Biological Invasions (2005) 7: 1017–1027
DOI 10.1007/s10530-004-3124-y

When invasive species have benefits as well as costs: managing *Carex kobomugi* (Asiatic sand sedge) in New Jersey's coastal dunes

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Received 19 June 2003; accepted in revised form 12 July 2004

Key words: Asiatic sand sedge, *Carex kobomugi*, coastal parks, dune stabilization, impact on native species diversity, invasive, management strategies, New Jersey, spread rate

Abstract

Asiatic sand sedge, *Carex kobomugi,* was accidentally introduced into North America approximately a century ago and is now widespread along the Northeast coast of the USA. This paper documents the rapid spread rate of this species in two New Jersey coastal parks. Also documented are declines in native plant densities, species richness and diversity in invaded areas. Although *C. kobomugi* expansion is having negative ecological impacts, the species is a potentially important dune stabilizer, so its control or removal demands special care. A removal program was initiated in 1999, using carefully directed applications of Roundup®, which was designed such that it would spare non-target plants, leaving them in place to hold the dunes. We show that this approach reduced, but did not eliminate, *C. kobomugi*, even after repeated herbicide application. Native plant stem densities, species richness and species diversity in treated and untreated stands were similar, suggesting that this application technique did effectively spare non-target plants. However, effective eradication of *C. kobomugi* would probably require more frequent and aggressive broadband herbicide application, precluding beneficial effects of localized treatment (both ecological and increased dune stability due to spared plants).

Introduction

Carex kobomugi (Asiatic sand sedge) is a perennial plant of the family Cyperaceae, native to coastal areas of Japan, China, Korea and Russia. At 15–30 cm tall, *C. kobomugi* is shorter than native, American beach grass (*Ammophila breviligulata*) which often reaches heights in excess of 100 cm. However, *C. kobomugi* is a sturdy plant which forms a dense mat that can effectively crowd out other species. It reproduces asexually via extensive rhizomes and sexually through production of separate male and female flowers. Previous to this study, *C. kobomugi* had been reported to reach maximum densities of about 350 shoots m^{-2} (Small 1954), each with 5–10 blades, resulting in exceptionally high blade-densities. It is well adapted for colonizing coastal dunes, possessing a deep, well-developed root system and a high degree of drought resistance (Ishikawa et al. 1996). Its high blade density, combined with its dense network of subsurface rhizomes and deep root system, make *C. kobomugi* a potentially effective dune stabilizer.

C. kobomugi was first recorded in the USA in 1929 on sand dunes near Seaside Park New Jersey, just north of what is now Island Beach State Park (IBSP) (Small 1954). Two hypotheses have been suggested for the transport vector for this plant: (1) propagules were discarded in ship's ballast, off the New Jersey coast (Small 1954) and (2) plants, possibly with viable seeds, may have been used as packing materials in barrels of fine china imported from Asia at the turn of the century and the seeds are postulated to have been released when the barrels broke open when ships wrecked near the Jersey shore (Halsey 2002). The species was initially found only in New Jersey. However, deliberate plantings for dune stabilization from the late 1960s through the mid-1980s (summarized in Shisler et al. 1987), combined with natural expansion, resulted in the species' spread to coastal dunes from Massachusetts to North Carolina (Standley 1983; USDA 1983). Plantings of *C. kobomugi* were initially promoted because it is resistant to a number of diseases and pests that impede growth of native beach grasses, and is also more tolerant to trampling than the native beach grasses (USDA 1983; Belcher et al. 1984). Moreover, although its growth is more vigorous on actively accreting or stable dunes, *C. kobomugi* prospers in inter-swale areas, back dunes and other areas where American beach grass and other native species grow poorly (Hawk and Sharp 1967; Shisler et al. 1987). *C. kobomugi's* spiky flowers and sharp rhizomes also form a natural way to deter foot traffic from areas away from established trails. Thus, it seemed an ideal species to plant in areas needing dune stabilization.

After the prolific invasion of the zebra mussel (*Dreissena polymorpha*) in the Great Lakes and other US waterways in the late 1980s, tolerance for alien or exotic species plummeted. Armed with federal laws, states passed regulations that led to avoidance of non-native species in land management. Consequently, planting of *C. kobomugi* in the USA ceased by the early 1990s. By the turn of the millennium, the species slid from endangered species designation (Fairbrothers and Hough 1973) to being one of the 'ten most unwanted plant species in New Jersey' (Robert Cartica, NJDEP, personal communication).

