Available online at www.sciencedirect.com
ScienceDirect
Aquaculture 259 (2006) 202–210
Aquaculture
www.elsevier.com/locate/aqua-online

Invasion of *Codium fragile* ssp. *tomentosoides* in northern Chile: A new threat for *Gracilaria* farming

P.E. Neill [a,*], O. Alcalde [b], S. Faugeron [a,c], S.A. Navarrete [a,c,d], J.A. Correa [a,c]

[a] *Center for Advanced Studies in Ecology and Biodiversity, Departamento de Ecología, Facultad de Ciencias Biológicas, Pontificia Universidad Católica de Chile, Santiago, CP: 6513677, Chile*
[b] *Cultivos Marinos Caldera Ltda., Chile*
[c] *Laboratoire International Associe LIA-DIAMS CMRS-UPMC-PUCCh, Chile*
[d] *Estación Costera de Investigaciones Marinas, Pontificia Universidad Catolica de Chile, Casilla 114-D, Santiago, Chile*

Received 29 March 2006; accepted 10 May 2006

Abstract

Invasive species are key components of the burgeoning global change in ecological communities. The green alga *Codium fragile* ssp. *tomentosoides* (Chlorophyta) is a recognized invader in marine ecosystems around the world, with described ecological effects ranging from minor changes in native species abundance to major changes in community structure, as well as negative economic effects on aquaculture species. The objective of this work is to provide an assessment of the extension of the *C. fragile* invasion along the coast of Chile, and characterize the pattern of temporal fluctuations in abundance, and potential economic effects of this algal invader in a *Gracilaria chilensis* farm in northern Chile. In 2005 we recorded *C. fragile* at 34 of 123 sites sampled along the Chilean coast, with over half of the invaded sites occurring between 26° and 30°S latitude. At 12 sites *C. fragile* was present only on artificial substrata, suggesting that artificial structures may act as corridors for the dispersal of this alga into subtidal or intertidal habitats where it is otherwise not able to survive. At one site (Calderilla Bay) *C. fragile* has reached high levels of abundance within *G. chilensis* farms. At this site we observed marked seasonality in the monthly *C. fragile* abundance index, with greater *C. fragile* abundances in summer and fall months, associated with higher sea surface temperatures (SST). In addition, we report a significant long-term trend of increasing *C. fragile* abundances over the 5 years of observations in the plantation. If the distribution of *C. fragile* in Chile is largely determined by SST, we expect faster spread of northern populations towards the north. Weedy species had a negative effect on the farmed species, *G. chilensis*. During the 4 months in which algae wet weights were measured, the estimated *C. fragile* biomass averaged 22.9 kg m^{-2}, compared with an estimated average of 18.5 kg m^{-2} of the harvested red alga, *G. chilensis*. In addition, we recorded a negative effect of *C. fragile* abundances on the Catch Per Unit Effort (CPUE) of *G. chilensis* with a significant upper limit to CPUE at the 94th quantile. Since weedy species generate a great loss of time and money in *G. chilensis* farms, it is likely that without intervention, the costs associated with the *C. fragile* invasion threaten the persistence of *G. chilensis* farms in northern Chile. Stakeholders should implement preventative measures to stop *C. fragile* spread from focal points.
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Keywords: Algal farming; Invasion ecology; Marine invasion; Non-indigenous species; Seaweed; South America

1. Introduction

Invasive species are key components of the burgeoning global change in the environment (e.g., Vitousek, 1994;

* Corresponding author. Tel.: +56 2 354 2610; fax: +56 2 354 2621.
E-mail address: pneill@bio.puc.cl (P.E. Neill).

0044-8486/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.aquaculture.2006.05.009

Simberloff, 2000; D'Antonio et al., 2001; Pimentel et al., 2005), widely recognized for their effects on the biodiversity of native communities (Mack et al., 2000). Much concern has been centered on changes in native species biodiversity when communities receive an aggressive invader (e.g. Elton, 1958; Bertness, 1984; Boudouresque et al., 1995; Kennedy et al., 2002; Sax and Gaines, 2003; Stachowicz and Tilman, 2005) and the changes they cause in the structure and functioning of ecological systems (e.g. *Dreissena polymorpha*, Strayer et al., 1999; *Pyura praeputialis*, Cerda and Castilla, 2001; *Castor canadensis*, Iriarte et al., 2005). These invaders frequently attain vast social importance when they impact economically important species, such as agricultural crops or fisheries (see examples in Naylor, 2000; Mack et al., 2000; Pimentel et al., 2005).

