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Providing current information on monitoring and controlling the spread of harmful nonindigenous species.

The Spartina Invasion of San Francisco Bay

By Debra R. Ayres and Donald R. Strong

Invasive species often exhibit resistant characteristics. Even the extreme ecological conditions of tidal salt marshes, high salinity, and anoxic soils, do not exclude invasive species. The inter-tidal, salt marsh habitats of San Francisco Bay were invaded by a non-indigenous smooth cordgrass, *Spartina alterniflora,* which was intentionally introduced from the Atlantic seaboard for erosion control in the early 1970s (Callaway and Josselyn 1992). This invader hybridized with native California cordgrass, *Spartina foliosa,* and produced hybrid swarms that can potentially spread down the inter-tidal gradient and cover the naturally open mud (Ayres et al, 1999).

The salt marshes and inter-tidal areas of San Francisco Bay are invaluable. Only a small fraction of the original extent of this habitat remains. Most has been diked, drained, and filled over the last century (Macdonald 1977). The remaining salt marshes of San Francisco Bay are home to valuable native species, including two federally listed endangered animal species, the salt marsh harvest

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Figure 1. *Spartina alterniflora* in San Francisco Bay

Snakeheads Represent an Increasing Threat to U.S. Waters

By Robert G. Howells, James D. Williams, and Walter R. Courtenay, Jr.

Snakeheads (Family Channidae) have long been recognized as a potentially problematic species if introduced and established in U.S. waters. In fact, Texas prohibited some or all species in this family as far back as the mid 1960s (Howells 1999). Since then, at least a dozen other states have added snakeheads to their prohibited species list. Original concerns focused on periodic importation by the aquarium trade and fear of release; however, recent shipments of living fish to seafood markets have highlighted an entirely new area of concern.

Also called serpent-headed fish, snakeheads are elongated, torpedo-shaped fish from tropical Africa and southern Asia (Nelson 1994). The name snakehead comes from the presence of large scales on the head, reminiscent of the large epidermal scales or cephalic plates on the heads of snakes, and the forward placement of the eyes on the head. Snakeheads have long dorsal and anal fins as well as rounded caudal fins and resemble the bowfin, *Amia calva*. Snakeheads vary in size, with one or two species reaching only about six inches in length as adults, but others may exceed four feet and weigh more than 44 pounds

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mouse, *Reithrodontomys raviventri*, the California clapper rail, *Rallus longirostris obsoletus*, and the federally listed endangered plant, soft bird's beak, *Cordylanthus mollis mollis*. These salt marshes support fisheries and recreation, and serve essential ecosystem functions such as flood control. The open mud of San Francisco Bay is the primary habitat of one of four Audubon Society "Hemispheric Reserves" for shorebirds. California cordgrass, *Spartina foliosa*, forms a natural lower boundary to salt marsh vegetation and provides essential habitat for a variety of native vertebrates and invertebrates, making the plant an essential component of natural California salt marshes. *Spartina foliosa* is a short cordgrass that grows sparsely, rarely attaining height greater than 75 cm. It is restricted to high elevations on the inter-tidal plane, and does not grow lower than the average high water level. This characteristic leaves mud areas open in Pacific estuaries. Other native cordgrasses do not exist on the Pacific coast. The range of *Spartina foliosa* extends from Bodega Bay, 100 km north of San Francisco, into Baja California, Mexico. Thus, biotic threats to the salt marsh habitats of San Francisco Bay could readily spread southward, even into Baja California.

Without control, the invader and hybrids will spread from south San Francisco Bay northward to threaten the North Bay and the Sacramento River estuary.

