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CONTAIN: Optimising the long-term management of invasive alien species using adaptive management

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Abstract

Invasive Alien Species (IAS) threaten biodiversity, ecosystem functions and services, modify landscapes and impose costs to national economies. Management efforts are underway globally to reduce these impacts, but little attention has been paid to optimising the use of the scarce available resources when IAS

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are impossible to eradicate, and therefore population reduction and containment of their advance are the only feasible solutions.
CONTAIN, a three-year multinational project involving partners from Argentina, Brazil, Chile and the UK, started in 2019. It develops and tests, via case study examples, a decision-making toolbox for managing different problematic IAS over large spatial extents. Given that vast areas are invaded, spatial prioritisation of management is necessary, often based on sparse data. In turn, these characteristics imply the need to make the best decisions possible under likely heavy uncertainty.
Our decision-support toolbox will integrate the following components:

(i) the relevant environmental, social, cultural, and economic impacts, including their spatial distribution;
(ii) the spatio-temporal dynamics of the target IAS (focusing on dispersal and population recovery);
(iii) the relationship between the abundance of the IAS and its impacts;
(iv) economic methods to estimate both benefits and costs to inform the spatial prioritisation of cost-effective interventions.

To ensure that our approach is relevant for different contexts in Latin America, we are working with model species having contrasting modes of dispersal, which have large environmental and/or economic impacts, and for which data already exist (invasive pines, privet, wasps, and American mink). We will also model plausible scenarios for data-poor pine and grass species, which impact local people in Argentina, Brazil and Chile. We seek the most effective strategic management actions supported by empirical data on the species' population dynamics and dispersal that underpin reinvasion, and on intervention costs in a spatial context. Our toolbox serves to identify key uncertainties driving the systems, and especially to highlight gaps where new data would most effectively reduce uncertainty on the best course of action. The problems we are tackling are complex, and we are embedding them in a process of co-operative adaptive management, so that both researchers and managers continually improve their effectiveness by confronting different models to data. Our project is also building research capacity in Latin America by sharing knowledge/information between countries and disciplines (i.e., biological, social and economic), by training early-career researchers through research visits, through our continuous collaboration with other researchers and by training and engaging stakeholders via workshops. Finally, all these activities will establish an international network of researchers, managers and decision-makers. We expect that our lessons learned will be of use in other regions of the world where complex and inherently context-specific realities shape how societies deal with IAS.

Keywords
abundance impact relationship, adaptive management, biological invasions, dispersal, *Ligustrum lucidum*, models, *Neovison vison*, *Pinus contorta*, *Pinus radiata*, *Urochloa* spp, *Vespula germanica*

Introduction

Globally, invasive alien species (IAS) threaten biodiversity, ecosystem functions and services, modify landscapes and traditional livelihoods, and impose costs to national economies. The impacts of IAS are increasingly being documented worldwide (e.g. Simberloff et al. 2013, Haider et al. 2018, Taylor et al. 2019). Eradication efforts have been successful in island ecosystems or during the early stages of invasions, but their results are very limited for most of the worst invaders in continental situations (Jones et al 2016). In contrast, population reduction and containment of existing populations are critical to reducing the cumulative impacts of those IAS that cannot be eradicated (Bomford and O'Brien 1995). This is because the prevention and detection have failed for numerous IAS; eradication is often not possible for IAS with cultural or economic importance, or those that are already widespread (Iriarte et al. 2005; Novillo and Ojeda 2008). A variety of frameworks have accordingly been developed to help manage these IAS, but the lack of available management tools remains a constraint on the ability of resource managers to develop long-term management plans (Larson et al. 2011). Responding to the challenge of established IAS requires the urgent development and implementation of evidence-based policy and decision-making systems for evaluating cost-effective strategies that limit their populations and reduce their impacts without eradication.

While there have been many advances in control techniques and management plans for species- and context-specific cases, multiple opportunities remain to advance in more holistic cross-taxa approaches. This is particularly pressing in developing regions, such as Latin America, where resources for management are extremely scarce, knowledge and data are limited, and the threat of IAS is large and increasing (Nuñez and Pauchard 2010). In these circumstances, managers must often shift their focus to a combination of slowing down or containing the invasion complemented with the long-term management of established populations in subsets of invaded areas where this is both practically feasible and cost-effective. For these strategies to be effective over their long operational horizons, there is a need to minimise reinvasion from existing populations, which in turn leads to recurring costs as the pressure from these populations remains constant over time. Local communities and management authorities bear those costs, and management must be optimised to minimise expenditure while retaining crucial ecosystem services and allowing the sustainable economic development of local communities.

