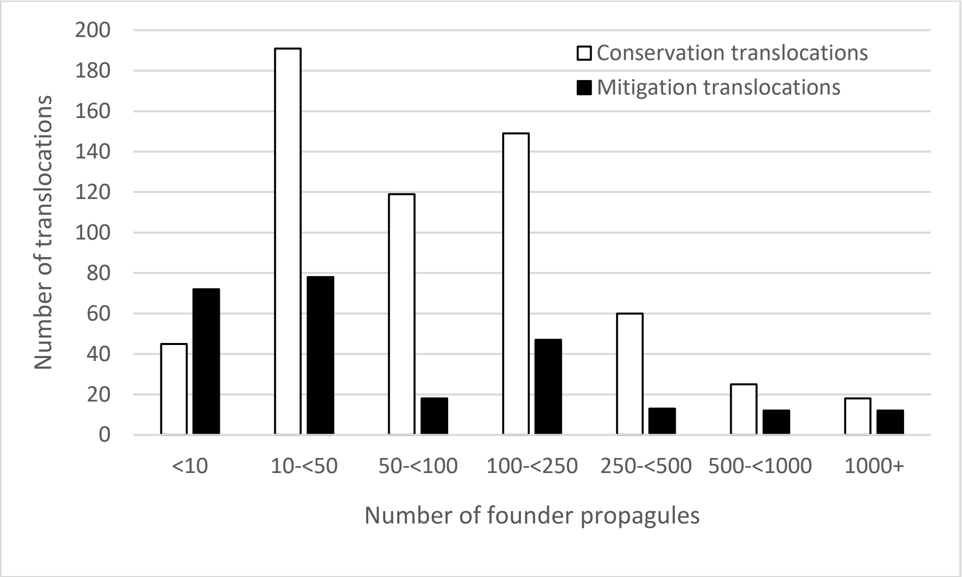

Figure 5. Number of propagules used in Australian plant translocations

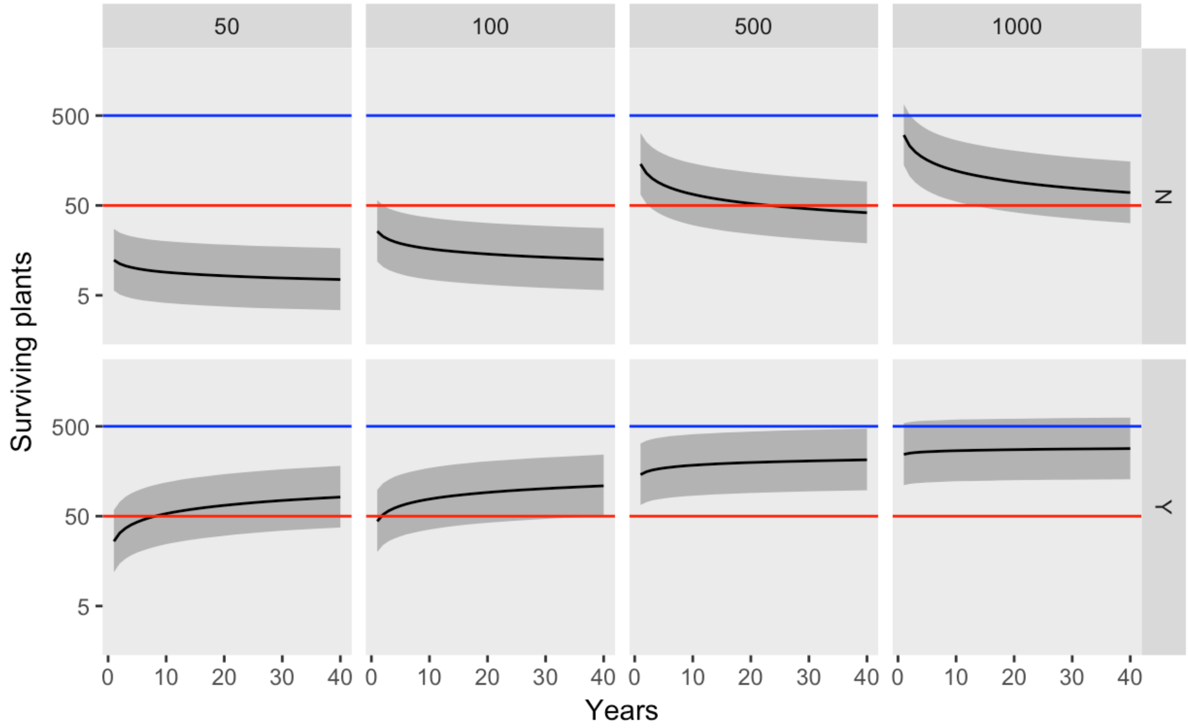

Figure 6. Predictions of the mean number of plants surviving (+ 95% credible interval) given the number planted (at top) and years elapsed since translocation (at last monitoring) and whether the population reached a second generation (recruitment, Y or N) in the rows. The red and blue horizontal lines indicate bad (50 surviving) and good outcomes (500 surviving) respectively. Note, the median number of founder propagules is 67.5, which falls between the left two panels. The median time to last monitoring was 5 years.