Concerns over the potential invasiveness of *C. kobomugi* led New Jersey's Department of Environmental Protection (NJDEP) to initiate an aggressive management strategy aimed at eradication of this species. This decision was based largely on managers' qualitative observations, since there was little quantitative data on *C. kobomugi's* geographic extent, or its impacts on species diversity, dune ecology or geomorphology. We set out to establish: (1) Spread rates and ecological impacts of *C. kobomugi* in New Jersey's coastal dunes, (2) Effectiveness of the current eradication program at IBSP and (3) Implications of these findings for management of this species in light of its conflicting roles as invasive competitor and beneficial dune stabilizer.

Materials and methods

This study was conducted at IBSP and the Sandy Hook Unit (SHU) of the Gateway Recreational Area. Both parks are located on New Jersey's coast (Figure 1), and include large expanses of sand dunes, as well as extensive sandy beaches that are heavily used by both residents and tourists. The size and position of all *C. kobomugi* stands on the coastal dunes of both parks were mapped in summer 2002 using the methods of Shisler et al. (1987). Each stand was measured along its longshore axis, and widths were taken at 5 m intervals (2 m intervals on smaller stands). Calculated areas were compared with Shisler et al.'s data to determine the intervening rates of change.

Stem densities and species composition were determined by counting and identifying all plants in 1 m^2 plots within each stand of *C. kobomugi*. Plots were selected using a systematic sampling design supplemented by randomly selected plots until approximately 1% of the stand area had been surveyed. Similar plots were established and sampled at multiple points 5 m outside the seaward and landward edges of the stand, and at both ends. Mean stem densities for each species encountered in plots inside and outside the stands in both parks, were compared using independent *t*-tests for those data sets meeting the requirements for parametric analysis or Mann–Wittney tests for those which did not. All analyses were run using the Statistical Program for Social Sciences (SPSS) 11.0.

To assess relative vigor of plants present inside and outside *C. kobomugi* stands, 0.1 m^2 quadrats were placed randomly within each 1 m^2 plot. All stems in these plots were clipped at ground level and placed in labeled paper bags. In the laboratory, samples were sorted and the number of

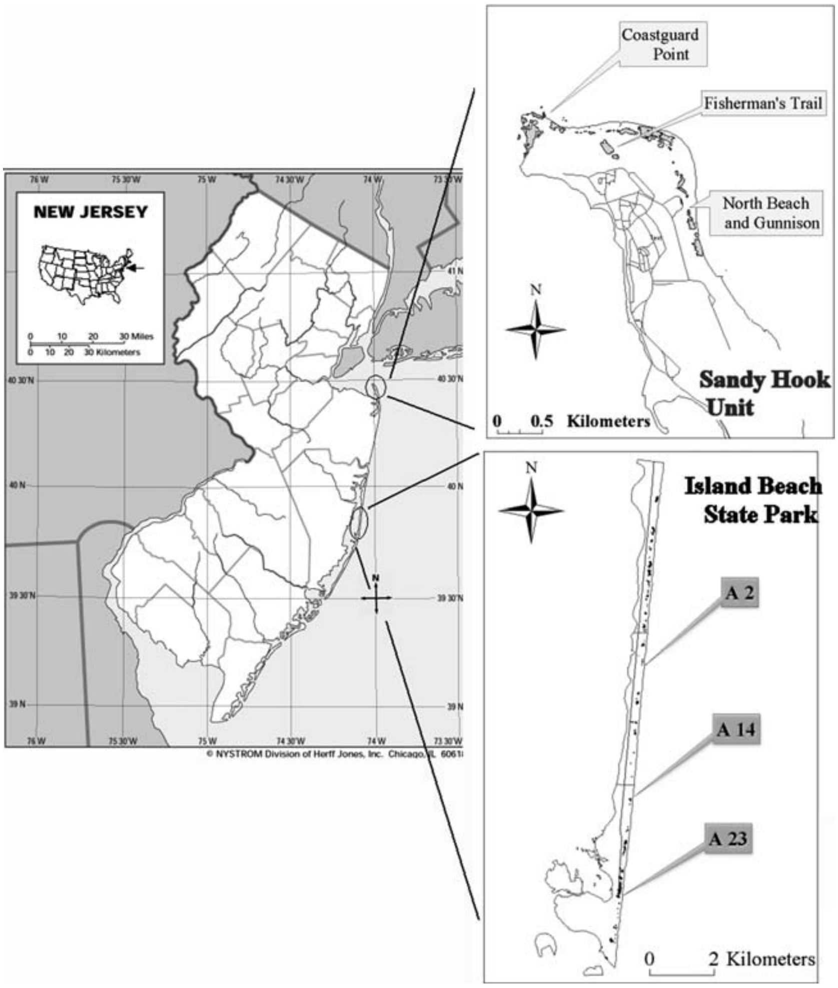

Figure 1. Location of study sites within New Jersey. Shaded regions of inserts indicate areas invaded by *C. kobomugi*. Study sites at IBSP are identified according to the numbers of the beach access trails that transect the park and are numbered sequentially north–south from A2 (near the public bathing areas) to A23.

stems of each species was counted. Samples from each species and plot were placed in separate bags, dried in an oven at 60 °C, weighed and the average biomass (gm d.w. stem^{-1}) of plants from each quadrat was calculated.