The long-term management of IAS is plagued with uncertainties and complexities. While much of the invasion science literature contributes to the understanding of the mechanisms underpinning biological invasions, the exchange of resources and information on how to deal appropriately with established IAS in different social, economic, and ecological systems is substantially less advanced. Adaptive management or 'learning by doing' provides a suitable framework to create collaborative and interdisciplinary approaches focused on resolving the problems associated with IAS (Allen 2000, Johnson et al. 2015). Adaptive management involves specifying dynamic models of the case-study system, parameterized with empirical data and recursively updated by monitoring the response of the system to management interventions. This approach helps contend with uncertainties, incorporates existing knowledge in a quantitative fashion, considers the different dimensions of IAS management, and evaluates the adequacy of the interventions.

Our aim in this paper is to introduce an applied three-year multinational project and a group of more than 20 researchers and practitioners from Argentina, Brazil, Chile and the UK, which seeks to improve the strategic, long-term management of harmful IAS that cannot be eradicated and must be managed. Our work centers around four priority, data rich, and six secondary, relatively data-poor, problematic exemplar species established in Latin America. Our priority species are the glossy privet (*Ligustrum lucidum* – privet hereafter) in Argentina, pines in Chile and Argentina (*Pinus contorta* and *P. radiata* - pines hereafter), and the American mink (*Neovison vison* – mink hereafter) in Chile and Argentina. Secondary, relatively data-poor, species are the yellowjacket wasp in Chile (*Vespula germanica* – yellowjacket hereafter), invasive African grasses (*Urochloa decumbens*, *U. brizantha*), and the pines *P. elliottii* and *P. taeda* in Brazil and Argentina. The name of this project (CONTAIN) refers to the impossibility of IAS eradication and the need for containment of their population growth and impacts in the face of reinvasion.

Latin America, our study system

A colonial history and a heavy reliance on horticulture, industrialised agriculture, forestry, and aquaculture, resulted in the introduction of numerous alien species in Latin America. For example, 18 alien mammal species are present in Latin America (20% of world mammalian species introduced), creating a hotspot of alien mammals in the southern temperate ecoregion of South America (Iriarte et al. 2005; Novillo and Ojeda 2008). Some of these alien species became damaging IAS, and now pose substantial problems. Some ecosystems are being fundamentally transformed by these IAS, as they dominate landscapes and drive major ecological processes. These include the novel communities of muskrat (*Ondatra zibethicus*), Canadian beaver (*Castor canadensis*), and mink now found in parts of Patagonia (Fasola and Valenzuela 2014). Notably, one recent study estimated that should Canadian beaver occupy all its suitable habitat in Tierra Del Fuego islands, it would result in >1 million tonnes of carbon being released to the atmosphere as a result of dam-building (Papier et al. 2019). Many plants with known invasive potential have also been introduced to support horticulture and forestry, as well as for ornamental purposes and pastures. Some of these species became invasive while others are naturalized and only now are beginning to spread across both semi-natural and human-disturbed ecosystems. These IAS include several *Pinus* species (specifically, *P. radiata*, *P. contorta*, *P. elliottii*), which have been described as representing a potential time-bomb, or invasion debt, based on their impacts elsewhere (Taylor et al. 2019). IAS from other taxa are also raising concerns such as the glossy privet, an evergreen tree dispersed by native birds. These species disrupt successional processes in forests in many parts of the world, threatening biodiversity and ecosystem services (Richardson and Rejmánek 2011). Besides impacting vegetation dynamics (Damasceno et al. 2018), African invasive grasses are changing fire regimes due to the increase in fuel load, leading to more intense and severe fires in tropical savannahs such as those covering large tracts of Brazil (Gorgone-Barbosa et al. 2015). Introduced carnivorous *Vespula* wasps notoriously restructure communities and alter resource flows, having a detrimental impact on pollination services and the apicultural industry in many parts of the world, including Latin America (Lester and Beggs 2019).

Project approach

Following the tenets of adaptive management, we will develop and trial on the ground a decision-support toolbox to allocate management interventions in space and time effectively, based on conceptual and practical advances from IAS management practices in e.g. New Zealand, Australia, and the United States (e.g. Baker 2017). The key elements of this decision-support toolbox include:

(i) the relevant environmental, social, cultural and economic impacts of IAS, including their spatial and temporal distribution;
(ii) the spatio-temporal dynamics of the target species, with a focus on understanding and forecasting how dispersal and population recovery after management shape reinvasion and spread;
(iii) the relationship between the abundance of the focal IAS and its relevant impacts in the focal areas;
(iv) economic methods to estimate both the benefits and costs of interventions to spatially develop and rank prioritisation of cost-effective actions to manage interventions associated with IAS in space and time.