The original control efforts with invasive smooth cordgrass, *S. alterniflora*, in San Francisco Bay centered upon ecological competition with native California cordgrass, *S. foliosa* (Callaway and Josselyn, 1992). What was thought to be invasive smooth cordgrass, initiated growth earlier in the spring, had grown 10-fold the above-ground and 2-fold the below-ground annual biomass, grew as much as 60 cm taller, and spread laterally 1.5 times faster than the native. In a field competition experiment, 75% of cleared patches were re-colonized by what was inferred by these authors to be pure smooth cordgrass. The invader produced more flowers and set more seed, and its seeds had higher germination than the native. Finally, what was believed to be pure smooth cordgrass grew as high or higher in the marsh, and from 9-20 cm lower, than the native, suggesting a lack of refuge in San Francisco Bay for California cordgrass from competition with this aggressive exotic species. After further studies, the majority, if not all, of the plants considered to be pure smooth cordgrass in this pioneering work, turned out to be hybrids between the invading *S. alterniflora* and the native *S. foliosa*.

Recent studies suggest that hybrids between native California cordgrass and the invasive smooth cordgrass are probably the most menacing of the more than 200 known non-indigenous species in this "world's most invaded estuary" (Cohen and Carlton, 1998). If left uncontrolled, this invasion has the potential to convert the salt marshes and open mud of San Francisco Bay into vast stands of hybrid and invader cordgrass, which will accumulate sediment, elevating the marsh. The probable ecological outcome can be seen from the results of the spread of hybrid *S. anglica* in England 100 years ago. After hybridization and chromosome doubling led to the formation of *S. anglica*, this hybrid was sufficiently vigorous to displace the native European cordgrass in the English marshes and even the introduced *S. alterniflora* parent. As *S. anglica* spread, the numbers of wading birds were reduced in invaded marshes; these birds feed upon open mud but not within *S. angelica* (Goss-Custard et al. 1995). Rapid sediment accretion elevated English marshes by as much as four cm/year and periodic dieback silted navigation channels (Ranwell 1964). Today, dense stands of *S. anglica* remain in some English estuaries changing navigational routes and estuary flow patterns (Raybould 1999).

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Using nuclear DNA markers, genes of the invader *S. alterniflora* have been found to spread rapidly through San Francisco Bay cordgrasses (Ayres et al. 1999). Already, California cordgrass is very rare in three marshes where alien smooth cordgrass and/or hybrids were deliberately planted. In these three sites, inter-specific hybrids and smooth cordgrass now grow in high densities. Recently opened salt ponds in the area, such as Cogswell marsh in Hayward, CA, are vulnerable to colonization by hybrid seed.

Through a combination of nuclear DNA analysis, field observations on flowering, and repeated attempts to cross the two species, researchers have discovered that the formation of an inter-specific F1 hybrid is an extremely rare event. However, crossing between hybrids and *S. foliosa* readily occurs. Research leaders have concluded that the sweep of invader genes through native cordgrass populations is driven by hybrids. Thus, spread of hybrids to other marshes in California could be more immediately threatening to the native species than introductions of *S. alterniflora* itself

With chloroplast DNA (cpDNA) researchers have studied patterns of maternity in hybrid cordgrass (Anttila et al, 2000). CpDNA is maternally inherited, providing information on the seed-parents of hybrids. *S. foliosa* had but a single chloroplast haplotype, and this was unique to California cordgrass. *S. alterniflora* from the native range along the Atlantic coast of North America had three chloroplast haplotypes. The most significant findings of the study were that hybridization between *S. alterniflora* and *S. foliosa* in San Francisco Bay has proceeded in both directions. The majority, 26 of the 36, of hybrids contained the *S. foliosa* cpDNA haplotype , indicating that in the majority of instances, the seed parent of the hybrids was native California cordgrass. Nine of the hybrids analyzed contained cpDNA haplotypes of the invading *S. alterniflora*, which indicates that the alien is not immune from hybridization itself.

Researchers have found that some genotypes of hybrid cordgrass grow more rapidly and ultimately taller than either parental species. This vigorous morphology has particular significance for growth in the salt marsh habitat. A reasonable hypothesis is that taller plants can survive and flourish at greater depths on the inter-tidal plane, consistent with the difference in height and growth between the two parental species. Tidal submergence time controls the distribution of cordgrasses on the inter-tidal plane; *S. alterniflora* in Long Island extends over 1m farther down the tidal plane than *S. foliosa* in San Francisco Bay (Hinde, 1954). Thus, hybridization could create genotypes that encroach upon the open mud of Pacific estuaries even farther or more rapidly than the alien species alone.

