Article

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The Economic Value of Controlling an Invasive Shrub

Recent interest in the valuation of ecosystem services has provided tools for assessing the costs of invasive species in natural areas. This study evaluates the economic impacts of tamarisk (*Tamarix* sp.), an invasive woody shrub, on societally-valued ecosystem services in its naturalized range. Tamarisk, intentionally introduced from Eurasia, has invaded most riparian areas of the arid and semiarid western United States. In its naturalized range, tamarisk consumes more water than native vegetation, with significant economic implications in a region marked by water scarcity. Tamarisk also increases sedimentation in river channels, leading to increased frequency and severity of flood damage. Conservative economic estimates of these impacts indicate that the annual costs of tamarisk to the western United States total USD 280–450 ha^{-1}. Eradicating the invader and restoring native riparian communities throughout the region would cost approximately USD 7400 ha^{-1}. Full recovery of these costs, even with a highly conservative benefits estimate, would occur in as few as 17 years, after which the societal, ecological, and economic benefits of restoration would continue to accrue indefinitely.

Tamarisk in flower in Big Bend National Park, Texas, USA. Photo: K. Bonine.

INTRODUCTION

The increasing interest in "nature's services" (1) has prompted several efforts to estimate the monetary value of societal benefits provided by natural ecosystems (2–4). Many of these studies have estimated the global or regional values of services such as waste recycling and pollination, and of biosphere components such as fresh water and fertile soil. Few, though, have enlisted the tools of ecosystem service valuation in order to guide decisions to invest funds in the management and restoration of human-impacted ecosystems (3). The assigning of value to elements of the natural world regarded by most as priceless has aroused well-justified suspicion (1). If nature has finite value, skeptics reason, it becomes possible for economics to favor a decision to sacrifice it. However, decisions in modern times have if anything consistently assigned too little value to natural services that we now have the tools to grant full consideration. When funds are scarce, and social and ecological arguments alone are not sufficient to impel expenditures on conservation, economic measures of the value of restored ecosystems can provide crucial catalysts for management action (3).

Biological invasions now rank among the world's greatest threats to native ecosystems. The prevention and control of invasions, however, can be extremely costly and therefore require economic justification. Economic analyses of invasions have stimulated a few efforts to manage harmful invasives on a regional scale (3, 5–7). More such studies are badly needed to inform further management decisions, as well as to illustrate the nature and magnitude of impacts that invasions have on society. I present here a case study of how the invasion of riparian areas in the western United States by tamarisk shrubs (*Tamarix* sp.) has impacted the delivery of ecosystem services. I evaluate the costs to the region of lost water supplies and flood protection, two important natural services to the region that the invader has impaired. I compare these costs to the expense of mounting a regional campaign to remove tamarisk and restore native riparian plant communities. The case of tamarisk illustrates that the eradication of an established invader can require enormous expenditures. However, this case also illustrates that despite its high costs, a campaign to eradicate harmful invaders can yield net economic gains as well as considerable ecological and societal benefits.

Scholars refer to the 100th meridian as the "edge of arid America" (8) (Fig. 1). To the west of this line, rainfall drops below 450 mm yr^{-1} and virtually all agriculture becomes dependent on irrigation. Large areas of the region, including much of Nevada, Arizona, and southern California, receive less than 200 mm yr^{-1}. In these arid lands, riparian areas and surface waters harbor a disproportionate amount of the region's biological diversity and provide stopover habitat and water sources for wildlife ranging from migratory birds to bighorn sheep (9). These same areas are experiencing explosive human population growth rates, with accompanying increases in demand for water, hydropower, recreational opportunities, and aesthetic values (10) (Table 1). Some regions of the southwest—notably, the lower Colorado River—are already in imminent danger of falling short of their growing populations' need for water (10, 11). Meanwhile, long-term warming driven by global increases in atmospheric greenhouse gas concentrations are expected to reduce water availability in the region by as much as 20% (12). The ecological and economic stakes of protecting waterways and riparian areas in the arid western states are hence extremely high. Explicit valuation of the losses associated with tamarisk, which directly impacts the functioning of western riparian systems and the delivery of water throughout the region, is an important step to guiding management action as the invader continues to advance.

THE INTRODUCTION AND SPREAD OF TAMARISK

Thicket-forming members of the *Tamarix* species complex were intentionally introduced to North America from their native Eurasian range as ornamentals, windbreaks, and agents of erosion control in the mid-19th century (13–15). In the last 50 years,