Mean species richness inside and outside each stand was calculated by averaging the number of species observed in each 1 m^2 plot sampled at each site. Species diversity of each 1 m^2 plot sampled, was calculated using the Shannon–Weiner diversity index according to the formula

$$H' = -\sum_{i=1}^{S} Pi \ln P_i,$$

where S is the number of species in sample and P_i is relative abundance of 'ith' species (i.e. P is the number of individuals of species 'i' divided by total number of individuals in plot). The resulting estimates of species diversity were averaged by site and compared using ANOVA and post hoc pairwise Student–Newman Kuels (SNK) comparisons (when sample sizes were approximately equivalent) or Dunnett's T3 tests using SPSS 11.0.

The eradication program implemented at IBSP involved carefully-directed spray applications of Roundup® to individual *C. kobomugi* plants (Lea and McLaughlin 2002), and was intended to eliminate the sedge while sparing any native plants growing in the same areas. To assess effectiveness of this strategy, we studied two of the four stands treated to date: (1) A relatively small and isolated stand (parking lot A14; Figure 1) that had been treated three times, twice in 1999 and once more in 2000; (2) A larger and less isolated stand of *C. kobomugi* (parking lot A23N, Figure 1) which had been treated only once, in the fall of 2001. Surviving plants within the two treated stands were surveyed by counting numbers and types of plants in 1 m^2 plots within and outside the treated stand using the design described above. Since spraying had commenced before the study begun, numbers and types of plant species within the treated stands were not determined prior to implementation of the spray program. In addition, no *in situ* controls (untreated areas within treated stands) were left. We thus used nearby untreated *C. kobomugi* stands as reference areas. Differences in species richness and species diversity within 1 m^2 plots in treated *versus* untreated stands were assessed using ANOVA and post hoc pair-wise SNK comparisons (when sample sizes were approximately equivalent) or Dunnett's T3 tests using SPSS 11.0.

Results

The stand described by Townsend in 1929 at IBSP as 'a much battered pocket population' had expanded to 2000 m^2 by 1939 and to 3000 m^2 by 1951 (Small 1954). Our survey delineated a total of 90,032 m^2 (22.2 acres) for this same population at IBSP. In addition we found 6,053 m^2 (16.3 acres) of *C. kobomugi* at SHU. Relative to two previous studies (Shisler et al. 1987; Pronio 1989), the number of stands at IBSP has approximately doubled, while those at SHU have increased 20-fold. Total area occupied by the species at IBSP has increased by about 300% since 1985. At SHU, the documented area occupied by *C. kobomugi* has increased by 780% over the same period, largely as a result of the addition of new stands rather than expansion of older ones. Overall, expansion of *C. kobomugi* in both areas has been approximately exponential (Figure 2).

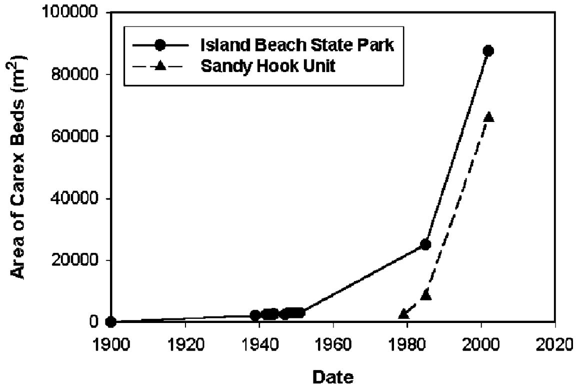

Figure 2. Increase in extent of *C. kobomugi* stands in New Jersey's coastal parks over time assuming an introduction date of approximately 1900 at IBSP based on data from Small (1950), Stalter (1980), Shisler et al. (1987), Pronio 1989 and current study).

Mean shoot densities of *C. kobomugi* at both IBSP and SHU in 2002 were similar to those recorded in 1950 (Small 1954), and higher than those observed by Shisler et al. in 1985 (Table 1). Maximum stem densities observed in the current study of 459 shoots m^{-2} at IBSP and 512 shoots m^{-2} at SHU were higher than the 357 shoots m^{-2} maximum noted for these stands at IBSP in 1939 (Small 1954). Unfortunately, Shisler et al. (1987) and Pronio (1989) did not report maximum stem densities, so comparison of this parameter over the intermediate period is not possible.

Table 1. Comparison of shoot densities m^{-2} in stands reported from previous studies with those from the same stands in the current study.

