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Discussion Paper

# Integrating social-ecological outcomes into invasive species management: the *Tamarix* case

Eduardo González-Sargas[1], Patrick B. Shafroth[2], Francesc Baró[3]

1 Colorado State University, Department of Biology, 251 W Pitkin St., Fort Collins, CO 80521, USA
2 U.S. Geological Survey, Fort Collins Science Center, 2150 Centre Ave., Building C, Fort Collins, CO 80526, USA
3 Vrije Universiteit Brussel (VUB), Department of Geography and Department of Sociology, Pleinlaan 2, 1050 Brussels, Belgium
Corresponding author: Eduardo González-Sargas (eduglez@colostate.edu)

## Abstract

Incorporating societal considerations into decisions related to invasive species management is desirable, but can be challenging because it requires a solid understanding of the ecological functions and socio-cultural and economic benefits and values of the invaded environment before and after invasion. The ecosystem service (ES) concept was designed to facilitate such decision-making by establishing direct connections between ecosystem properties and human well-being, but its application in invasive species management has not been systematic. In this Discussion paper, we propose the adoption of the ES cascade model as a framework for understanding the environmental effects, costs and benefits associated with controlling an invasive shrub (*Tamarix* spp.) in riparian systems of the western United States. The cascade model has the advantage of explicitly dissecting social-ecological systems into five components: ecosystem structure and processes, ecological functions, ecosystem services, benefits and the economic and socio-cultural valuation of these services and benefits. The first two have received significant attention in the evaluation of *Tamarix* control effectiveness. The last three have long been implicitly acknowledged over decades of *Tamarix* management in the region, but have not been formally accounted for, which we believe would increase the effectiveness, accountability and transparency of management efforts.

**Key words:** Conceptual framework, ecosystem services, riparian systems, rivers, saltcedar, operationalisation, tamarisk

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## Introduction

Over the last two decades, the ecosystem service (ES, or ecosystem services - ESs) concept has emerged as a powerful tool to facilitate decision-making in environmental planning and natural resources management. The greatest contribution of the ES concept to decision-making is that it uncovers the linkages between ecosystem structure and functioning and the constituents of human well-being (Fisher et al. 2009). By explicitly acknowledging and documenting the dependence of humans on ecosystems (La Notte et al. 2017), the ES concept contributes to the increasingly popular concept of social-ecological systems, encompassing not only economic perspectives, but also other various facets of human-nature relationships such as health, social relations, indigenous and local knowledge and culture and perceptions (Anderies et al. 2004; Potschin-Young et al. 2018).

The ES concept has been employed by international organisations such as the IUCN (Neugarten et al. 2018), the European Commission (Maes et al. 2012; EU FP7 OpenNESS 2017), UNEP (UNEP 2014), and the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) to craft policy and management guidelines (Tengö et al. 2017; IPBES 2019). However, its widespread integration into practical decision-making contexts (i.e. "real-world" situations) has proven challenging (e.g. Rozas-Vasquez et al. (2019) for spatial planning) and has seen slower progress in some fields such as invasive species management. While the effects of invasive species on ESs have been extensively studied (Charles and Dukes 2007; Vilà and Hulme 2017; Rai and Singh 2020), the ES concept has been rarely used in the evaluation of outcomes of invasive species management (Funk et al. 2014; Schaffner et al. 2020). This is unfortunate considering the overall importance of socio-cultural values and perceptions in invasive species management and decision-making (Verbrugge et al. 2013). Using the ES concept would address questions related to the typically conflicting positive (services) and negative (disservices) effects of invasive species on socio-economic systems (Dickie et al. 2014) and would be particularly helpful to justify potential economic returns on investment for invasives' control (Funk et al. 2014; Hanley and Roberts 2019).

In this Discussion paper, we invite land managers and scientists to consider employing the ES concept to integrate social-ecological outcomes in the evaluation of control of invasive species. We frame our discussion around the case of invasive shrubs in the genus *Tamarix* (tamarisk, saltcedar) that have extensively invaded western U.S. river systems (Friedman et al. 2005; Nagler et al. 2011). To date, assessments of the effectiveness of *Tamarix* control have mainly focused on biophysical responses of invaded ecosystems (Goetz et al. 2024). We suggest that the 'ES cascade model' (or simply, the 'cascade model'; *sensu* Haines-Young and Potschin (2010)) could serve as a framework to integrate socio-economic aspects with these more traditional ecological assessments.