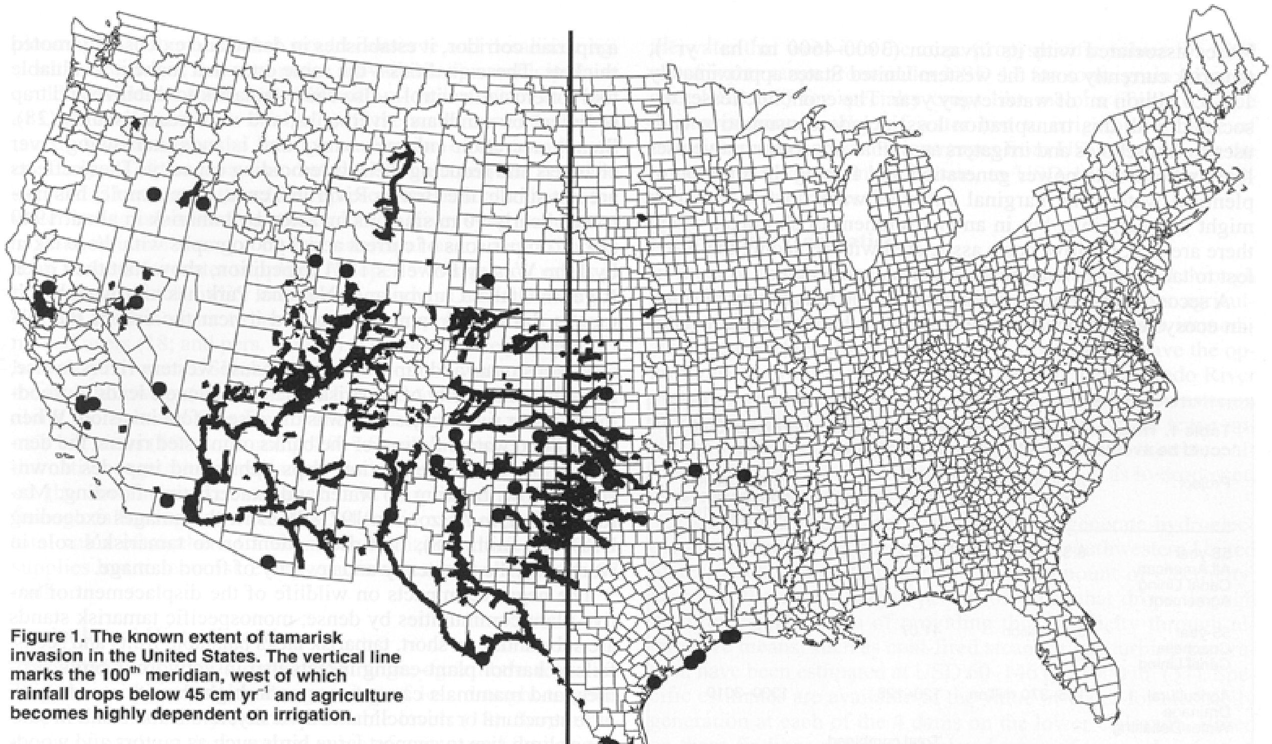


Figure 1. The known extent of tamarisk invasion in the United States. The vertical line marks the 100th meridian, west of which rainfall drops below 45 cm yr^{-1} and agriculture becomes highly dependent on irrigation.

tamarisk has spread rapidly into nearly every perennial drainage in the arid and semiarid regions of the western United States (Fig. 1). It has benefitted from human interference with the natural flood cycles of rivers, invading dammed waterways with particular speed (16). To date, it has replaced native riparian forest and scrub communities in 470 000–650 000 ha of riparian floodplain habitat in 23 states, from sea level to 2500 m (16, 17). It is especially pervasive in the dry, southwestern states of Arizona, New Mexico, west Texas, Nevada, Utah, and southern California, but is also widespread in the Rocky Mountain states, the western Plains states, and parts of Oregon and Idaho. While less information exists on its naturalized range outside of the United States, tamarisk is known to occur throughout large areas of northwestern Mexico (18).

Tamarisk possesses many classic weedy characteristics to which it owes its rapid spread and effective displacement of native vegetation. It produces tremendous numbers of seeds which germinate quickly in a wide range of conditions, and the resulting plants can grow rapidly, up to 4 cm day^{-1} (16, 19, 20). In the process, tamarisk plants consume tremendous quantities of water and draw salts up to the surface from deep in the soil. These salts, secreted on the invader's leaves, give rise to increasingly saline soils not tolerated by native riparian species, such as Goodding willow (*Salix gooddingii*) and Fremont cottonwood (*Populus fremontii*) (21). Tamarisk can tolerate both drought and flooding to degrees that native species cannot (22, 23). It can withstand submersion for up to 3 months, but it can also survive prolonged desiccation and is more able than native species to establish in areas with deep zones of permanent water availability (15). Fire may also be assisting the spread of tamarisk, both because the invader resprouts readily from belowground parts, and because the accumulation of its litter increases the probability of fire and salinizes the soil when fires do occur (24, 25).

At present, tamarisk continues to expand its range and may have spread as much as 200 000 ha during 1989–1999 (18). In particular, it has made recent advances into higher elevations in arid regions and into wetter areas such as central California and the Texas Gulf Coast. Long-term warming and drying trends are likely to further expand the potential range of the invader north, uphill, and into regions of higher rainfall (Zavaleta and Royval, unpubl. data).