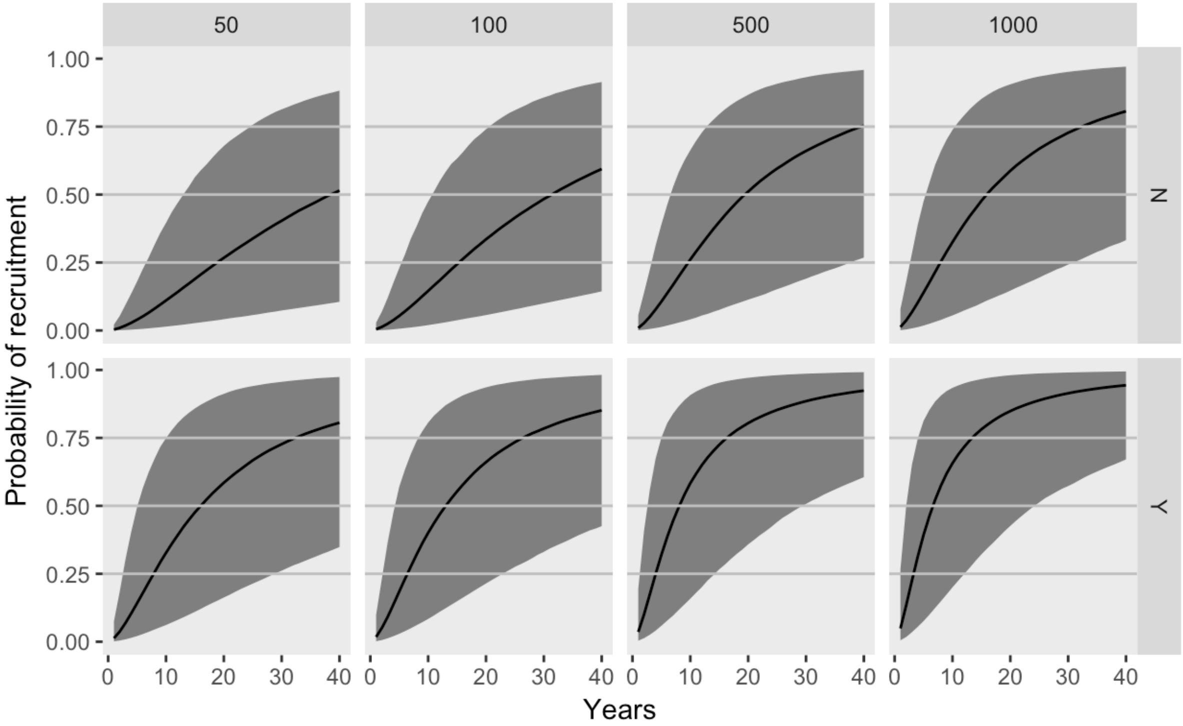

Figure 7. Probability of recruitment into translocated populations, based on number of founder propagules (50, 100, 500, 1000), and whether the translocation was for mitigation (Y or N) in the rows and years since translocation on the x-axis. Black line is the mean, grey envelope is 95% credible interval.