## Brief history of *Tamarix* invasion and management

The history of non-native *Tamarix* in North America reflects a dynamic interplay of ecosystem services and disservices that *Tamarix* provided to a changing society, as has been the case for many other invasive tree species worldwide (Dickie et al. 2014). *Tamarix* was initially introduced to North America in the 19th century for ornamental purposes. In the first half of the 20th century, *Tamarix* not only escaped cultivation, but was also intentionally planted along riversides and reservoir shorelines to control sediment erosion (Chew 2009). This facilitated its widespread invasion across the western United States (Robinson 1965; Friedman et al. 2005; Nagler et al. 2011).

Control of *Tamarix* did not become common management practice until the second half of the 20th century, when large amounts of local, regional and federal funds were allocated for this purpose. Beliefs that *Tamarix* consumed more water than native vegetation, coupled with the need to increase water yield in arid river systems was the main motivation for control efforts in the 1950s and 1960s ('water salvage', Stromberg et al. (2009) and references therein). Beginning in the 1970s, society's growing recognition of the importance of natural systems and their preservation triggered interest in assessing the value of *Tamarix* as a wildlife habitat (Anderson and Ohmart 1977) and determining its influence on fluvial geomorphologic processes (Everitt 1980). *Tamarix* control was then justified by alterations in ecosystem functions and other disservices that *Tamarix* was purported to cause, such as increased soil salinity, increased fire risk, degradation of cultural significance of riparian forests, replacement of species with higher suitability as livestock feed and, more recently, restricted recreational access to rivers (e.g. rafting, fishing, camping) (Di Tomaso 1998; Chew 2009; Hadley et al. 2018). Scientists and managers devoted considerable attention to evaluating the effectiveness of different control methods in terms of both compliance and ecological effects during these decades (Taylor and McDaniel 1998; O'Meara et al. 2010; Sher and Quigley 2013; González et al. 2017).

The difficulty of controlling the invasion through conventional chemical or mechanical methods prompted the development of a biocontrol programme that culminated in the release of a host-specific defoliating beetle (*Diorhabda*) at the beginning of the 21$^{st}$ century (DeLoach et al. 2003). Biocontrol has been generally successful in reducing *Tamarix* biomass and growth at the continental scale (Nagler et al. 2018). However, the release of the biocontrol agent was temporarily halted after the realisation that a bird species federally listed as endangered, the Southwestern Willow Flycatcher (*Empidonax traillii extimus*), used *Tamarix* habitat and could be negatively affected by the programme (Bean and Dudley 2018).

We believe the identification and valuation of ESs could help to provide information for decisions regarding potential management interventions in areas where *Tamarix* remains a significant component of the riparian plant community. Although biological control beetles have established along rivers across the American West, residual *Tamarix* populations still occur and are sometimes managed by using targeted chemical and mechanical control combined with active introduction of native vegetation. The presence of *Tamarix* is generally accepted within western riparian ecosystems (Raynor et al. 2017; Darrah and van Riper 2018). It has been recognised that *Tamarix* contributes to some ecological functions and ESs (Sogge et al. 2008; Sher and Quigley 2013; Bean and Dudley 2018) in the absence of comprehensive restoration of riparian systems that are degraded by multiple factors (Shafroth et al. 2008; Stella and Bendix 2019; Briggs and Osterkamp 2021). Nevertheless, no attempts have been made to quantify these ESs.

## The cascade model as framework to understand social-ecological systems

ES emerged as a concept in 1981 (Ehrlich and Ehrlich 1981) after early discussions by the Club of Rome in the 1970s (Haines-Young and Potschin 2010; Vermaat et al. 2013), but did not gain popularity until the Millennium Ecosystem Assessment (MEA 2005) used ESs to assess the effects of ecosystem degradation on human well-being. The widespread promotion of ESs into market and payment schemes (Gómez-Baggethun et al. 2010) triggered efforts for a better understanding of the ES delivery process and, hence, its quantification and valuation. The cascade model (Haines-Young and Potschin 2010) addressed this need as it formalised a theoretical pathway from ecosystem structure and functioning to human well-being including valuation of ESs. The model consists of a five-step sequence from identifying: 1) biophysical structure and processes and 2) ecological functions of ecosystems that give the 3) potential basis for human well-being (ESs) in terms of 4) realised gains to society (benefits) that can be 5) valued in economic and socio-cultural terms (Fig. 1).