THE IMPACTS OF TAMARISK ON ECOSYSTEM SERVICES

In the arid western states, municipalities, farmers, the hydropower industry, fishermen, and other recreationists all clamor for access to surface and groundwater. Tamarisk stands, with their dense and leafy canopies and rapid growth rates, consume water more rapidly than native vegetation, drawing down watertables, drying desert springs, and lowering river flow rates and lake levels (15, 20, 26). Nearly 20 studies of transpiration rates by tamarisk and native riparian species have been conducted (26). Transpiration rates vary with weather, stand density, and water availability, but under no condition has tamarisk been found to transpire less than native vegetation. On average, after accounting for possible returns of transpired water to the region, tamarisk stands consume 3000 to 4600 m^3 ha^{-1} yr^{-1} more water than the native vegetation that they replace. Marginal water losses to tamarisk are hence comparable to annual precipitation totals, which remain below 4500 m^3 ha^{-1} yr^{-1} throughout the invaded region and below 2000 m^3 ha^{-1} yr^{-1} in much of it.

Tamarisk also increases the area covered by riparian vegetation in two ways. It reaches deeper for groundwater farther from waterways, and it builds up banks and islands, which it then colonizes, through sediment capture (27). Tamarisk invasion therefore represents not only a ha-per-ha replacement of less thirsty vegetation by a species that consumes more water; it also increases the extent of heavily vegetated (and therefore heavily transpiring) areas near waterways. Given estimates of tamarisk's current areal extent (470 000–650 000 ha) and marginal water losses associated with its invasion (3000-4600 m^3 ha^{-1} yr^{-1}), tamarisk currently costs the western United States approximately 1.4–3.0 billion m^3 of water every year. The economic losses associated with this transpiration loss include consumptive end-uses by households and irrigators as well as nonconsumptive uses like hydroelectric power generation and fishing. In a region of plentiful water, the marginal value of water lost to tamarisk might be negligible, but in an environment of shortage, where there are real, positive costs associated with replacing the water lost to tamarisk, its marginal value is considerable.

A second major impact of tamarisk on the functioning of riparian ecosystems concerns flood control. When tamarisk invades a riparian corridor, it establishes in dense and extensively rooted thickets. These qualities—the same ones that make it a valuable tool for erosion control—also cause tamarisk to stabilize and trap sediment on sandbars, riverbanks, and midstream islands (28). Steady accretion enlarges banks and islands, narrowing river channels and reducing their waterholding capacity. These effects are not subtle: the Brazos River in Texas, for example, has narrowed nearly 90 m since its invasion by tamarisk in about 1940 (27). Comparisons of current aerial photographs with those taken by John Wesley Powell's 1871 expedition, show that the Green River in Utah's Canyonlands National Park has narrowed by almost a third since tamarisk reached it near the end of the 19th century (29).

When storms and rapid snowmelt cause western rivers to rise, the reduced capacity of tamarisk-infested channels leads to flooding at lower river stages than was the case before invasion. When these flood waters flow over the banks of infested rivers, the density of the exotic vegetation traps debris and impedes downstream flow, backing up water and exacerbating flooding. Major flooding in Arizona in 1977–1979, with damages exceeding USD 150 mill. (18), first drew attention to tamarisk's role in worsening the frequency and severity of flood damage.

The negative impacts on wildlife of the displacement of native plant communities by dense, monospecific tamarisk stands are substantial. In short, tamarisk lacks palatable fruits and seeds, fails to harbor plant-eating insects that insectivorous birds, reptiles, and mammals can eat, occurs in high-density stands with little structural or microclimatic diversity, and is too small in stature or limb size to support large birds such as raptors and woodpeckers (30). In the southwestern deserts, tamarisk dries up springs and oases—necessary habitat and water sources for wildlife ranging from bighorn sheep and quail to endangered pupfishes (9, 20, 30). Losses of insect diversity and abundance associated with tamarisk also compromise pollinator services, crucial and economically valuable inputs to crop production (31). Despite controversy over the importance of tamarisk stands to the endangered Southwest willow flycatcher (*Empidonax trailii extimus*), available evidence indicates that native riparian vegetation provides superior habitat to the songbird (32–34). Protecting flycatcher populations during restoration from tamarisk to native stands will, however, require careful planning.

Table 1. Three planned Metropolitan Water District projects that could be avoided through *Tamarisk* eradication.