We seek to integrate the components described above in a mechanistic and streamlined fashion adapted to the idiosyncrasies and local contexts of our case studies in Latin America. To do so, we need to identify rules for selecting management strategies based on species' life histories, environmental goals, and socio-economic objectives. Indeed, planning durable IAS management requires determining the extent to which abundance of IAS should be reduced. Specifying what residual density is tolerable is a socio-ecological question involving consideration of the resilience of native species to IAS, the economic costs of IAS damage and the management costs required to achieve the residual density. Such costs typically rise exponentially as density decreases (Holmes et al. 2015). Furthermore, the ability of native species and ecosystem functions to be maintained in the presence of IAS is highly variable (Bradley et al. 2019). Different species and economic activities have different density-impact functions on native biota (Norbury et al. 2015). Some highly vulnerable species are devastated by even occasional incursions (e.g. predator-naïve flightless birds, Blackburn et al. 2004), while others can persist under low to moderate IAS density. The propensity of a small number of IAS individuals (e.g. small tree stands) to fuel the further spread of IAS also varies according to species traits, impinging on what residual density is manageable (Yokomizo et al. 2009). Thus, specifying management objectives in a spatial and temporal context is non-trivial, and indeed, it is often the case that such objectives are lacking or only vaguely articulated.

We identify the dispersal dynamics of IAS as critical to the success of management strategies, representing both a challenge and an opportunity. Whether mainly active (in animals) or passive (in plants), dispersal is notoriously subject to complex patterns of density and resource dependence. Propagule pressure after the naturalization stage may depend upon the age and stage structure of the source populations (Travis et al. 2011) and may be constrained by the permeability of the environment (Schurr et al. 2008). Yet, despite rapid advances in the understanding of dispersal biology, a knowledge gap exists regarding how to use this understanding to reduce the negative impacts of IAS on native species. A better understanding of IAS dispersal strategies may expose their vulnerabilities and incorporating such knowledge could improve management efficiency. For instance, depending on the target species, control may be more effective if performed in areas that act as sources (Baker 2017), or where active dispersers may be intercepted before they reach vulnerable areas (Caplat et al. 2014). Other species, such as the mink, may be best controlled if habitat selection by dispersers makes them settle reliably in high quality sites that are turned into ecological traps through targeted culling (Melero et al. 2018).

A final crucial issue to consider is that there is scant guidance for practitioners on how to allocate limited effort spatially, given that IAS spread through active or seed dispersal. This is necessary, as it has been recognized that there is spatial heterogeneity in IAS impacts within invaded landscapes (Latzka et al. 2016), and it is also known that impacts often increase exponentially with IAS density (Norbury et al. 2015; Bradley et al. 2019). Considering this explicitly is a key novelty of CONTAIN. Different management actions can target different stages of IAS spread, and the effects of management depend largely on the spatial configuration of the targeted area and on spatial aspects of spread. Source areas may produce propagules that spread through the landscape, fuelling reinvasion and further spread of the IAS. Their success depends on the behavior of dispersers, and the spatial and temporal variation in establishment success. The latter often co-varies with gradients in habitat quality and conspecific density, including those created by management. Thus, the redistribution of IAS in space in response to management actions may create 'halos' of decreased density spanning larger areas and delivering collateral benefits to local communities using natural resources in the vicinity of management action (Glen et al. 2013). Conversely, compensatory reproduction and dispersal (or increased establishment rate) may negate the impact of interventions according to the prevailing flux of dispersers or variation in the effects of land-use on establishment. Exploiting the potential predictability in the patterns of dispersal-driven reinvasion is particularly valuable in areas where access is limited or difficult and agencies would require substantial resources to tackle IAS. Therefore, this predictability can be harnessed to optimize management operations in challenging and uncertain circumstances.

Preserving and enhancing the livelihoods and biodiversity affected by the most damaging IAS in Latin America is likely to require recurrent management interventions extending in perpetuity. This challenge is ideally suited for adaptive management. Despite its success for achieving good outcomes, implementations of formal adaptive management approaches are scarce, owing to a lack of suitably trained staff able to operate in an interdisciplinary context at the interface between quantitative research and management (Williams et al. 2009). This deficit of human capacity in Latin America is critical, and even though there are increasing efforts to manage IAS, they do not necessarily contribute to an applied body of knowledge, and they sometimes lack a solid scientific foundation, which increases costs and reduces effectiveness. We present a program of research and reciprocal knowledge transfer representing a genuine, multi-country partnership using an adaptive management approach for tackling the challenges of securing biodiversity for sustainable livelihoods and economy and for maintaining and restoring natural capital in the face of IAS.