The sequential nature of the cascade model helped to solve the problem of double counting ESs in valuation approaches, by clearly identifying "intermediate" or sup-

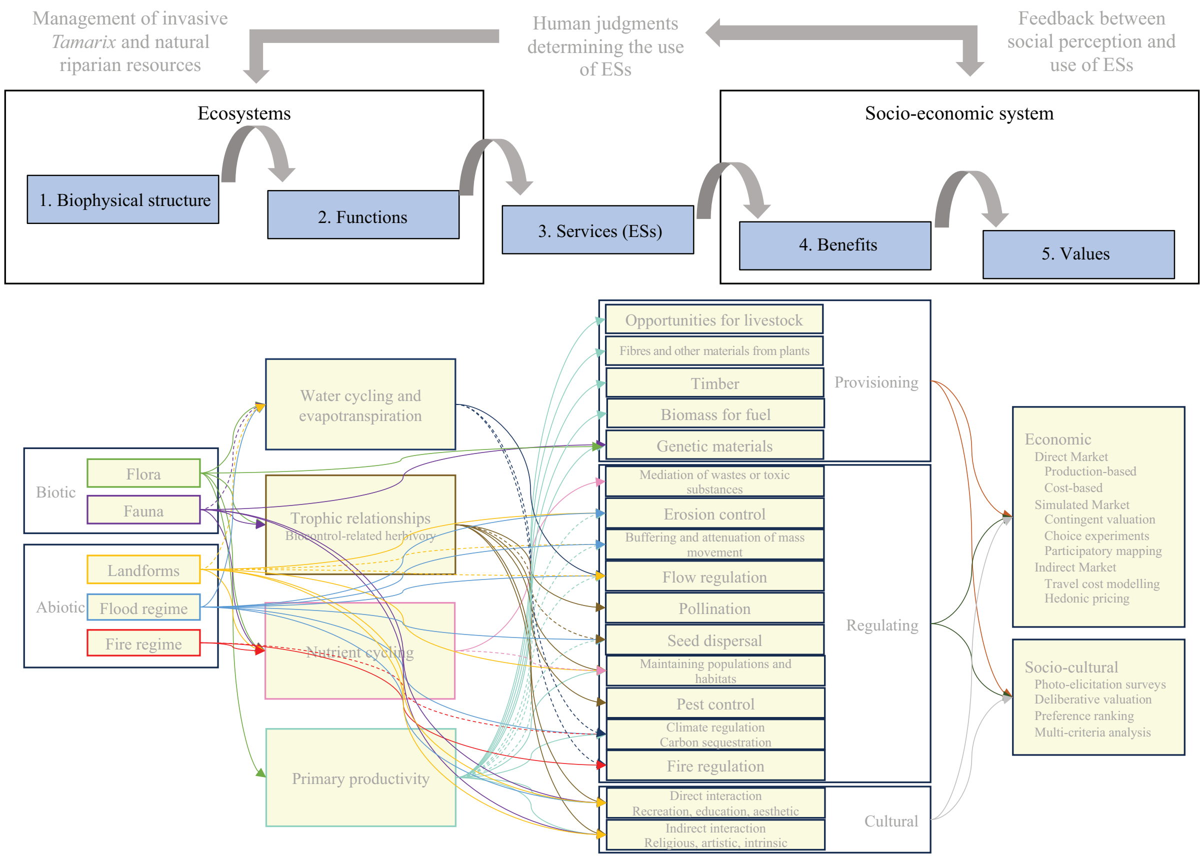


**Figure 1.** Ecosystem service cascade model of Haines-Young and Potschin (2010) adapted to represent a conceptual framework that integrates socio-economic factors into *Tamarix* control monitoring across U.S. Southwestern rivers. Blue boxes represent the five steps of the model. Processes were considered conjointly with functions (step 2) instead of as part of biophysical structure (step 1) as in the original design. Yellow boxes include elements that can be used to develop the model steps for the *Tamarix* case. For an in-depth development of biophysical structure indicators, see Goetz et al. (2024). We have combined the elements associated with ecosystem services (ESs) (step 3) and benefits (step 4), given that they overlap considerably and to simplify the figure. Arrows reflect linkages between ecosystem structure, functions, ecosystem services/benefits, and values, based on our best judgment. Suppl. material 1: appendix S1 provides a list of references studying the functions of water cycling and evapotranspiration and biocontrol-related herbivory (trophic relationships). Suppl. material 1: appendix S2 includes an extended list of ecosystem services and benefits provided by systems dominated by *Tamarix* and replacement vegetation such as native riparian forest and meadow vegetation that follows the CICES v.5.1 classification (Haines-Young and Potschin 2018). Suppl. material 1: appendix S3 describes economic valuation methods.

porting services (processes and functions in the model) that are necessary to produce final services or ESs in the model (Wallace 2007; Costanza 2008; De Groot et al. 2010; Fu et al. 2011). Primary productivity is an example of a supporting service. A second problem that the cascade model tried to address was the scarce knowledge of how ESs are produced, maintained and affected by changes in the structure and functioning of ecosystems (De Groot et al. 2010). By breaking down each step of the cascade into categories and sub-categories, explicit links between the ecological and socio-economic components of social-ecological systems can be created (Haines-Young and Potschin 2010; Vermaat et al. 2013; Vidal-Abarca et al. 2016). However, the model did not solve the problem of limited knowledge. There is a lack of empirical data for biophysical structure, processes and functions of ecosystems, which have typically been replaced by expert knowledge in ESs quantification (e.g. Riis et al. (2020) for riparian systems). The cascade model