Project	Annual water yield (m^3)	Cost (USD 1000 m^{-3})	Total cost over 55-year lifespan (USD mill. 1998)
55-year All American Canal Lining Agreement	8.35 million	25.73	118.1
55-year Coachella Canal Lining	3.17 million	41.07	71.5
Agricultural Drainage Water Desalting	185–370 million	120–128	1300–3010
		Total combined costs:	1180–3200

Source: J. Matusak (Metropolitan Water District), unpublished

Table 2. Annual values of irrigation water lost to *Tamarix* by subregion

	Water value[1] (USD 1998 1000 m^{-3})		Total annual losses (USD 1998)	
	low[2]	high[3]	low[4]	high[5]
Subregion Arizona	11.80	698	819 000	20 178 000
Texas High Plains	43.00	159	28 476 000	72 548 000
Oklahoma[6]	43.00	159	3 290 000	11 325 000
Rocky Mountains	12.70	24.30	16 000	43 000
Ogallala region (Kansas, South Dakota, eastern Colorado)	52.50	59.10	2 835 000	7 971 000
Idaho and Wyoming	13.10	19.70	42 000	97 000
New Mexico, Texas[6], Great Basin	11.80	11.80	3 170 000	9 133 000

1 All values are adjusted to 1998 dollars using the general U. S. CPI. Crop CPI values were not selected because farm input prices reflect price changes in a number of categories. The value of a unit of water is not expected to change in response to *Tamarix* control because the proportional change in water supply due to eradication would be small.
2,3 Lowest and highest reported values, respectively, for 1000 m^3 of water in the specified region. Per-unit economic values of water reflect both crop type and weather.
4 Low estimates of annual lost irrigation water value for the specified region are calculated using only the lowest unit water value reported for each region, and using the low estimates of *Tamarix* areal extent and water use.
5 High estimates for each region are calculated using a weighted average of 80% low per-unit water value and 20% high per-unit water value, reflecting an approximate distribution of crops typically grown in the western United States (36). The values reported here were calculated using the higher estimate of *Tamarix* areal extent and the mean value of its water use reported across all studies.
6 No values were available in the literature for Oklahoma, which is assumed to share agricultural characteristics of the Texas High Plains; and for the arid Great Basin and Chihuahuan desert regions, which are conservatively assumed to share Arizona's lowest water value for all crops.

THE COSTS OF TOLERATING TAMARISK

While techniques exist for the assigning of value to nonmarket ecosystem services such as wildlife protection and aesthetic value, a conservative assessment of recoverable economic damage by tamarisk must begin with market goods and services. I used current, measurable market values to estimate tamarisk's economic impacts on water supplies for municipalities, farmers, and hydropower generation, and on flood control as a conservative first approximation of the invader's regional economic impacts.

Municipal Water Losses

Two urban areas in the region affected by tamarisk are actively pursuing, at significant cost, schemes to augment their water supplies: southern California's Metropolitan Water District (including Los Angeles) and the four major cities of central Arizona (Phoenix, Tucson, Scottsdale, and Mesa) (18). In each case, additional water generated by replacing tamarisk with native vegetation would help to meet municipal water demands.

An estimated 260–570 mill. m^3 of water that otherwise would be available to southern California are lost every year through transpiration by tamarisk on the Colorado River. Meanwhile, the Metropolitan Water District (MWD) has had to turn to purchasing extra water from farmers with priority water rights and to long-term, costly schemes to augment its water supplies. Three planned MWD projects that would conserve and desalinate agricultural water in order to make it available for municipal use could provide the same 260–570 mill. m^3 yr^{-1} of water at a cost of USD 22–58 mill. yr^{-1} (Table 1). If the water currently lost to tamarisk were recovered through eradication of the invader, all or nearly all of the costs associated with these projects could be avoided. These costs therefore represent the annual value of the water lost to tamarisk from the Colorado River system alone.

Near Arizona's major cities, municipal users also compete with farmers for water supplies. An open water market exists in the area in which utility companies purchase and fallow agricultural land in order to increase water supplies to sell to municipal users (18; and pers. comm.). The mean price paid for this land is just over USD 120 per 1000 m^3 of water recovered through fallowing (18). Tamarisk has infested 13 000–17 000 ha along the Salt and Gila Rivers and their tributaries near Arizona's big cities (18), consuming 4.0–7.9 mill. m^3 more water than the native vegetation it replaced. The value of this water, based on the current market value of land purchased to replace it through fallowing is, hence, USD 4.9–9.6 mill. each year. The total value of southern California and Arizona municipal water supplies lost to tamarisk every year is an estimated USD 26–67 million.

Agricultural Water Losses

Throughout tamarisk's naturalized range, agriculture relies on irrigation either to allow the growing of less drought-tolerant crops or to increase yields to profitable levels (18). Several reviews of work on the marginal value of water used for agricultural irrigation provide region- and crop-specific estimates for much of the tamarisk's range (35–38). Most of these studies subtract all nonwater inputs to crop production from the total revenue generated by a crop, then treat the residual as the value of the water that went into the crop. Crop-specific values for 1000 m^3 of water range from under USD 17 for some grain crops to over USD 650 for specialty crops like melons (Table 2). The estimated annual value of water lost to irrigators because of tamarisk's water consumption ranges from USD 38 mill., for the lowest water values in each state, to USD 120 mill. for crop-weighted water values (36).