Methodology

Our project is organized around five work packages (WPs, Fig. 1). The sequence of the WPs fits the adaptive management and forecasting cycle, which presupposes:

(i) development of an initial model of the system using whatever data are available,
(ii) use of the model to identify key parameters and uncertainties,
(iii) design and collection of data to address those uncertainties,
(iv) specifying and exploring management scenarios (with associated costs and benefits).
(v) WP5 crosses over other WPs and is designed to build social capital and capabilities of managers, NGOs, government agencies, and scientists to achieve a sustainable and positive change in the way IAS are managed in Latin America.

WP1. Specify generic models of IAS range reinvasion in response to management using RangeShifter

The goal of this WP is to develop and test a modelling platform to be applied as a decision tool for informing management efforts targeted at controlling IAS. We will incorporate key ecological mechanisms as well as costs of management, in order to test the effectiveness of alternative management options.

We will build upon the strong foundations provided by the RangeShifter software developed at the University of Aberdeen (Bocedi et al. 2014). RangeShifter is a flexible platform for modelling species' ecological and evolutionary dynamics across spatially complex landscapes. It applies an individual-based modelling approach with considerable flexibility for adapting to the biology of a user's focal species. RangeShifter has already been used for a broad range of applications, which consider how demography, landscape structure and dispersal behavior influence spread rates of plants and animals, including the case of mink in Scotland (Fraser et al. 2015). The software already contains two process-based models for simulating the transfer phase of dispersal for actively dispersing animals and two dispersal kernels for simulating plant seed disper-

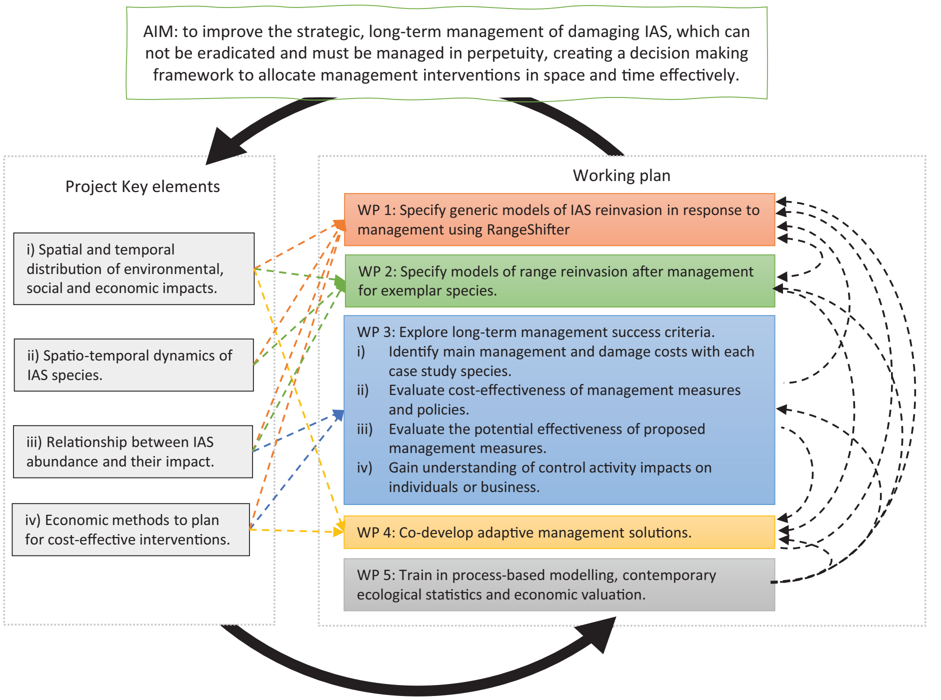

Figure 1. Diagram describing links between different Work packages (WPs) of CONTAIN. IAS refer to Invasive Alien Species.

sal. We will add new modules to model 1) wind-dispersal of seeds, 2) animal-mediated dispersal of seeds, 3) land use/cover changes and 4) IAS control in space and time.

We will model the spatial dynamics of wind-dispersed invasive plants using the WALD model (e.g. Caplat et al. 2012), a simplified mechanistic dispersal model which retains the essential physics while being mathematically tractable (Katul et al. 2005). WALD parameters can be calibrated from the field or estimated from literature values, and the model has been shown to provide a close fit to empirical measurements of wind dispersal (see Caplat et al. 2012).

We will also model seed dispersal by animals using the 2Dt dispersal kernel (Clark et al. 1999), because this approach allows us to fit short and long dispersal distances, which is suitable for zoochorous seed dispersal (Herrera et al. 2011). The parameters for the 2Dt kernel for privet are already available for the Yungas ecoregion in Argentina (Powell and Aráoz 2018), which is one of the study systems for the CONTAIN project, including also environmental variability effects on dispersal (e.g. tree density).