	1950 (Small 1954)	1985 (Shisler et al. 1987)		2002 (this study)		Increase since 1987 (%)
	Mean shoot density	Mean shoot density (S.D.)	*n*	Mean shoot density (S.D.)	*n*	
Sandy Hook	–	118.7	24	188.4 (92.4)	97	159
IBSP	123.3	65.8	140	132.9 (83.0)	515	202

Table 2. Comparison of shoot densities m^{-2} of native species within and outside untreated *Carex kobomugi* stands in 2001.

	Mean number of shoots (1 S.E.) SHU		Mean number of shoots (1 S.E.) IBSP	
	Inside stand (n = 360)	Outside stand (n = 228)	Inside stand (n = 740)	Outside stand (n = 469)
A. breviligulata beach grass	7.8 (0.8)[a]	14.4 (1.5)[b]	8.0 (0.5)[a]	17.8 (1.2)[b]
S. sempervirens golden rod	1.0 (0.1)[a]	3.2 (0.7)[b]	2.5 (0.3)[a]	2.0 (0.3)[a]
S. scoparium little blue stem	4.1 (0.6)[a]	10.5 (2.1)[b]	0	0
A. biennis wormwood	0.6 (0.1)[a]	0.6 (0.2)[a]	0	0
E. polygonifolia sea spurge	0.003 (0.003)[a]	0[a]	0.5 (0.1)[b]	1.0 (0.3)[b]
Cakile edentula sea rocket	0.001 (0.001)[a]	0[a]	1.7 (0.1)[b]	1.9 (0.1)[b]
Cenchrus tribuloides dune sandbur	0	0	0.3 (0.1)[a]	0.6 (0.1)[a]
Cyperus sp. nut sedges	0	0	0.5 (0.1)[a]	1.0 (0.3)[a]
Lathyrus maritimus beach pea	1.6 (0.3)[a]	0.6 (0.2)[b]	0.1 (0.0)[c]	0.1 (0.0)[c]

For each species-comparison within and between sites (i.e. across rows), means denoted with the same letter are statistically similar (belong to the same homogeneous subsets). Means denoted with different letters are statistically different at the $P < 0.05$ level.

Fewer than 50% of quadrats in most stands surveyed contained only *C. kobomugi*. However, abundances of many species, including American beach grass (*A. breviligulata*), cheatgrass (*Bromus tectorum*), seaside goldenrod (*Solidago sempervirens*), seaside spurge (*Euphorbia polygonifolia*) and little bluestem (*Schizachyrium scoparium*), were reduced by 50–75% within *C. kobomugi* stands (Table 2). However, there were several species whose abundances within *C. kobomugi* stands were not statistically distinguishable from those in surrounding areas. These included wormwood (*Artemisia biennis*) and dune sandbur (*Cenchrus tribuloides*).

Mean biomass of native plants growing inside *C. kobomugi* stands was generally similar to that of individuals of the same species outside the stands in both parks, suggesting no detectable decline in vigor of native plants. The only exception to this was *A. breviligulata* at IBSP, where a significant decline (0.6 ± 0.02 g inside versus 0.7 ± 0.03 g outside, $P < 0.001$) in mean shoot biomass was detected.

Mean species richness for all samples taken at SHU was 2.7 (S.E. 0.05) species m^{-2} ($n = 398$) in *C. kobomugi* stands, and 2.4 (S.E. 0.10) species m^{-2} ($n = 233$) outside the stands. Mean species richness for all samples in *C. kobomugi* stands at IBSP was 2.3 (S.E. 0.04) species m^{-2} ($n = 757$) while that immediately outside the stands was 1.6 (S.E. 0.06) species m^{-2} ($n = 480$). Statistically, the patterns of species richness were: Outside *C. kobomugi* stands at IBSP < Inside *C. kobomugi* stands at IBSP = Inside *C. kobomugi* stands at SHU < Outside *C. kobomugi* stands at SHU (ANOVA and SNK, $P > 0.001$).

Species diversity was lower inside *C. kobomugi* stands (0.30, S.E. 0.02, $n = 356$) than outside (0.46, S.E. 0.03, $n = 228$) at SHU ($P < 0.001$). However there was no difference in species diversity inside *C. kobomugi* stands (0.31, S.E. 0.01, $n = 676$) versus outside (0.32, S.E. 0.02, $n = 445$) stands at IBSP. Species diversities both inside and outside *C. kobomugi* stands at IBSP were lower ($P < 0.01$) than those in unaffected dune communities at SHU.

The size of *C. kobomugi* stands was very different between the two parks. Of 61 stands surveyed at SHU, only 12 were larger than 100 m^2, nine were larger than 1000 m^2 and two (one at Coastguard Point and one along the Fisherman's Trail) were larger than 10,000 m^2 (Figure 1). By contrast, of 117 stands surveyed at IBSP, 18 stands were larger than 1000 m^2, but the largest bed was less than 8000 m^2. Many of the stands encountered at SHU, particularly in the northern tip of the park, were small, scattered fragments (Figure 1).