Hydropower Generation

In most of the western United States, water recovered through tamarisk eradication would most likely be removed for agricultural end-uses. Since this water would be withdrawn immediately from surface flows for irrigation, it would not have the opportunity to provide instream use values. In the Colorado River system, however, the highest-valued end use is by downstream municipal users. The optimal course of action would leave upstream water generated by tamarisk eradication in the river, allowing it to generate instream flow values, such as hydropower, as it travels to southern California.

Four dams on the lower Colorado River generate hydroelectric power to growing energy markets in the southwestern United States. Each is able to generate a given amount of electricity, based on the dam's height, per m^3 of water that drops through its turbines. The costs of providing this electricity through alternative means, such as coal-fired steam or gas turbine generation, have been estimated at USD 60–146 per 1000 m^3 (37). Specific estimates are available of the value of water for electricity generation at each of the 4 dams on the lower Colorado. Based on these findings and the calculated areas of tamarisk infestion above each of the dams, the value of hydropower generation lost to the invader is approximately USD 16–44 mill. yr^{-1} (Table 3).

Flood Control Losses

In 1989, a consulting firm employed an Army Corps of Engineers hydrological flow model to simluate the effects of tamarisk on flood events in 2 major rivers of the western United States (18). They extrapolated their results to other invaded areas and developed economic damage estimates associated with the presence of tamarisk. Their figures represent at best a rough estimate of the flood control costs associated with tolerating tamarisk. Nevertheless, their estimates are conservative for at least three reasons. First, they considered 90%, not 100%, removal of tamarisk and considered damages based on the 1989, not the larger 1999 areal extent of the invader along rivers. Second, their study ignored the effect of long-term channel narrowing by tamarisk and considered only the increased resistance of dense tamarisk thickets to overbank flow. Channel narrowing arguably has the greatest impact on flood damages because by substantially reducing channel capacity, it greatly increases the likelihood that overbank flow will occur at all. Finally, economic flood damage estimates reflect the amount of urban, agricultural, and other development that exists in river floodplains. With rapid population expansion, development within the boundaries of potential flood areas is likely to have increased since their 1989 study. Converting these results to 1998 USD yields an estimate of the average impact of tamarisk on flood damages of USD 52 mill. yr^{-1}.

Table 3. Annual value of hydroelectric power generation lost to *Tamarisk* on the Colorado River.

Dam	Value of water (USD 1998 1000 m^{-3})	Estimated upstream invaded area (ha)	Annual lost value (USD 1998)
Glen Canyon	19.20	40 220– 79 450	2 357 000– 6 985 000
Hoover	36.70	50 450– 92 780	5 634 000–15 540 000
Parker	21.10	57 670–102 290	3 701 000– 9 845 000
Davis	24.20	57 670–102 290	4 245 000–11 294 000
		Total	15 937 000-43 664 000

Table 4. Summary of annual values lost to *Tamarix* in the western United States (USD mill. 1998).

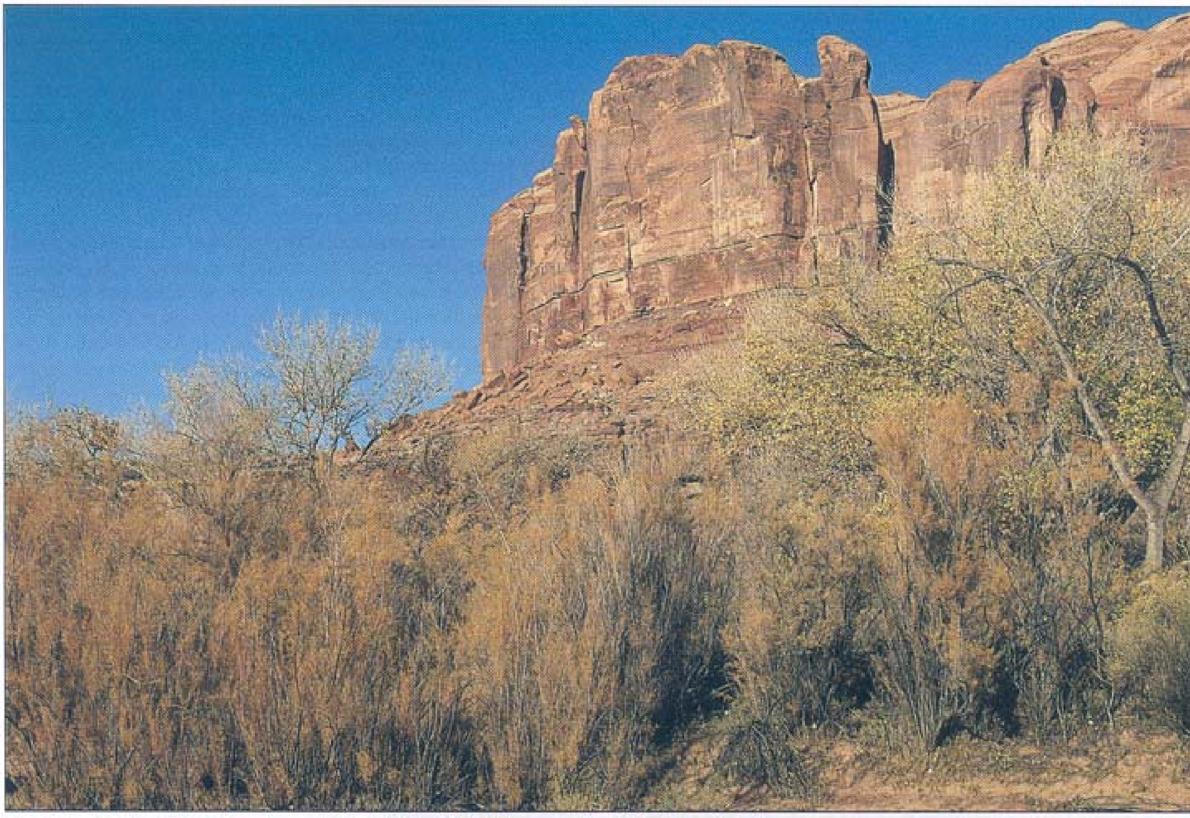
Ecosystem service	low	high
Irrigation water	38.6	121
Municipal water	26.3	67.8
Hydropower (Colorado River)	15.9	43.7
Flood control	52.0	52.0
Total	133	285