set up a conceptual framework necessary to address this limitation (Potschin and Haines-Young 2016; Potschin-Young et al. 2018). In the following section, we develop each step of the cascade model in more detail and discuss how the monitoring of *Tamarix* control outcomes has been following this conceptual framework. Additionally, we offer suggestions for implementing the framework in cases where it is not being followed.

## Integrating monitoring of *Tamarix* control outcomes within the ecosystem service cascade model

### Biophysical structure and processes of ecosystems

The first step of the cascade model is the assessment of the biophysical structure and processes of ecosystems. The biophysical structure of ecosystems includes the species composition, the structural and genetic diversity of flora and fauna and the description of the physical environment that supports life (Fig. 1). In the original definition of the cascade model of Haines-Young and Potschin (2010), processes are simply the precursor of functions and they are the result of the activities and dynamics of each ecosystem component without an explicit consideration of their interactions (e.g. vegetation growth and river channel formation in our case study) (see also De Groot et al. (2010)). The distinction between processes and functions is ambiguous in literature. However, this distinction does not have high relevance in the determination and valuation of ESs (Spangenberg et al. 2014; Baró et al. 2016; Czucz et al. 2020). For this reason, we only discussed here how biophysical structure has been considered in *Tamarix* control studies and treated processes and functions together in the next section. Thus, we followed the recommendation by Potschin-Young et al. (2018) for adapting the ES cascade model to our case study.

Goetz et al. (2024) exhaustively reviewed the outcomes of *Tamarix* control through monitoring using vote count and a meta-analysis of 96 studies published from 1990 to 2020. They provided a list of indicators and ecosystem components that have been monitored and noted an over-representation of vegetation monitoring and a paucity of studies examining the response of other biotic and abiotic ecosystem components, such as fauna, physicochemical properties of water and soil and geomorphic characteristics of fluvial landforms that riparian vegetation occupies. We agree with the conclusions of Goetz et al. (2024) that more research on effects of *Tamarix* control beyond the vegetation component is necessary and essential to provide information for the next steps of the cascade model and achieve an integrative evaluation of riparian social-ecological systems across the American West.

