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A review of three decades of research on the invasive kelp *Undaria pinnatifida* in Australasia: An assessment of its success, impacts and status as one of the world's worst invaders

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ABSTRACT

Marine invasive macroalgae can have severe local-scale impacts on ecological communities. The kelp *Undaria pinnatifida* is one of the most successful marine invasive species worldwide, and is widely regarded as one of the worst. Here, we review research on *Undaria* in Australasia, where the kelp is established throughout much of New Zealand and south-eastern Australia. The presence of *Undaria* for at least three decades in these locations makes Australasia one of the longest-invaded bioregions globally, and a valuable case study for considering *Undaria*'s invasion success and associated impacts. In Australasia, *Undaria* has primarily invaded open spaces, turf communities, and gaps in native canopies within a relatively narrow elevation band on rocky shores. Despite its high biomass, *Undaria* has relatively few direct impacts on native species, and can increase community-wide attributes such as primary productivity and the provision of biogenic habitat. Therefore, Australasian *Undaria* research provides an example of a decoupling between the success and impact of an invasive species. *Undaria* will most likely continue to spread along thousands of kilometres of rocky coastline in temperate Australasia, due to its tolerance to large variations in temperature, ability to exploit disturbances to local communities, and the continued transfer among regions via vessel movements and aquaculture activities. However, the spread of *Undaria* remains difficult to manage as eradication is challenging and seldom successful. Therefore, understanding potential invasion pathways, maintaining native canopy-forming species that limit *Undaria* success, and effectively managing anthropogenic vectors of *Undaria* spread, should be key management priorities.

Contents

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1. Introduction

Biological invasions are a significant threat to native biodiversity and the ecological services it provides. The rate of biological invasions has increased throughout the world and many high profile invaders have been implicated in structural and functional changes in recipient ecosystems (Crooks, 2002; Thomsen et al., 2009; Maggi et al., 2015). In recent years, many species of introduced macroalgae have become conspicuous components of coastal ecosystems, where they can have a wide range of impacts on local communities, ecosystem function and ecosystem services (Thomsen et al., 2016b).

One of the most successful and purportedly problematic macroalgal invaders is the laminarian kelp, *Undaria pinnatifida* (Harvey) Suringar (hereafter *Undaria*). *Undaria* has been included as one of nine marine species in a list of the world's 100 worst invasive species (Lowe et al., 2000), and in Europe was rated as one of the top 10 worst invasive species (Gallardo, 2014) and the third most hazardous of 113 macroalgal introductions (Nyberg and Wallentinus, 2005).

Undaria is native to Russia and Asia, with large populations in China, Japan and North Korea, and is extensively cultivated to provide a highly prized food resource (e.g., Chaoyuan and Jianxin, 1997; Morita et al., 2003; Skriptsova et al., 2004; Na et al., 2016). As a result of its commercial importance, *Undaria* has been widely studied, with aspects of its early life history, genetics and chemical composition receiving particular attention (Lee et al., 2004; Prabhasankar et al., 2009; Wang et al., 2009). However, *Undaria* has also become one of the most widely distributed invasive marine macroalgae worldwide, having established in extensive areas in the NE Atlantic, SW Atlantic, NE Pacific, SE Pacific, SW Pacific and the Mediterranean and North Seas.

In the light of the continuing spread of *Undaria* into native communities, and its increasing encroachment onto port and aquaculture facilities (Dellatorre et al., 2014; Heiser et al., 2014; James et al., 2014; Minchin and Nunn, 2014; Pereyra et al., 2015; Atalah et al., 2016b), it is useful to assess the scientific findings with respect to the kelp's invasiveness, impacts and management. Here, we focus on Australasia (Australia and New Zealand), where *Undaria* was observed for the first time three decades ago, making this part of the world one of *Undaria*'s longest-invaded bioregions globally (Fig. 1). Australasia is also the most studied bioregion with respect to *Undaria*'s dispersal (Forrest et al., 2000; Sliwa et al., 2006; Russell et al., 2008; James and Shears, 2016a), population biology (Schaffelke et al., 2005; Primo et al., 2010; Schiel and Thompson, 2012; James and Shears, 2016b), ecological interactions (Forrest and Taylor, 2002; Valentine and Johnson, 2004; 2005; Thompson and Schiel, 2012), and management (Hewitt et al., 2005; Forrest and Hopkins, 2013), reflecting concerns regarding the impacts of this species on the area's unique and diverse native marine biota (Battershill et al., 1998). Additionally, the high connectivity of coastal areas by anthropogenic activities (e.g., vessel movements) within Australia and New Zealand means there is potential for *Undaria* to invade vast areas of coast in the future (Hayden et al., 2009). Therefore, research in Australasia provides unique insight into *Undaria*'s role as an invasive species, and an opportunity to critically evaluate its reputation as being among the world's worst invaders.

More specifically, we collate, summarise and review peer-reviewed research on *Undaria* in New Zealand and Australia, drawing on literature from other invaded regions where doing so leads to greater insight. We highlight factors that drive *Undaria*'s invasion success, the types of impacts it causes, its future invasion potential, and associated research gaps. We also consider management successes and failures of *Undaria*. In total, our review includes 50 published journal articles and 6 unpublished postgraduate theses specific to *Undaria* in Australasia, focusing on content that was electronically available following searches on Google Scholar, SCOPUS and Web of Science (S 1). The review is not exhaustive in terms of the grey literature on *Undaria*, and does not necessarily include published research in which *Undaria* was not the sole focus.

2. Establishment and spread of *Undaria* in Australasia

2.1. Discovery and vectors of initial introduction

Undaria was first discovered in Australasia in Wellington, New Zealand, in 1987, and in Tasmania, Australia, in 1988 (Figs. 1 and 2). However, the arrival time in each location was likely several years earlier, given the extensive populations documented in the first reports of its occurrence (Hay and Luckens, 1987; Sanderson, 1990). For example, the Tasmanian population already extended over 10 km of coastline (Sanderson, 1990), while, in Wellington Harbour, thousands of sporophytes were recorded over 7–8 km (Hay and Luckens, 1987). International shipping and fishing vessels are considered to be the likely vectors of initial introduction; for example, mature sporophytes were found on recently-arrived ocean-going vessels in the early stages of the invasion in New Zealand (Hay, 1990). However, there have been multiple subsequent introductions to Australasia (Stuart et al., 1999; Wotton et al., 2004; Uwai et al., 2006). In the southern South Island of New Zealand (e.g., Lyttelton, Timaru and Oamaru Harbours), genetic variation among populations suggests that, before 2005, there had been at least eight different introductions from source populations in continental Asia and northern Japan (Uwai et al., 2006). Interestingly, genetic analyses appear to confirm initial hypotheses on the origins of *Undaria* into different regions of New Zealand that were based on morphological comparisons (Hay and Villouta, 1993; Campbell and Burridge, 1998). In Australia, invaded sites showed little haplotype variation, indicating a lower number of successful introductions (Voisin et al., 2005; Uwai et al., 2006).

2.2. Ongoing human-mediated spread

Anthropogenic vectors, including commercial shipping, fishing

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