Table 5. Estimated costs of comprehensive eradication and restoration.

Activity	Cost (USD 1998 ha^{-1})
Site evaluation (year 1)	124
Root plowing (year 2)	145
Hand application of herbicide (years 3–6)	1540
Revegetation (years 7–14)	4940 [reported range: 165-8 000]
Monitoring (years 15–20)	675
Total	7420

COMPARING THE COSTS AND BENEFITS OF RESTORATION

In total, the presence of tamarisk in the western United States will cost an estimated annual USD 127–291 mill. in lost ecosystem services (Table 4). This loss amounts to USD 284–447 ha^{-1} of land currently infested by the invader. These represent the benefits to be recovered by removing tamarisk from its current naturalized range and restoring native riparian communities in its place.



Tamarisk shedding foliage in autumn in Moab, Utah, USA. Its leaves will salinize the soil and increase the potential for wildfires. Photo: K. Bonine.

Highly successful tamarisk eradication and revegetation projects conducted on a local scale have ranged in cost from USD 500 ha^{-1} in central Texas, where post-planting care of the native species replacing tamarisk is unnecessary, to over USD 12 000 ha^{-1} in the most arid pockets of the southwest, where several years of watering of native transplants must take place to ensure their establishment (39). Tamarisk is a candidate for biocontrol with imported insects (34, 40), but until this approach has been more thoroughly tested it cannot be considered a substitute for the prevailing, conventional methods.

I evaluated the costs of controlling tamarisk and restoring native communities based on a comprehensive, 20-year program of planning, eradication, revegetation, and monitoring (Table 5). Initial site evaluation, which typically costs USD 75–125 ha^{-1} would guide the selection of native species to plant, minimizing the costs associated with revegetation failure (39). The actual removal of tamarisk through cutting and root plowing the following year would cost approximately USD 145 ha^{-1}. The hand application of relatively expensive, but environmentally safe, water-based herbicides to root stumps in years 3 to 6 would minimize the chances of resprouting and seed germination at an estimated cost of slightly over USD 1500 ha^{-1} (39).

While revegetation costs vary substantially, the mean cost per ha is likely to be low because economies of scale drastically reduce costs (18); initial site evaluation will guide selection of the most suitable species for each location; some areas such as the near-bank portions of tamarisk-narrowed rivers will not be revegetated at all; and recent, successful programs in arid areas have been able to revegetate for well under USD 5000 (41). I computed a mean value of just under USD 5000 ha^{-1} over years 7 to 14 for greenhouse rearing, transplanting, and watering of native trees and shrubs. Finally, monitoring the course of revegetation and checking for recolonization by tamarisk typically add 10% to a project's costs (39), approximately USD 680 ha^{-1} in this case.

The 20-year total cost of this program is USD 7400 ha^{-1}, approximately USD 2400 more than the most successful eradication campaign currently underway in the region (41). At a discount rate of 0%, these control costs would be offset by economic benefits within 17–26 years of the invader's initial removal (Table 6). Since initial removal occurs at the beginning of the restoration process, benefits essentially keep pace with

Table 6. Number of years required to recover the costs of controlling *Tamarix* throughout the western United States.

Discount rate (%)	Number of years[1]
0	17–26
1	17–28
2	17–29
3	17–31
4	16–34
5	16–39
6	16–50

[1] The range in values reflects the range in estimates of the annual benefits that would be associated with tamarisk removal. Because control costs are incurred gradually over 20 years and benefits begin to accrue near the beginning of this period (tamarisk is removed in year 2), benefits recovered within the first 18 years would immediately offset control costs.

control costs throughout the range of estimated annual benefit values (USD 248–447 ha^{-1}). At discount rates of 1–6%, benefits keep pace with costs at the high end of the range of benefit estimates. If benefits fall in the low range of estimates, the number of years required to recover costs is sensitive to discount rate and ranges from 28 to 51 years (8 to 31 years after the completion of eradication and revegetation). After control and restoration costs have been offset by the accummulating benefits of restored riparian ecosystems in the region, these benefits would continue to accrue indefinitely.