A recognized invasive species in marine ecosystems around the world is the siphonous green alga *Codium fragile* (Suringar) Hariot ssp. *tomentosoides* (Van Goor) Silva (Chapman, 1999; Trowbridge, 1998, 1999; Mathieson et al., 2003; Provan et al., 2005). Currently this subspecies has a wide distribution on temperate and tropical coasts, although its invasive capacity (e.g. ability to reach high densities at the invaded site) varies spatially (Chapman, 1999; Trowbridge, 1998, 1999; Mathieson et al., 2003). Originally from Japan, this alga has invaded numerous coastal sites around the world, including the Pacific and Atlantic coasts of North America, the Atlantic coast of Europe, the Mediterranean coast, areas of Australia and New Zealand, as well as the coast of Chile (Provan et al., 2005). Although this alga mainly inhabits protected bays and estuaries, it is also found in semi-exposed coastal areas, where it tends to be smaller, have fewer dichotomies, and occur in lower densities (Chapman, 1999; Harris and Jones, 2005). This alga is found attached to hard substrata in both the intertidal and subtidal zones, down to approximately 15 m depth (Chapman, 1999). On sandy or muddy bottoms *C. fragile* utilizes many types of secondary hard substrata, including mollusk and crustacean shells, rocks, coralline crustose algae, as well as artificial materials such as ropes, plastic structures and stone breakwaters (Carlton and Scanlon, 1985; Trowbridge, 1999; Bulleri and Airoldi, 2005, P.E. Neill, personal observation).

C. fragile presents a number of traits which seem to favor its ability to invade new habitats, including a high tolerance to fluctuations of abiotic factors such as temperature, salinity, light and nutrients, as well as the possibility of reproducing both sexually via gamete fusion and asexually through parthenogenesis and fragmentation (Chapman, 1999; Trowbridge, 1998, 1999; Mathieson et al., 2003; Harris and Jones, 2005). Within invaded regions, high abundances of *C. fragile* have been reported to be associated with high temperatures, increased illumination, and anthropogenic activities, such as artificial marine structures and aquaculture equipment (Trowbridge, 1998, 1999; Harris and Tyrrell, 2001; Naylor et al., 2001; Mathieson et al., 2003; Bulleri and Airoldi, 2005; Harris and Jones, 2005).

Various studies have reported ecological and economic effects of *C. fragile* ssp. *tomentosoides* within its introduced range (e.g. Trowbridge, 1998; Colautti et al., 2006 and references therein). In a recent study comparing species traits of 113 introduced macroalgal species in Europe, *C. fragile* ssp. *tomentosoides* ranked as the number one most risky macroalgae in terms of dispersal capability, probability of establishment and ecological impact on the receiving community (Nyberg and Wallentinus, 2005). Reported ecological effects of this invasive alga range from minor changes in the abundances of native species (Trowbridge, 1999; Mathieson et al., 2003; Harris and Jones, 2005) to changes in the structure of entire communities (Harris and Tyrrell, 2001). This alga has also been reported to be damaging to the aquaculture industry by fouling nets, as well as by attaching to, uplifting and transporting shellfish (Fralick and Mathieson, 1973; Carlton and Scanlon, 1985; Mathieson et al., 2003). In Canada estimated economic loss to the aquaculture industry as a result of the *C. fragile* invasion was estimated at over $1.2 million USD per year (Colautti et al., 2006).

In northern Chile, the green alga *C. fragile* ssp. *tomentosoides* was registered for the first time in 1998 (Neill et al., 2003; Castilla et al., 2005; Castilla and Neill, in press), and it soon became a pest affecting the farming operations of the economically important red alga *Gracilaria chilensis* (Neill et al., 2003; González and Santelices, 2004; Provan et al., 2005; Leonardi et al., 2006). This red alga is harvested in both northern and southern Chile as raw material to produce agar, and represents an important economic resource to the country (Buschmann et al., 2001; SERNAPESCA, 2004). Since the introduction of *C. fragile*, red algae farmers must invest additional time and money in removing this pest, which becomes entangled in the thalli of *G. chilensis* and pulls the red alga off the bottom before it can be harvested by divers.

In spite of the known ecological and economic effects of *C. fragile* in other parts of the world, in Chile there is little quantitative information regarding its range of distribution, abundances, and its potential effects on local assemblages of benthic organisms and economic resources (Castilla et al., 2005; Castilla and Neill, in press). The objective of this work is to provide an assessment of the extension of the *C. fragile* invasion along the coast of Chile, and characterize the pattern of temporal fluctuations

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