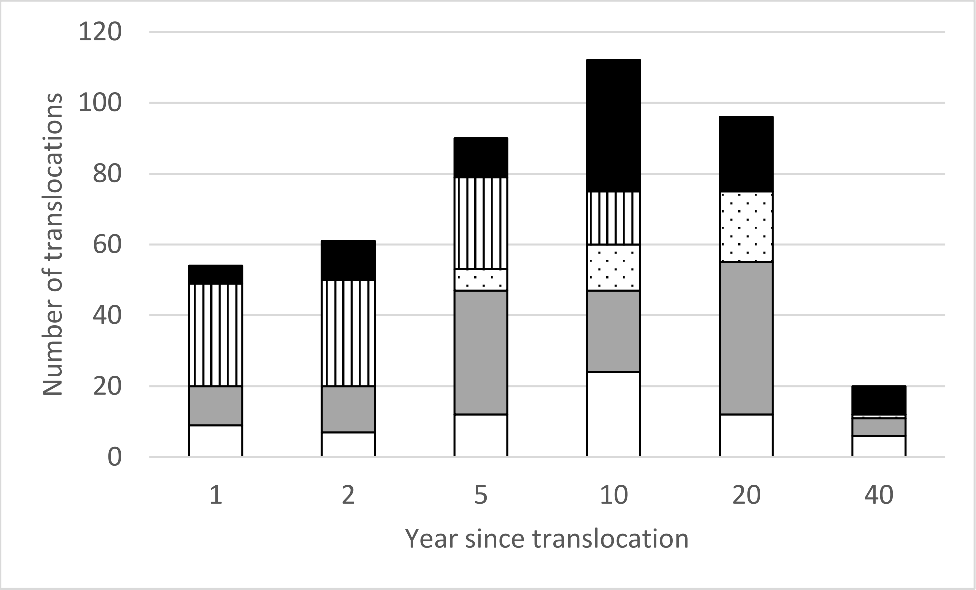

Figure 8. Performance of translocations in relation to years since propagules were translocated to a site, based on year last monitored. White bars represent attempts with no plants surviving; grey bars represent attempts with too few plants surviving to be likely to result in viable populations without further augmentation (typically <50); dotted bars represent extant translocations with no recruitment; striped bars represent extant translocations but too soon for recruitment; black bars represent translocations with some recruitment into the population. Only translocations that had founder populations of at least 50 plants are included (n=433).

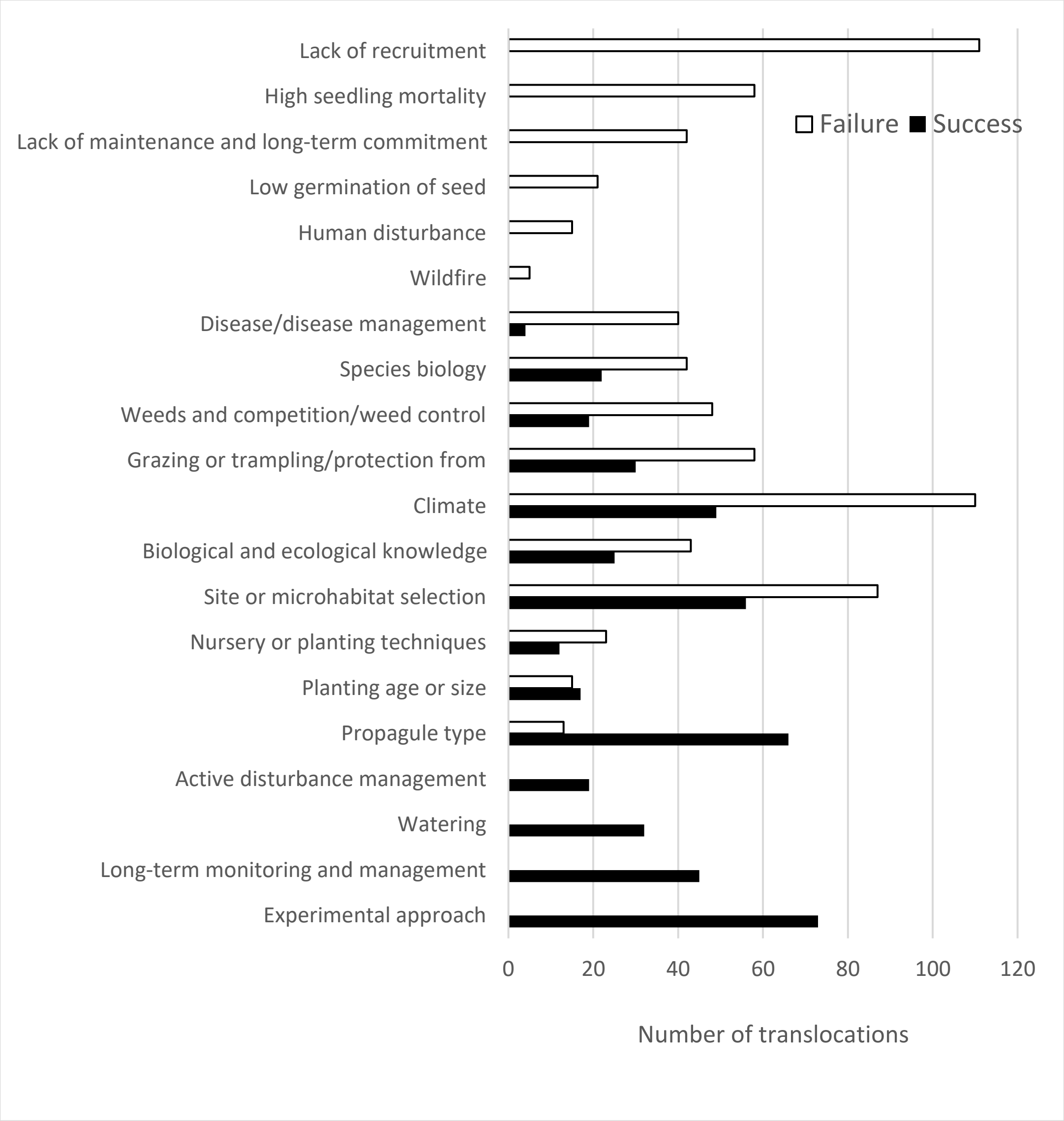

Figure 9. Factors perceived by practitioners to be driving success or failure of translocation attempts in Australia.