IMPLICATIONS

While further research and planning would have to precede the adoption of a program of *Tamarix* eradication in the United States, this study illustrates the likelihood that such a course of action would have clear benefits, economically as well as socially and ecologically. Additional studies of this kind may help to establish that the worsening global problem of biological invasions is likely to be accompanied by serious—and quantifiable—economic damage to the services that natural ecosystems provide.

Economics cannot be the sole measure of the worth of a species, nor the single tool used to guide decisions about ecosystem management. However, when social and ecological arguments already militate in favor of a particular action, the finding that economics also favor it makes a compelling case to pursue it. The findings presented here can be considered only preliminary and incomplete estimates of the costs and benefits that controlling *Tamarix* would incur. The execution of an eradication and restoration campaign would require a detailed partitioning of benefits and costs, perhaps to groups whose responsibility to contribute to control costs may be unclear such as farmers and floodplain residents. The practical challenges of eliminating *Tamarix* in a coordinated way from throughout its naturalized range (which includes northern Mexico) while preventing recolonization are not trivial.

Conversely, the economic importance of many potential benefits of tamarisk eradication and restoration, from decreased water salinity and groundwater pumping costs to improved recreational revenues, crop pollination, and support for native wildlife, have not yet been evaluated. These values would only strengthen the economic argument in favor of control. The results presented here, hence, strongly suggest that an economic motivation can be added to social and ecological arguments for aggressively eliminating *Tamarix* from the western United States and restoring the native riparian forests and shrublands that it has displaced over the last century.