### Ecosystem functioning

Describing ecosystem functioning is the second step in the cascade model (Fig. 1). Ecosystem functions are the subset of interactions between the biological and physical structure and processes that govern the flow of matter and energy across ecosystems (Potschin and Haines-Young 2016; Raimundo et al. 2018; Hu et al. 2022). Recommendations for integrating ecosystem functioning into evaluation of management of natural resources, including invasive species management (e.g. International Standards for Ecological Restoration, Gann et al. (2019)), have not been as widely implemented as those related to biophysical structure (see Palmer et al. (2014) in the field of ecological restoration and González et al. (2015) for restoration of riparian vegetation specifically). Ecosystem functioning has been overlooked for multiple reasons. First, structural indicators are usually sufficient to evaluate compliance of management projects, which is often the only goal of monitoring (Matzek 2018). Second, there is a tendency to remain at the "structural phase" of evaluation because of the common belief that, if the biophysical structure is restored, recovery of processes and functions will follow (the 'Field of Dreams' hypothesis; see Palmer et al. (1997) and Suding (2011)). Finally, ecological functions are harder to conceptualise and monitor, despite efforts to simplify their quantification (e.g. Meyer et al. (2015)). Advances in functional ecology, such as the emergence and application of functional traits and functional diversity to understand ecosystem dynamics, can help to better characterise ecosystem functions (Díaz et al. 2007; Haines-Young and Potschin 2010; Funk et al. 2014). We are aware of only one study that used functional traits and functional diversity to assess the effectiveness of *Tamarix* control. Henry et al. (2023) used specific leaf area, plant height and seed mass to explore the response of the riparian plant community to *Tamarix* biocontrol, but their choice of traits was intended to reflect responses to environmental change ("response" traits) instead of to reflect effects on ecosystem functioning ("effect" traits). Effect traits are still underutilised in monitoring outcomes of management interventions (for example, in ecological restoration, see Loureiro et al. (2023)).

A variety of ecosystem functions have been evaluated in the context of *Tamarix* control; however, many of these functions have been relatively understudied. As increasing water yield (or 'water salvage') was a long-standing management goal for *Tamarix* control, the ecosystem function that has received most attention in the evaluation of *Tamarix* control outcomes is water cycling and evapotranspiration (Suppl. material 1: appendix S1). A growing body of literature has also been considering trophic relationships, directly or indirectly, via studies of the effects of the biocontrol beetle on *Tamarix* defoliation, dieback, plant physiology and cover and on other ecosystem components (biocontrol-related herbivory; Suppl. material 1: appendix S1). However, a paucity of studies reflecting ecosystem functions other than water cycling, evapotranspiration and biocontrol-related herbivory in *Tamarix* control evaluations has been explicitly acknowledged by the scientific community. For example, in a paper discussing the possible unintended consequences of the *Tamarix* biocontrol programme that was beginning to unfold by the time of its publication, Hultine et al. (2010) suggested that the decline in *Tamarix* may lead to reduced carbon storage and sequestration, at least in the short-term, a reduced carbon exchange in the ecosystem and a release of nitrogen through defoliation and downstream export following erosion of unstable landforms. They made a call to the scientific community to test these hypotheses. More than ten years later, however, little has been done to understand the changes in nutrient cycling that U.S. rivers have experienced after the biocontrol programme was put in place or as a result of *Tamarix* control efforts using other techniques (but see Uselman et al. (2011), Snyder et al. (2012) and Snyder and Scott (2020), in Suppl. material 1: appendix S1). At least two other studies have quantified the response of other ecosystem functions to *Tamarix* management. Kennedy et al. (2005) studied changes in aquatic food webs after mechanical clearing of *Tamarix* along a small creek in Nevada. Tredick et al. (2016) examined black bear scat to understand potential changes in bear diet after removal of *Tamarix* in Canyon de Chelly National Monument, Arizona.

A core function that remains overlooked and supports several ecosystem services is primary productivity (Fig. 1). In general, a more thorough understanding of ecological functions associated with *Tamarix* control evaluations could be achieved with more frequent implementation of the methodologies and experience developed in the evaluation of invasive species management and other types of restoration approaches in a riparian context. This includes assessing ecological functions other than water cycling and evapotranspiration, trophic relationships and nutrient cycling.