Invasion by *S. alterniflora* and hybrids is a dynamic process that raises the inter-tidal plane by means of the accretion of sediment within the densely packed canes of the invader and hybrids. This means that the total area of the encroachment will be even greater than if there was no feedback between elevation of the site and occupation by alien and hybrid cordgrass. Robust hybrids are predicted to overgrow native cordgrass, as discovered in the work of Callaway and Josselyn (1992). A further prediction is that the hybrids will even out-compete *S. alterniflora* in areas of co-occurrence. From ecological competition alone, the eventual result could be the elimination by hybrids of the invader itself as well as the elimination of native cordgrass. Growing far down onto the mudflat, hybrid cordgrass, strengthened by genetic contributions from both parents, may be the final successor of Bay marshes, replacing primarily open inter-tidal mud flat habitats with dense populations of hybrid cordgrass. Ecosystem impacts to the San Francisco Bay estuary and beyond will be devastating.

Cordgrasses disperse primarily by seeds that float on the tide (Daehler and Strong 1994). Seeds are set in late summer and fall and germinate in late winter and spring on the mud of the inter-tidal plane. Seedlings are usually scarce, and by the second year of growth, the characteristic circular clone of stems can be seen spreading outward from the initial position of the single seedling tiller.

Without control, the invader and hybrids will spread from south San Francisco Bay northward to threaten the North Bay and the Sacramento River estuary. Hybrid seeds will float from the Golden Gate and ultimately find their way into estuaries at Bolinas, Drakes Estero, Tomales Bay, and Bodega Bay, CA (Daehler and Strong 1996). Similar dispersal has already occurred from the invasion of smooth cordgrass in Willapa Bay, WA to the north (K. Sayce, personal communication). Absent control, native ovules would be swamped by hybrid pollen, producing hybrid swarms that overwhelm each marsh in succession leading to the extinction of *S. foliosa* and the transformation of the native ecosystem.

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San Francisco Bay and Beyond: Invasive *Spartina* Continues to Spread Among

By Debra Smith, Shannon Klohr, Katy Zaremba
San Francisco Estuary Invasive Spartina Project
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Four nonnative species of *Spartina*, or cordgrass, are quietly spreading in San Francisco Bay; *Spartina alterniflora* and its hybrids with the native *S. foliosa* (see page 37 Ayres & Strong article), *S. anglica, S. densiflora,* and *S. patens.* Each of these cordgrass species is a highly aggressive invader capable of inducing physical and biological alteration of Pacific coastal habitats in California, Oregon, and Washington. (Daehler and Strong 1996). At least three of these four species were introduced intentionally to the San Francisco Estuary to revegetate wetland restoration sites in the 1970's.

In 2000, the California State Coastal Conservancy formed the San Francisco Estuary Invasive *Spartina* Project (ISP) in response to a growing need for a regionally coordinated cordgrass control effort in San Francisco Bay. An extensive ground-based survey conducted by ISP in 2001 found that combined, nonnative *Spartina* species have expanded to nearly five hundred net acres over a period of twenty-five years. Ninety-seven percent of the population is *S. alterniflora* or hybrid. The invasion has spread into seven Bay Area counties with some outlying populations of *S. alterniflora* and hybrids established as far as forty miles north of the original plantings. It appears that *S. alterniflora x foliosa* hybrids, in particular, may be poised to aggressively spread into Suisun Bay and possibly upstream into the lower Sacramento River Delta. During the survey, biologists observed that *S. alterniflora* and hybrids establish lower in elevation on the inter-tidal plane than any other native plant species, are choking creeks, tidal sloughs, and flood control channels, and are rapidly colonizing many tidal wetland restoration projects. In heavily infested areas there is significant loss of native species such as pickleweed *(Salicornia*) and *Spartina foliosa* (native California cordgrass). *S. patens* was observed to be directly encroaching on the federally and state endangered soft bird's beak (*Cordylanthus mollis*) in one location.