A single application of Roundup® reduced *C. kobomugi* abundances by approximately 70%, but left live *C. kobomugi* in approximately 95% of the 1 m^2 quadrats sampled (Table 3). Repeated Roundup® application reduced *C. kobomugi* abundances by approximately 90%, but viable individuals were still found in approximately 55% of quadrats sampled (Table 3). Stem densities of non-target plants in treated stands were similar to, or higher than, those in untreated stands and

Table 3. Effectiveness of Roundup® application in the removal of *Carex kobomugi* at IBSP. "Control type 1" sites are *Carex* stands near treated sites which have not yet been treated. "Control type 2" sites are areas 5 m outside the *Carex* stands that are currently unaffected by this species. These were not planned experiments so paired controls were not available. *A.a. A. breviligulata*. *S.s. Solidago sempervirens*. *C.* sp. *Cyperus* sp. *C.l. Cenchrus longispinus*, *E.p. Euphorbia polygonifolia*

Location	Treatment	Average shoots m^{-2} in stand (1 S.E.)	% quadrats containing viable *Carex*	*A.a.* shoots (m^{-2})	*S.s.* shoots (m^{-2})	*C.* sp. shoots (m^{-2})	*C.l.* shoots (m^{-2})	*E.p.* shoots (m^{-2})	Species richness (1 S.E.)	Species diversity (1 S.E.)
IBSP A23N (n = 39)	Sprayed once (late summer 2001)	$30.8\ (4.6)^{a}$	95	$15.6\ (3.2)^{ab}$	$2.7\ (1.8)^{a}$	0^{a}	$0.23\ (0.23)^{a}$	0^{a}	$2.4\ (0.1)^{a}$	$0.34\ (0.04)^{a}$
IBSP A23S oceanside (n = 20)	Control type 1	$142.8\ (14.8)^{b}$	100	$26.4\ (5.6)^{a}$	0.05 (0.05)	0^{a}	0^{a}	0^{a}	$2.0\ (0.1)^{a}$	$0.34\ (0.05)^{a}$
IBSP A23 parking lot (n = 11)	Control type 1	$124.6\ (14.5)^{b}$	100	$2.1\ (1.0)^{b}$	0^{a}	$5.1\ (4.5)^{b}$	0^{a}	$0.3\ (0.90)^{a}$	$1.9\ (0.3)^{a}$	$0.\ 20\ (0.08)^{a}$
IBSP A23 buggy trail (n = 18)	Control type 1	$115.4\ (15.9)^{b}$	89	$2.7\ (7.7)^{b}$	$1.1\ (2.2)^{a}$	$0.2\ (0.2)^{a}$	0^{a}	0^{a}	$1.8\ (0.2)^{a}$	$0.14\ (0.04)^{b}$
IBSP A23N outside Stand (n = 20)	Control type 2	N/A	N/A	$30.8\ (9.8)^{a}$	$2.15\ (2.1)^{a}$	0^{a}	0^{a}	$0.5\ (0.3)^{a}$	$1.2\ (0.3)^{b}$	$0.16\ (0.06)^{a}$
IBSP A14 (n = 19)	Sprayed twice in 1999 & again in 2000) replanted with *A.b.*	$10.1\ (5.4)^{a}$	58	$14.8\ (3.3)^{a}$	$0.7\ (0.3)^{ab}$	$0.6\ (0.6)^{a}$	$0.8\ (0.5)^{a}$	$0.8\ (0.3)^{ab}$	$2.7\ (0.3)^{a}$	$0.57\ (0.14)^{a}$
A8S (n = 24)	Control type 1	$135.3\ (14.8)^{b}$	100	$17.6\ (6.5)^{a}$	$5.0\ (1.9)^{a}$	0^{a}	0^{a}	0^{a}	$2.2\ (0.2)^{ab}$	$0.28\ (0.06)^{ab}$
A11 (n = 7)	Control type 1	$133.6\ (41.3)^{b}$	86	$34.7\ (9.4)^{a}$	$3.1\ (1.6)^{ab}$	0^{a}	0^{a}	$2.1\ (1.7)^{b}$	$2.3\ (0.6)^{ab}$	$0.15\ (0.07)^{b}$
A18 (n = 37)	Control type 1	$153.9\ (11.6)^{b}$	100	$10.5\ (2.5)^{a}$	$1.1\ (0.5)^{ab}$	0^{a}	0^{a}	$0.1\ (0.1)^{a}$	$2.5\ (0.1)^{ab}$	$0.28\ (0.04)^{a}$
IBSP A14 outside stand (n = 19)	Control type 2	N/A	N/A	$12.4\ (5.6)^{a}$	$0.1\ (0.1)^{b}$	$0.9\ (0.9)^{a}$	$0.7\ (0.4)^{a}$	$2.0\ (0.6)^{b}$	$1.6\ (0.2)^{b}$	$0.35\ (0.09)^{a}$