## Ecosystem services and benefits

ESs and benefits are two sides of the same coin. ESs reflect what the ecosystem provides to human welfare in biophysical terms, while benefits represent the contributions to aspects of well-being, such as health and safety. As ESs and benefits commonly overlap and their distinction is not critical for the valuation of the latter, we will concentrate here on the definition and description of ESs and will not distinguish between ESs and benefits in the next sections of the article. ESs are distinguished from functions (step 2) in that there is a direct or indirect use of an ecosystem resource or property by ESs beneficiaries, while functions represent the "capacity" or ability of the ecosystem to generate ESs (Czucz et al. 2020). There are several classifications of ESs (e.g. MEA (2005); The Economics of Ecosystems and Biodiversity – TEEB – developed by De Groot et al. (2010); to name two of the most popular). One of the most used is the Common International Classification of Ecosystem Services (CICES, Haines-Young and Potschin (2013)). In its last published version (v.5.1, Haines-Young and Potschin (2018)), 90 "classes" of ESs are detailed and grouped hierarchically into "groups", "divisions" and "sections". At the highest level (sections), services are classed into: "a) the provisioning of material and energy needs, b) regulation and maintenance of the environment for humans or c) the non-material characteristics of ecosystems that affect physical and mental states of people". These are three of the four main categories of ESs that the MEA (2005) originally referred to as "provisioning", "regulating" and "cultural", respectively. A consensus was reached to consider a fourth category "supporting" as intermediate services. Supporting services are integrated in the previous steps of the cascade model as ecosystem structure, processes and functions (Carpenter et al. 2009). This matching with the MEA framework ultimately reflects the intention of the CICES v.5.1 to cross-reference other classifications and facilitate international comparisons (Haines-Young and Potschin 2018).

The CICES v.5.1 classification particularly addressed the complexity in distinguishing between ESs and benefits (Haines-Young and Potschin 2018). The definition of each service is made up of two parts; one describing the biophysical output from the ecosystem (i.e., what the ecosystem delivers) and the other describing the contribution it makes to human well-being (i.e. how that output is used or enjoyed by people in terms of health, good social relations, security, basic needs etc.). While the CICES list is rather exhaustive, it is not practical to include all ESs in actual evaluations (Matzek 2018). Moreover, the contingent nature of the ES concept implies that establishing a universally applicable, final checklist of ecosystem-supported services is an unachievable (and unnecessary) objective. The list of services should be treated more as a "menu" of ESs and benefits themes, with steps one and two of the cascade model serving to examine how particular systems operate and provide information for the choice and quantification of ESs (Haines-Young and Potschin 2010; Potschin and Haines-Young 2016; Potschin-Young et al. 2018). We are unaware of studies evaluating the effectiveness of invasive riparian plant species management under the prism of an ES approach. However, assessments of ESs outcomes of river restoration have generated lists of ESs, based on project and system singularities (e.g. Acuña et al. (2013); Terrado et al. (2016); Vermaat et al. (2013); Gerner et al. (2018)).

We identified the ESs and associated benefits that riparian systems dominated by native species could provide compared to those dominated by *Tamarix*, as replacing *Tamarix* with native vegetation is one of the main goals of *Tamarix* control (Shafroth et al. 2008). We modified the list of ESs and benefits provided by riparian systems in Riis et al. (2020) for four types of dominant vegetation. We present an abbreviated version of the list in Fig. 1 and an annotated, extended version in Suppl. material 1: appendix S2. Dickie et al. (2014) also listed the ESs provided by *Tamarix*, but we chose to use the classification by Riis et al. (2020) because Dickie et al. (2014) did not use vegetation categories or compare between control/impact or before/after *Tamarix* control. Dickie et al. (2014) simply enumerated the ESs provided by *Tamarix* trees: visual amenity/ornamental (cultural ESs); timber, building materials, poles, posts, pulp, crafts and firewood and charcoal (provisioning ESs); habitat for wildlife, protection from predators (supporting ESs); erosion control, including windbreaks and temperature regulation via shading (regulating ESs).