The San Francisco Estuary, the largest estuary in North America, opens into the Pacific Ocean at the famous Golden Gate. Beyond the Golden Gate, north along the coast, are the smaller pristine estuaries of Drakes Estero and Tomales Bay in the Pt. Reyes National Seashore, Bolinas Lagoon, and Bodega Bay - all part of the Gulf of the Farallones National Marine Sanctuary. Bolinas Lagoon is the only designated Wetland of International Importance (Ramsar Site) within California, Oregon, and Washington. Tomales Bay is currently proposed for such designation. The concern has been that *Spartina* seeds might travel out the Golden Gate with the currents and invade these outer coast estuaries. Prior to October of 2001, each of these important estuaries was believed to be free of invasive *Spartina*.

A Rapid Response Plan

In October 2001, while conducting routine follow-up on local *Spartina* invasions, ISP found a population of *S. densiflora*, originally composed of three plants and believed eradicated in 1999 from Tomales Bay, had re-established and spread. Several mature plants and more than 60 seedlings were growing at the same site, unbeknownst to the landowner. Encouraged by the landowner's interest in identifying and eradicating the plants, ISP quickly decided to expand its geographic scope to include Tomales Bay, and organized a *Spartina* species identification workshop for local Tomales Bay biologists, private landowners, and open space managers for the following week. At the workshop's conclusion, attendees each agreed to survey a section of shoreline for invasive *Spartina* and report findings to ISP. ISP agreed to conduct a portion of the surveys, assist in surveys where needed, coordinate necessary lab tests, and act as central clearinghouse for all collected data. Within three weeks, the bay had been surveyed, two additional populations of *Spartina densiflora* found, and all known populations dug out with a shovel and removed from the area. Ongoing monitoring is planned. The cost for this entire effort of early detection, survey and control was virtually zero due to volunteer efforts and ISP providing expertise, training, and equipment. The incredible interest and response from the local community were essential components to this early detection success story.

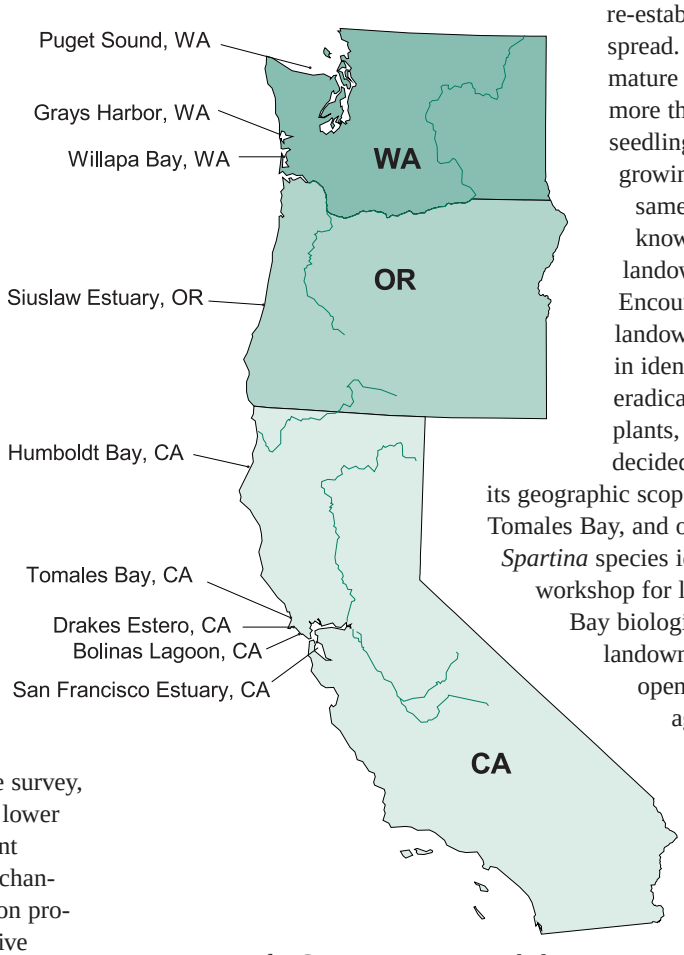

Figure 1. Pacific Coast Estuaries Invaded by Non-native Spartina (2001)