For each species-comparison within and between sites (i.e. across rows), means denoted with the same letter are statistically similar (belong to the same homogeneous subsets). Means denoted with different letters are statistically different at the $P < 0.05$ level.

to those in the areas immediately outside the treated stand (Table 3). Species richness and diversity were also similar, or even slightly elevated, in treated stands relative to those in untreated stands or in the areas immediately outside the treated stands (Table 3).

Discussion

Ecological impact assessment

In a recent evaluation of the impact of the invasion of *Phragmites australis* in US marshes, Weis and Weis (2003) note that, while removal programs for invasive species may be justified, they are often carried out before any scientific investigation of the effects of the targeted invasive species upon the rest of the ecosystem. This accurately describes the situation for *C. kobomugi* in North America. Prior to the current study, little was known about the ecological impacts of this species and there had been no formal assessment of the potential impacts of the species' removal. The argument for removal of invasive species before conducting impact studies is usually that rapid response is the key to successful containment of biological invasions. Indeed, if *C. kobomugi* had been aggressively removed when it was first observed, the current problems could probably have been avoided. However, as we are now 100 years into this species' invasion, taking time to study the spread rate and patterns (direction, formation of new beds versus expansion of existing ones, etc.) and biological impacts of this species before implementing further management strategies seems warranted.

The invasion of *C. kobomugi* in New Jersey started with a long period of slow spread, followed by an extremely rapid expansion (Figure 2). Such a long 'lag phase' is common in invasive species (Hobbs and Humphries 1994) and may occur because initial colonizers are not initially genetically suited to rapid expansion but, over time, accumulation of genetic diversity results in development of an invasive genotype. A specific event or set of environmental conditions may also allow a species to start expanding more rapidly (Hobbs and Humphries 1994). While both of these mechanisms (and others not explored here) may be pertinent in this case, a series of major storms hit coastal New Jersey from the 1940s to mid-1960s, including a Class 2 hurricane in 1944 and a devastating and highly unusual northeast storm that became known as 'The Great Atlantic Storm' of March 1962. These storms may have distributed propagules of the invasive species broadly around the area, leading to the subsequent rapid spread of the species (Pronio 1989). These storms also introduced a great deal of disturbance into New Jersey's dune systems by which the susceptibility of the dunes to invasion by exotic species might have increased (Wiedemann and Pickart 1996). Because germination rates of *C. kobomugi* are strongly temperature dependent, with a 35 °C optimum (Ishikawa et al. 1993), numerous recent hot summers associated with global warming may also have promoted expansion of this species.

Shoot densities of *C. kobomugi* (Table 1) appear to have fluctuated greatly over time (Small 1954; Shisler et al. 1987; Pronio 1989). These differences do not simply represent bias from inclusion of younger, less established sites in the 1985 study, since, in some cases, data are available from all three studies for stands whose geographical location is identical, and these data show the same trends. Why *C. kobomugi* shoot densities in 1985 were so much lower than those seen in 1950 and 2002 is unclear.

The 18 plant taxa we observed at IBSP are fewer than the 26 taxa observed by Freestone and Nordstrom (2001) on restored dunes (not impacted by *C. kobomugi*) a little further south in New Jersey, but are comparable to the 14 taxa observed at IBSP by Shisler et al. (1987). Freestone and Nordstrom (2001) found the highest numbers of species on the most mature back dunes, whereas most of the *C. kobomugi* stands we surveyed were in foredune and dune swale areas. This makes the 42 taxa we observed at SHU even more remarkable. Non-impacted dunes at SHU, showed significantly higher mean species richness and species diversity relative to similar systems at IBSP. However, in both parks and in both impacted and non-impacted dunes, calculated levels of species richness fell within the range reported by Freestone and Nordstrom (2001), whose estimates of species richness varied from approximately 3.5 species m^{-1} in the mature back dunes to approximately 1.5 m^{-1} in the most seaward sites.

Mean shoot densities of native plants inside the areas invaded by *C. kobomugi* were often lower than those in nearby unaffected areas (Table 2), suggesting that this species negatively affects dune ecology. This impact is much stronger at SHU than at IBSP. By contrast, the only significant detectable impact of *C. kobomugi* on native plant's shoot biomass, we were able to detect was for *A. breviligulata* at IBSP. For less abundant species, such as *A. biennis* (wormwood), a 'species of concern,' in New Jersey, our inability to show significant effects may reflect the variability associated with their clumped distribution patterns as well as the reduced statistical power associated with small sample sizes, which in turn reflect low encounter rates.