We will develop a population management module in RangeShifter to simulate the removal of varying numbers of the focal IAS across space and time. It will provide a range of management strategies that differentially target specific ages/stages/sexes and spatial locations in an approach where management options can be compared according to their *effectiveness* at reducing the impacts of IAS (Caplat et al. 2014) and limiting the damage they cause. We will further expand this approach by incorporating the costs of management into the model, enabling management options to be ranked by *cost effectiveness*, which is highly relevant for managers.

WP 2. Specify models of range reinvasion after management for exemplar species.

We will apply our generic IAS model (WP1) to the exemplar species mentioned earlier and for which sufficient knowledge exists such that we can develop management models. We will parameterize the models with data from the literature, results from ongoing management interventions and new data when necessary. We will test model predictions against data collected in the field using an integrated approach.

To parameterize the models and kickstart an adaptive management programme, we will consider three exemplar plant species (privet, *P. contorta*, *and P. radiata*, Box 1), and we will derive stage-structured estimates for survival and fecundity as well as rate of seedling/sapling establishment. For privet, appropriate data exist on bird-mediated seed dispersal distances, gut passage time (needed for mechanistic dispersal model, Powell and Aráoz 2018), canopy height, land cover (Montti et al. 2017), and their potential impacts (Fernandez et al. 2017). To develop spatially realistic management scenarios, we will additionally use the outputs from WP1 to include spatially varying costs for realistic management options.

To start the adaptive management of privet, we will conduct experimental management of privet invasion sources in the subtropical montane forests (Yungas) in Northwestern Argentina. We will test different types of interventions (cutting privet individuals by mechanical and chemical methods against no actions) in the invasion front of privet adjoining the native forest. Additionally, we will measure the effects of active restoration of native vegetation, which includes planting saplings of native species. We will evaluate the effectiveness of these treatments by measuring privet individual and population recovery (re-sprout, survival, seed arrival and reestablishment) and natural regeneration (seed arrival, establishment, survival and growth of native trees) to find the most effective method to manage the invasion and restore native plant diversity in invaded forests. During two fruiting seasons, we will determine how the distance to privet seed sources and seedbank suppression affects seed arrival, germination, and sapling growth of privets as well as native trees.

For pines, our mechanistic models of effective dispersal will be based on the characteristics of the source population (propagule pressure, canopy height, distance, wind speed, and direction), and habitat characteristics for seedling recruitment (canopy cover, ground cover, and microclimate). We will build upon our extensive data on *P. contorta* invasion and management, and potentially re-survey permanent plots set up in Chile and Argentina to understand invasion trajectories, legacy effects, and the reinvasion after management (Pauchard et al. 2016). We will also estimate individual seed production for pines across different sites, for both plantations and stands arising from invasion. In addition, we will evaluate the impact of pine invasions on the productivity of native grasslands along a gradient of pine invasion density. Furthermore, we will conduct experimental management of *P. radiata*, the most widely planted pine species in Chile (c. 1.8 million ha). Realistic management (i.e. following current practices in the region) will be applied (i.e. mechanical removal or girdling) to plots stratified by habitat (native forests, grasslands, and shrublands), landscape context (distance to pine plantations, adjacent patches) and invasion stage (early or advanced). We will measure reinvasion from the seed bank and adjacent stands to estimate dispersal parameters. We will assess the economic costs and logistic constraints for all these treatments in order to parameterize the models.

The estimation of model parameters for mink will be based on studies in its native and European invaded ranges, including previous removal interventions (Melero et al. 2015, 2018; Oliver et al. 2016; Fasola and Roesler 2018). Our models will account for settlement probability relative to distance from natal site, habitat metrics and conspecific density (Melero et al. 2018), and the relationships between reproductive parameters and density (Melero et al. 2015). Our models will be tested against data from empirical work on mink focussing on ongoing management in highly contrasting regions of Chile and Argentina. We will estimate the effective dispersal of reinvading mink culled in Los Ríos, Chile, and in Buenos Aires Plateau, Argentina, using georeferenced archived tissue samples. Following genotyping, we will reconstruct likely pedigrees (Oliver et al. 2016), estimating dispersal as the distance between the location of capture and likely natal site. The outcome will be a quantification of the probability of successful dispersal from one area to another given variation in mink density caused by management activity and habitat productivity. Metrics of success will include the viability and population dynamics of affected endemic bird species as well as indicators of farmers' livelihoods. We will evaluate the former through field surveys and detailed monitoring data on aquatic bird abundance and breeding success that we will retrospectively link to model predictions and observations on residual mink density. Previous surveys of farmers, collected as part of a participatory management program in Los Rios region (SAG 2017), will be extended to assess the relationship between region-wide mink density and losses of poultry to mink predation.

WP3. Explore long-term management success criteria

Providing model-informed advice on management effectiveness requires clear criteria for success to have been determined. Such criteria are lacking. Here, we take an interdisciplinary participatory approach to determine the economic impacts of IAS and the costs associated with their removal at different spatial and organisational scales.