References and Notes

1. Daily, G.C. (ed.). 1997. *Nature's Services: Societal Dependence on Natural Ecosystems*. Island Press, Washington, USA.
2. Costanza, R., d'Arge, R., deGroot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P. and van den Belt, M. 1997. The value of the world's ecosystem services and natural capital. *Nature 387*, 253–260.
3. van Wilgen, B.W., Cowling, R.M. and Burgers, C.J. 1996. Valuation of ecosystem services: a case study from South African fynbos ecosystems. *BioScience 46*, 184–189.
4. Pimentel, D., Wilson, C., McCullum, C., Huang, R., Dwen, P., Flack, J., Tran, Q., Saltman, T. and Cliff, B. 1997. Economic and environmental benefits of biodiversity. *Bioscience 47*, 747–757.
5. Simberloff, D., Schmitz, D.C. and Brown, T.C. 1997. *Strangers in Paradise: Impact and Management of Nonindigenous Species in Florida*. Island Press, Washington, DC, USA.
6. U.S. Bureau of Reclamation. 1995. *Vegetation Management Study, Lower Colorado River: Phase II Final Report*. Bureau of Reclamation, Lower Colorado Region, Boulder City, NV, USA.
7. U.S. Congress, Office of Technology Assessment. 1993. *Harmful Non-Indigenous Species in the United States*. U. S. Government Printing Office, Washington, DC, USA.
8. Center of the American West, University of Colorado at Boulder. 1997. *Atlas of the New West*. W.W. Norton & Company, New York, USA.
9. Neill, W.M. 1983. *The Tamarisk Invasion of Desert Riparian Areas*. Desert Protective Council, Inc., Spring Valley, CA, USA.
10. Morrison, J.I. 1996. *The Sustainable Use of Water in the Lower Colorado River Basin*. The Pacific Institute and the Global Water Policy Project, Oakland, CA, USA.
11. Waggoner, P.E. and Schefter, J. 1990. Future water use in the present climate. In: *Climate Change and US Water Resources*. Wiley Series in Climate and the Biosphere. Waggoner, P.E. (ed.). Wiley & Sons, New York, pp. 19–40.
12. Nash, L.L. and Gleick, P.H. 1991. Sensitivity of streamflow in the Colorado Basin to climatic changes. *J. Hydrol. 125*, 221–241.
13. Baum, B.R. 1978. *The Genus* Tamarix. Israel Academy of Sciences and Humanities, Jerusalem, Israel.
14. Walker, L.R. and Smith, S.D. 1997. Impacts of invasive plants on community and ecosystem properties. In: *Assessment and Management of Plant Invasions*. Springer Series on Environmental Management Luken, J.O. and Thieret, J.W (eds). Springer, New York, USA. pp. 69–86.
15. Brock, J.H. 1994. *Tamarix* spp. (Salt Cedar), an invasive exotic woody plant in arid and semi-arid riparian habitats of western USA. In: *Ecology and Management of Invasive Riverside Plants*. Landscape Ecology Series. deWaal, L.C., Child, L.E., Wade, P.M. and Brock, J.H. (eds). John Wiley & Sons, Chichester, England. pp. 27–43.
16. Everitt, B.L. 1980. Ecology of saltcedar: a plea for research. *Environ. Geol. 3*, 77–84.
17. Robinson, T.W. 1965. *Introduction, Spread, and Areal Extent of Saltcedar (*Tamarix*) in the Western States*. US Geological Survey, Washington, DC, USA.
18. Great Western Research. 1989. *Economic Analysis of Harmful and Beneficial Aspects of Saltcedar*. Bureau of Reclamation, Mesa, AZ, USA.
19. Warren, D.K. and Turner, R.M. 1975. Saltcedar seed production, seedling establishment, and response to inundation. *Arizona Acad. Sci. 10*, 131–144.
20. Loope, L.L., Sanchez, P.G., Tarr, P.W., Loope, W.L. and Anderson, R.L. 1988. Biological invasions of arid land reserves. *Biol. Conserv. 44*, 95–118.
21. Shafroth, P.B., Friedman, J.M. and Ischinger, L.S. 1995. Effects of salinity on establishment of *Populus fremontii* (cottonwood) and *Tamarix ramosissima* (saltcedar) in southwestern United States. *Great Basin Natural. 55*, 58–65.
22. Cleverly, J.R., Smith, S.D., Sala, A. and Devitt, D.A. 1997. Invasive capacity of *Tamarix ramosissima* in a Mojave Desert floodplain: the role of drought. *Oecologia 111*, 12–18.
23. Busch, D.E. and Smith, S.D. 1995. Mechanisms associated with decline of woody species in riparian ecosystems of the southwestern U.S. *Ecol. Monogr. 65*, 347–370.
24. Wiesenborn, W.D. 1996. Saltcedar impacts on salinity, water, fire frequency, and flooding. In: *Proc. Saltcedar Management Workshop*. Rancho Mirage, CA, USA pp. 9–12.
25. Busch, D.E. and Smith, S.D. 1993. Effects of fire on water and salinity relations of riparian woody taxa. *Oecologia 94*, 186–194.
26. Johns, E.L. 1990. *Vegetation Management Study, Lower Colorado River: Appendix Water Use of Naturally Occurring Vegetation*. Bureau of Reclamation, Denver, CO USA.
27. Blackburn, W.H., Knight, R.W. and Schuster, J.L. 1982. Saltcedar influence on sedimentation in the Brazos River. *J. Soil Water Conserv. 37*, 298–301.
28. Graf, W.L. 1980. Riparian management: a flood control perspective. *J. Soil Water Conserv. 35*, 158–161.
29. Graf, W.L. 1978. Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region. *Geol. Soc. Am. Bull. 89*, 1491–1501.
30. DeLoach, J. 1997. Saltcedar; ecological interactions and potential effects of biological control. In: *Woody Plant Wetland Workshop*, Grand Junction, CO, USA.
31. Nabhan, G.P. and Buchmann, S.L. 1997. Services provided by pollinators. In: *Nature's Services: Societal Dependence on Natural Ecosystems*. Daily, G.C. (ed.). Island Press, Washington, USA, pp. 133–150.
32. Brown, B.T. and Trosset, M.W. 1989. Nesting-habitat relationships of riparian birds along the Colorado River in Grand Canyon, Arizona. *Southwestern Natural. 34*, 260–270.
33. Yong, W. and Finch, D.M. 1997. Migration of the willow flycatcher along the Middle Rio Grande. *Wilson Bull. 109*, 253–268.
34. DeLoach, C.J. 1997. Biological control of weeds in the United States and Canada. In: *Assessment and Management of Plant Invasions*. Luken, J.O. and Thieret, J.W. (eds). Springer, New York, pp. 172–194.
35. Colby, B.G. 1989. Estimating the value of water in alternative uses. *Nat. Res. J. 29*, 511–527.
36. Colby, B.G. 1989. The economic value of instream flows—can instream values compete in the market for water rights? In: *Instream Flow Protection in the West*. MacDonnell, L.J., Rice, T.A. and Shupe, S.J. (eds). Natural Resources Law Center, Boulder. pp. 87–102.
37. Gibbons, D.C. 1986. *The Economic Value of Water. Resources for the Future*, Washington, DC, USA.
38. Young, R.A. 1984. Local and regional economic impacts. In: *Water Scarcity: Impacts on Western Agriculture*. Englebert, E.A. and Schuering, A.F. (eds). University of California Press, Berkeley, pp. 244–272.
39. U.S. Bureau of Reclamation 1992. *Vegetation Management Study—Lower Colorado River, Phase I*. Bureau of Reclamation, Lower Colorado Region, Boulder City, NV USA.
40. DeLoach, J. 1997. Biological control of exotic saltcedar in western riparian areas. In: *Woody Plant Wetland Workshop*, Grand Junction, CO, USA.
41. Taylor, J.P. and McDaniel, K.C. 1998. Restoration of saltcedar infested flood plain on the Bosque del Apache National Wildlife Refuge. *Weed Technol. 12*, 345–352.

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