The observed expansion rates of *C. kobomugi* in New Jersey (Figure 2) are relatively high. For comparison, expansion of *Ammophila arenaria* on America's NW coast (570% in 50 years) was characterized as 'extremely rapid' (Wiedemann and Pickart 1996). Spread of *C. kobomugi* is not likely to slow down due to natural factors in the near future. Indeed, a large number of new, small stands of this species, particularly at SHU, suggests that the species is poised for continued acceleration of its spread in this region.

Effectiveness of current management strategy

When describing the strategy of highly localized Roundup® application used at IBSP, Lea and McLaughlin (2002) recommend follow-up monitoring to check for continued presence of *C. kobomugi* in treated areas. Prior to this study, such monitoring had not been carried out. Our study showed that treatment with Roundup® reduced *C. kobomugi* abundance but did not eliminate it, even with repeated applications (Table 4). Given the rapid growth rate of this species, if treatments are not continued, surviving individuals are likely to rapidly re-establish the stand. Stands treated to date were relatively 'simple' systems (discrete patches of *C. kobomugi* within 'seas' of grasses). The remaining stands where *C. kobomugi* is growing in complex, 3-dimensional communities of plants like beach plum, bayberry or poison ivy, will be more challenging to treat.

Removal of a dune-stabilizing species like *C. kobomugi* is a delicate and potentially controversial decision. The North American view on this species' effectiveness as a dune stabilizer has been ambivalent at best. *C. kobomugi* dunes appear to be generally lower than those formed in association with *A. breviligulata* (Shisler et al. 1987; Pronio 1989). Lea and McLaughlin (2002) and this suggests that *C. kobomugi*-stabilized dunes are more vulnerable to wind blowouts and storm erosion than are those stabilized by *A. breviligulata*, but no evidence could be cited for the view. Small (1954) describes *C. kobomugi* as an effective dune stabilizer, and this is certainly our impression after having hiked over dunes stabilized by this species. Anecdotal evidence, supported by aerial photographic evidence, suggests that dunes stabilized by *C. kobomugi* survived several serious storms in the 1960s and early 1990s better than those stabilized by *A. breviligulata*.

Whether or not *C. kobomugi* eventually is shown to be more or less effective as a dune stabilizer than *A. breviligulata*, dunes populated by this species are more stable than those with few or no plants present. Use of localized herbicide application methods to control *C. kobomugi* at IBSP was intended to eliminate that species while leaving any native plants in place to maintain dune integrity and accelerate restoration of the dune community. While this strategy did not completely eliminate *C. kobomugi*, it seems to have effectively spared the native dune community, since there were no significant differences in stem count for any non-target species between treated and untreated stands (Table 3, control type 1). The fact that species richness in treated and untreated stands was similar also suggests that the spray program is effectively maintaining non-target plant diversity. Slightly higher levels of species richness in treated stands relative to areas that had never been invaded by *C. kobomugi* (Table 3, control type 2) reflects a combination of (1) generally low levels of species diversity at IBSP and (2) addition of surviving *C. kobomugi* to overall number of species per plot.

Species diversity indices are strongly influenced by the degree of species evenness in a sample, having highest values when two or more species are co-dominant. The current spray program selectively targets and reduces the numerically dominant *C. kobomugi*, increasing species evenness. Consequently, treated stands would be expected to have higher calculated values of any species diversity index, even if no changes in abundance or number of species types of non-target plants occurred between treated and untreated stands. Alternately, since nothing is known about the invaded areas before herbicide treatment, higher levels of species diversity in herbicide-treated stands relative to some untreated stands (Table 3), may reflect a condition that predates treatment.

To effectively eradicate *C. kobomugi,* extensive (non-localized spray application) and frequent repetitions of herbicide treatment would be needed. Such extensive spray programs can negatively impact native species even when those species are not in the targeted areas (Matarczyk et al. 2002). Intensive spray applications would also eliminate the advantages of reduced impact on non-target plants within stands, leaving the dunes defoliated. Such defoliated dunes might become rapidly destabilized, resulting in loss of function as storm buffer, as well as loss of their scenic and recreational values. This is analogous to the problems experienced in managing *Ammophila arenaria* in northwest America (Wiedmann and Pickart 1996) and *Spartina anglica* in Tasmania (Kriwoken and Hedge 2000). Similarly, while the negative impacts of the *P. australis* invasion in North America are well known, this species also has been suggested to possess a number of positive ecosystem functions that should be considered when management decisions are made (Weis and Weis 2003).