The species chosen as case studies (Boxes 1, 2) differ in the nature of the economic costs produced, their spatial distribution, and their impact across different societal

Box 1. Exemplar plant species: **a** *Pinus contorta* invasion from a commercial plantation in the Patagonian steppe in Coyhaique Alto, Aysén Region, Chile. **b** *Turdus rufiventris* (a native bird in Yungas), eating *Ligustrum lucidum* fruits from an invaded forest in north western Argentina. **c** errado (tropical savannah) invaded by *Urochloa brizantha* evidencing the dominance of the invasive species.

Pinus contorta and *P. radiata* are our priority exemplar species of wind-dispersed IAS. Some pines are fast growing conifers highly suitable for forestry, which is why so many pine species have been widely introduced in Southern America, where there are no native pines. Pines are very successful at increasing their range due to a number of adaptations: a simple breeding system that allows selfing and cross-pollination by wind; high seed production from an early age; mechanisms for long-distance seed dispersal by wind; high seedling establishment in disturbed areas; and the ability to grow in a wide range of abiotic conditions (Richardson 1998). The invasion of pines generally originates from forestry plantations, which disperse most of their seeds to a distance of 100 m, but occasional long-distance dispersal events also occur (Caplat et al. 2012). This creates an invasion front that slowly advances from the plantation edge following the prevailing wind direction, but also many invasion islands far from the plantation that contribute to a faster range expansion. In general, very few abiotic or biotic conditions stop or even slow down a pine invasion, the lack of ectomycorrhizal fungi being one of the most important constrains to their spread (Nuñez et al. 2009). Because some pines are adapted to fire, this disturbance accelerates the invasion process and creates suitable habitats for seedling establishment in the absence of competition with native plants (Singh et al. 2018).

Pine invasions in Argentina, Chile and Brazil mainly affect treeless ecosystems, such as grasslands and shrublands (Richardson et al. 1994, Simberloff et al. 2010), with substantial impacts on the hydrological and nutrient cycles and modifications to the habitats of native species (Taylor et al. 2017, 2019). As a result, pastures invaded by pines in Argentina show a reduction in productivity affecting cattle grazing (Nuñez et al. 2017). In Chile, pine invasions increase the frequency and intensity of fires, with great risks for human settlements. The process of biotic homogenization, caused by replacement of native species during pine invasions, negatively affects the touristic scenery of Patagonia, which is one of the major sources of income in the region. In Argentina, the limited management efforts against pine invasions are restricted to protected areas carried out by the National Parks Administration, with no attention to most of the invaded areas in the country (Nuñez et al. 2017). In Chile, management efforts are focused on ecosystems that are critical for biodiversity conservation and largely driven by forestry certification standards (from the Forestry Stewardship Council) which foresters need to fulfil (Nuñez et al. 2017). Successful management experiences from New Zealand and South Africa show that pine invasions can be controlled using mechanical or chemical methods. Such interventions can be costly and do not guarantee the recovery of the native ecosystems, which may need to be actively restored (Nuñez et al. 2017).

African grasses are a threat to open ecosystems of South America, such as the Cerrado and the Llanos (Milton 2004). These species were intentionally planted for cattle pastures (Brossard and Barcelos 2005), but due to their physiological characteristics, such as high biomass and seed production, they can easily spread to protected areas (Pivello et al. 1999). The main species found in protected areas in Brazil are from the genus *Urochloa* (*U. brizantha*, *U. decumbens*, *U. humidicola*). Moreover, *Melinis minutiflora*, *Megathyrsus maximum*, *Hyparrenia rufa* and *Andropogon gayanus* are other major IAS commonly found in protected areas of Cerrado. Their presence in the natural systems leads to a decrease in the abundance and diversity of native species, mostly grasses (Damasceno et al. 2018), as well as an increase in dead biomass, leading to more severe fires (Gorgone-Barbosa et al. 2015). Some studies have had partial success in their control by using fire, herbicides, shading and manual removal (Assis 2017; Damasceno & Fidelis submitted). Therefore, adaptive management can be an important tool at least to reduce the damage that these species impose on invaded areas (Damasceno et al. 2018).