San Francisco Bay *continued on next page*

Pacific Estuaries

San Francisco Bay *continued from previous page*

The More You Look, the More You Find

In November of 2001, a biologist who had attended ISP's *Spartina* species identification workshop found a single *Spartina alterniflora* plant in Bolinas Lagoon while kayaking. In December, a concerned hiker in Pt. Reyes National Seashore reported a strange plant in Drake's Estero. Aware of the threat of Spartina, park biologists acted quickly to obtain genetic tests that confirmed this was *Spartina alterniflora*. Each of these plants appears to be several years old. Both of these estuaries were assumed free of invasive *Spartina*. Suddenly all such assumptions seem dangerously suspect. Vectors for these new invasions are not clear. Floating seed, aquaculture, and recreational activities between estuaries are all possible means of introduction. Clearly, all Pacific Coast estuaries need to be surveyed methodically for invasive *Spartina*. Early detection is critical for a successful and cost-efficient prevention and control program.

Surprise *Spartina* findings are not limited to California. In Washington, a wildlife technician conducting a noxious weed survey discovered a tenth of an acre patch of *Spartina densiflora* in Gray's Harbor in December, 2001. This was the first sighting of this species in the state of Washington. Scientists are in the process of identifying another cordgrass sample from north Puget Sound believed also to be *Spartina densiflora*. These continued and unexpected *Spartina* findings in well-studied estuaries further underscore the need for comprehensive surveys of all Pacific Coast estuaries.

The Pacific Coast Spartina Invasion: A Bird's Eye View

Thirty-one estuaries along the Pacific Coast have been identified as vulnerable to invasion by introduced species of *Spartina* (Daehler and Strong 1996). In 2001, five new introductions were detected on the Pacific coast including three in previously uninvaded estuaries. Currently, a total of nine have at least one species of introduced cordgrass. It is critical that vulnerable estuaries be comprehensively surveyed and a rapid response initiated to control any detected populations.

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Upcoming ANS Meetings and Events

National Invasive Weeds
Awareness Week 2002 (NIWAW III)
Date: February 25 - March 1, 2002
Location: Washington, DC
Contact: Rita Trostel
Phone: (970) 498-5767

4th Annual Southeast Exotic Pest
Plant Council Symposium
Date: April 3-5, 2002
Location: Renaissance Hotel, Nashville, Tennessee
Hosted by: Tennessee Exotic Pest Plant Council
Contact: Brian Bowen
Phone: (615) 532-0436
E-mail: nighttrain0@home.com

6th Meeting of the Convention on Biological Diversity
(CBD) Conference of the Parties
Date: April 8-26, 2002
Location: The Hague, Netherlands
Contact: CBD Secretariat
E-mail: www.biodiversity.org

Evolutionary Consequences of Invasions by Exotic Species
Date: April 12-13, 2002
Location: Minneapolis, Minnesota
Hosted by: University of Minnesota's College of Biological Sciences
For more information:
www.ima.umn.edu/geoscience/spring/bio_invasion

2002 Invasive Species Symposium
Date: June 18-19, 2002
Location: Freeborn Hall, University of California-Davis, Davis, California
Phone: (530) 757-3331
Fax: (530) 757-7943
E-mail: events@ucdavis.edu

European Weed Research Society, 12th International
Symposium on Aquatic Weeds
Date: June 24-27, 2002
Location: Papendal National Sports Centre, Papendallaan 3, Arnhem, The Netherlands
Phone: +31 26 370 8389
Fax: +31 26 370 6896
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