Suggestions for future management strategies

Not only does removal of *C. kobomugi* by localized herbicide application fail to effectively eliminate the species, the technique is labor intensive and thus relatively expensive. We assert that, although more extensive spray programs are likely to be more effective, the side effects in terms of loss of dune stability make this option undesirable. Localized herbicide use should slow down the expansion of the sedge population. It should also open up areas previously dominated by *C. kobomugi* that may support higher abundances of non-target plants, at least in the years immediately following treatment. Thus, for larger stands, continued use of localized spray application may be the best course of action, and repeated applications in excess of the 1–2 treatments currently being used appear to be required for real control of this species (Table 4).

Given the limitations of herbicide control methods for *C. kobomugi*, it seems appropriate to ask the question ‘What other options are available to managers coping with this species?’ Aronson et al. (1993) suggest that, when dealing with invasive species, the least damaged ecosystems should be restored, those with greater damage be rehabilitated, and ‘for those which cannot be helped, the new plant cover be reshaped by human intervention and reallocation should take place.’ In light of this advice we recommend that managers enlarge their focus on attempting elimination of *C. kobomugi* in large, existing stands by including strategies designed to control future expansion of the species, especially for preventing establishment of new stands. In particular, we suggest that managers remove small stands in high diversity regions where the damage to native species diversity by *C. kobomugi* invasion is most pronounced. When small beds are targeted, removal options that are impractical in larger stands can be employed. For example, removal of *A. arenaria* from dunes in northwest North America was achieved using volunteers to repeatedly dig up and remove the top few inches of the plant until it no longer returned (Wiedemann and Pickart 1996).

A related strategy that is likely to be beneficial for the management of *C. kobomugi* would be to identify high risk areas (appropriate habitats for establishment of the species, such as open or disturbed areas) located downdrift of current stands. Volunteers could be employed to survey these areas for *C. kobomugi* propagules, which could then be relatively easily removed before stands become established. Such a strategy was used successfully to control several species of invasive *Spartina* on the US West Coast (Daehler and Strong 1996).

A third strategy that we believe has the potential to be effective would be burial of *C. kobomugi* using sand. Repeated sand burial of *C. kobomugi* eventually results in its mortality (USDA 1983). In contrast, sand burial of *Ammophila* increases shoot vigor (Disraeli 1984; Seliskar 1994), perhaps as a result of the reduction of pathogen densities by dilution with fresh sand (Van der Putten et al. 1993). Nutrients adhering to freshly deposited sand grains, as well stimulation of internode elongation have been implicated in stimulation of growth by sand burial in *Uniola paniculata* (Wagner 1964).

Conclusions

The area occupied by *C. kobomugi* on sand dunes in the two study areas has increased exponentially in the last century. At IBSP this expansion had mostly resulted from growth of existing stands, whereas at SHU it reflected both expansion of older beds and addition of new stands. Abundances of many common native plant species were reduced significantly within *C. kobomugi* stands. Abundances of less common species such as wormwood (*A. biennis*), were also lower, but lack of statistical power prevented us from showing significant impacts on these species. Localized Roundup® application reduced *C. kobomugi* abundance within treated stands without harming non-targeted species. However even repeated Roundup® applications did not eliminate *C. kobomugi*. Effective eradication of *C. kobomugi* would probably require more frequent and aggressive, broadband herbicide application, and would sacrifce the retained ecological functionality and increased dune stability resulting from the continued presence of spared plants associated with the current localized treatment strategy. Continued localized herbicide use, perhaps enhanced by more frequent applications, may slow the invasion of this species. However, we suggest that managers enlarge their focus on attempting to eliminate *C. kobomugi* in large, existing stands, by including strategies designed to control future expansion of the species, especially for preventing establishment of new stands. In particular, we suggest that managers work to remove small stands, particularly those in regions with high species diversity, to prevent successful invasion of such critical areas. We also suggest that managers explore alternatives to herbicide application, such as sand burial, for the removal of this species.

Acknowledgements

This work could not have been conducted without the co-operation and support received from staff and managers at both Sandy Hook Unit and Island Beach State Parks. We also gratefully acknowledge Dr Michael Gross, Professor of Biology, Georgian Court University, who provided many plant identifications for this study. Sheetal Patel, Courtney Rella, Jim Burkitt, Crystal VanWagner, Sharon Myatt and Anna Shipman helped with the counting and mapping effort. Grateful thanks are extended to Drs Judith Pederson, Michael Gross and Peter Straub and two anonymous reviewers of this manuscript for their many insights and helpful suggestions for its improvement. This study was supported by the National Sea Grant College Program of the US Department of Commerce's National Oceanic and Atmospheric Administration under NOAA grant #NA16RG107. The views expressed herein do not necessarily reflect the views of any of those organizations. This is Sea Grant publication NJSG-03-528.

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