The privet is a bird-dispersed Asian tree species invading ecosystems globally (Aragón and Groom 2003; Aslan 2011). In Argentina, this species was introduced and initially spread by people, and is used primarily for urban shade, amenity, living fences and windbreaks. After its introduction, the first steps of the expansion process involve a rapid and massive colonization of disturbed habitats near the introduction points, which are generally human settlements (Hoyos et al. 2010, Montti et al. 2017). After this first stage, seed sources become more abundant and widespread. Finally, once the species is well established, privet may form mono-specific stands that will dominate the entire tree community of the invaded habitat. The effects of privet on native forest are evident, modifying community species composition (Ayup et al. 2014) and ecosystem functions (such as nutrient turnover), and producing shifts in environmental conditions such as soil moisture and light availability (Zamora Nasca et al. 2014). Additionally, privet can slowly invade the native forests without human intervention (Malizia et al. 2017), because the species is dispersed not only by humans but also by native fruit-eating birds (Aragón and Groom 2003). In 2015, the National Strategy on Invasive Exotic Species from the Argentinian Government included privet as one of their eight most relevant IAS to test and promote management initiatives (Ministerio de Ambiente y Desarrollo Sustentable, 2016).

groups. The plant species have impacts on both direct and indirect economic values, including through sustainability certification schemes of exotic crops. On the other hand, the animal species have potential differential and more significant effects on small-holders' livelihoods and nature-based tourism activities. Our exemplar species also differ in terms of the speed and nature of their dispersal, which affect the risks and benefits associated with immediate action relative to a responsive approach (Epanchin-Niell 2017). This WP comprises four main activities.

Identify the main management and damage costs associated with each case study species, using secondary data and benefit transfer approaches (estimating economic values for ecosystem services by transferring available information from studies elsewhere, see e.g. https://sciencebase.usgs.gov/benefit-transfer), plus focused primary data collection where necessary.

Evaluate the cost-effectiveness of management measures and policies. The range of measures to be considered will be determined through discussions with relevant stakeholders e.g. policy makers, from each national context. The impact of timing on policy effectiveness will also be considered (Sims et al. 2016).

Evaluate the potential effectiveness of proposed management measures accounting for how people's individuals' behavior may affect IAS management, e.g. cropping and management decisions made by farmers.

Gain an understanding of the degree to which individuals and businesses are likely to account for the impact of their management activity on other activities and establish how government interventions may effect changes in behavior related to managing IAS to the levels that lead to improved societal benefits.

WP4. Co-develop adaptive management solutions

Having built capacity in WP3 and show-cased the approach with the work on our focal study species, we will explore strategic options for a wider set of IAS and seek cross-taxonomic generalities. To this effect, we will co-design management strategies with stakeholders and other researchers for emerging and potential future IAS for which data are currently sparse, but for which there are high societal demands for effective management strategies.

Our partners, researchers and practitioners from Latin America, will take a leading role in this work package. For instance, while we selected our exemplar IAS because of their importance in the partner countries, other species such as *Pinus elliottii* and *P. taeda* are transforming grasslands in northern Argentina and southern Brazil (Zenni and Simberloff 2013; Brandes et al. 2019, Durigan et al. 2007; Box 1). We will carry out workshops with foresters to explore plausible management scenarios that might be applicable for data-poor species, as well as future scenarios involving synergies between IAS. Some IAS, like the yellowjackets, affect local communities wherever they occur by damaging beekeeping, horticulture, and tourism (Magunacelaya et al. 1985, Box 2), yet range-wide containment would be prohibitively expensive. Participatory management as performed by poultry farmers suffering from mink predation in Los Ríos

Box 2. Exemplar animal species: **a** Critically endangered Hooded grebes killed by a single American mink in Austral Patagonian highland plateau **b** Mink trapped in a raft deployed along rivers draining the plateau where Hooded grebe breed **c** Yellowjackets (*Vespula germanica*) feeding on a piece of meat.

Mink are our exemplar of a highly mobile and damaging mammalian predatory IAS. In Chile alone, the losses to invasive mink are estimated at US$9.5 million per year, with US$8.1millions corresponding to biodiversity losses and US$1.4 millions allocated to control operations (UNDP 2017). Mink have become extremely abundant in southern Chile, fully invading Los Ríos, Los Lagos, Aysén and Magallanes regions, which comprise part of the Valdivian rainforest ecoregion, a recognized global biodiversity hotspot. The livelihood of autochthonous communities inhabiting coastal areas is severely affected due to loss of intertidal bio-resources (Ruiz et al. 1996). Since 2015, Ministry of Agriculture staff (partners in CONTAIN) have initiated a large participatory pilot mink control project in Los Ríos region focused on reducing the hardship to smallholder poultry farmers caused by mink predation and, as a by-product, preserving the wildlife resources on which ecotourism relies. More than a thousand farmers have removed >5,000 mink in the first 5 years, resulting in marked declines in predation of poultry. Surveys of participants demonstrate very high levels (>99%) of support for the continuation of the project (SAG 2017), but the long-term goals of management and over what scale they can be achieved sustainably have not yet been articulated. In Austral Patagonia, Argentina, mink threaten endemic upland bird species, including the critically endangered hooded grebe *Podiceps gallardoi*, with extinction (Roesler et al 2012; Fasola and Roesler 2018). Here, Aves Argentina (partners in CONTAIN) is leading a determined, high investment, mink trapping effort to avert extinction of the grebe, focused on the Buenos Aires Plateau (Fasola and Roesler 2016), an area of few rivers and a steep productivity gradient. Dispersing mink invade the upland nesting lakes of grebes seasonally, and because grebes are naïve to predation, single dispersers devastate local populations by surplus killing. A broad strategic goal for management is to push mink back to the lowlands, near the newly established Patagonia National Park, where control can be sustained at lower costs and from where dispersers would not threaten endangered endemic species.

The German wasp or German yellowjacket is native to Eurasia and northern Africa and has invaded e.g. New Zealand, Australia, South Africa, Chile, Argentina, United States of America and Canada (D'Adamo and Lozada 2009). Since its introduction in Chile in the 1970s, it has expanded its distribution range and negatively affected several economic activities, including agriculture and tourism (Estay et al. 2008). The aggressive nature of this IAS and its impact on rural economies has moved local communities to organize around the management of this species, even though eradication is no longer possible.

region (Chile) is one solution not yet widely used in Latin America. We will kick-start participatory adaptive management with farmers in rural communities already part of the participatory program Comunidad Humedal in Chile. This will serve to evaluate the effectiveness of fipronil meat-baiting by local residents (Sackmann et al. 2001) to control yellowjackets while at the same time gathering information on the scale of subsequent recolonization by yellowjackets. This will directly feed into the pioneering local IAS management plans recently launched by the municipality of Valdivia in Los Ríos region and now emulated by others.

WP5. Train in process-based modelling, contemporary ecological statistics, and economic valuation

We implement adaptive management approaches to counteract problematic IAS. Our work involves different researchers, policy and decision-makers, and stakeholders associated with diverse species and ecosystems problems. To facilitate this international cooperation, we have created an inclusive training program open to external researchers and practitioners from other Latin America organizations. It runs in parallel with research to foster a common approach based on the modern population-modelling tools underpinning adaptive management. This was augmented by a training workshop on economic valuation which is also central to developing effective adaptive management. Our training seeks to empower researchers to represent IAS within Bayesian integrated population models (IPMs) to estimate demographic and dispersal parameters for the RangeShifter decision tool. Where observational data are scant, as is the case with some problematic IAS, prior information may be used from related systems. The ability of IPMs to propagate sources of uncertainty arising from observation error, parameter uncertainty and process stochasticity will feed into the co-design of monitoring programs that are crucial to continuously improve IAS management effectiveness through adaptive management beyond the lifespan of the funded project.

Outlook

CONTAIN brings together researchers with not only diverse taxonomic focus (mammals, insects, trees, and grasses) but also contrasting research traditions, even when it comes to IAS. This reflects the prevailing research cultures in the participating countries and a dominance of diagnostic-focussed research over management. Latin American researchers include plant scientists working on dispersal, experts in IAS biology and researchers and practitioners already involved in the management of the mink as part of mixed academic or government initiatives. The UK team contributes experience in large-scale participative adaptive management of mink, but also plant ecology, agent-based modelling, statistical methods and rural economy expertise. The researchers appointed by the project deliver crucial expertise, including from New Zealand IAS management and from the forestry industry. None of the participating researchers has individually yet attained CONTAIN's aim to combine ecological, economic and sociological knowledge in a decision-support toolbox of broad applicability to the management of IAS that cannot be eradicated. The first few months of CONTAIN have initiated a common journey towards this aim, facilitated by meetings and exchanges, involving joint learning, a blending of research cultures and a common understanding of the benefits of transnational cross-taxa approach, considering the idiosyncratic aspects of the diverse socio-ecological contexts in which long term management ought to take place. A shared and contagious vision of the importance of evidence and understanding to guide management will no doubt be one output of CONTAIN.

A major challenge CONTAIN faces is that adaptive management requires a long period of time to show results, while both the required research and implementation funding to achieve that goal are short-term, typically three years (Mill et al. 2020). There are grounds for optimism, however. We found that awareness of the societal issues caused by IAS is high and the appetite for trial solutions is higher still. Indeed, following the launch workshop of CONTAIN in Chile, where the achievements of the Service for Agriculture and Livestock (SAG)'s evidence-led participatory management program for mink in the Los Ríos region and the international interest this elicited were highlighted to regional and national authorities, substantial progress has been achieved with funding and trans-regional (in Chile) and trans-national (between Chile and Argentina) management of mink. Thus, the CONTAIN project emerges as a real opportunity to not only improve our understanding of management of IAS, but also to improve the way government and communities deal with this important problem.

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