Some have described ESs provided by riparian systems that were affected by *Tamarix* control (even though virtually none of them used the term "ecosystem service" in their assessments). Dykstra (2010) enumerated the multiple potential uses of *Tamarix* biomass obtained from removal efforts, including its transformation into composite wood, its use as biofuel in the form of wood pellets, bio oil and charcoal and for artistic creations ("Timber", "Biomass for fuel", "Indirect interaction – artistic", Fig. 1; Suppl. material 1: appendix S2). Bateman et al. (2012) assessed fire regulation by reduction of fuel loads ("Fire regulation", Fig. 1; Suppl. material 1: appendix S2). Wieting et al. (2023) and references therein showed that *Tamarix* removal promotes erosion ("Erosion control" and "Buffering and attenuation of mass movement", Fig. 1; Suppl. material 1: appendix S2) by reducing the stability of riverbanks and hydraulic roughness. This is typically perceived as a "disservice" by managers (Suppl. material 1: appendix S3). The ES that has received more attention in the context of *Tamarix* control assessments is "Maintaining populations and habitats" (Fig. 1; Suppl. material 1: appendix S2). Several publications have compared the suitability of *Tamarix*-dominated and *Tamarix*-restored sites as habitat for birds (e.g. Shanahan et al. (2011); Darrah and van Riper (2018); Mahoney et al. (2022)) and for herpetofauna (Bateman et al. 2012, 2015; Mosher and Bateman 2016). To our knowledge, there are no other publications that discuss and quantify the other ESs provided by forest patches and/or fluvial features dominated by *Tamarix* or where *Tamarix* has been controlled, listed in Fig. 1. We see this as an avenue for further research. A variety of methods for mapping and modelling the supply and demand of ESs were summarised by Harrison et al. (2018).

## Ecosystem service values

Once the ESs/benefits have been identified, the final step of the cascade model is to conduct economic and socio-cultural valuations of the ESs/benefits (Fig. 1). Values in general can be defined as the criteria by which we assign importance to something and valuation is the process of expressing or quantifying that value for a particular action or object (Farber et al. 2002; Potschin and Haines-Young 2016; IPBES 2019). Different valuation methods and techniques exist to give an economic, typically monetary value, to ESs/benefits. They are divided into direct market (e.g. production-based, cost-based), indirect market or "revealed preference" (e.g. travel cost modelling, hedonic pricing) and simulated market or "stated preference" (e.g. contingent valuation, choice experiments or conjoint analysis, participatory mapping) methods. We present definitions and hypothetical examples of their use in the *Tamarix* control context in Suppl. material 1: appendix S3. See Harrison et al. (2018) for an exhaustive list of ESs valuation methods.

Economic valuations are frequently used in cost-effectiveness, cost-benefit analyses and damage assessments. In the context of *Tamarix* control, cost-effectiveness and cost-benefit analyses could be used to combine monetary valuation of improvements on ecosystem status and ESs, respectively, with the cost of restoration actions (*sensu* Terrado et al. (2016)), while damage assessments value the loss of ESs (Unsworth and Petersen 1995; NPS 2005) and are more frequently used to investigate the negative effects of invasive species (Marbuah et al. 2014). Cost-effectiveness and cost-benefit analyses are key to assessing economic viability of management interventions and are particularly relevant for invasive species management (Hanley and Roberts 2019). Great Western Research (1989) analysed the economic, environmental and social effects of *Tamarix* control in the western United States and northern Mexico and estimated annual beneficial effects of $22 million and $40–62 million ($ are not inflation-corrected) for 50% and 90% control, respectively. Economic benefits outweighed adverse economic effects, but the study did not factor in the control programme costs (Barz et al. 2009). Zavaleta (2000) compared the monetary cost of water consumption and sediment retention by *Tamarix* with removal costs to conclude that the economic gains of potential eradication were considerable. The work by Zavaleta (2000) was frequently used to justify *Tamarix* control in the region, but her estimates of water consumption by *Tamarix* have been discredited by some (Stromberg et al. (2009) and references therein). McDaniel and Taylor (2003) estimated the cost of several removal methods and compared them in terms of their cost-effectiveness using *Tamarix* mortality as an indicator of project compliance. Hart et al. (2005) provided detailed costs of *Tamarix* removal during 1999–2003 along the Lower Pecos River (Texas), as well as estimates of percent mortality, changes in salinity of the river water, changes in water flow and estimates of water salvage. However, they did not calculate cost-effectiveness ratios. Barz et al. (2009) conducted more explicit cost-benefit analyses of *Tamarix* control efforts along the Middle Pecos River (New Mexico). They concluded that attempting *Tamarix* eradication was not worthwhile, based on consideration of different scenarios: direct costs of herbicide spraying, removal and revegetation; indirect costs of increased bank erosion and reservoir sediment accumulation following the eventual reduction of *Tamarix*; and benefits such as water salvage and associated groundwater recharge. O'Meara et al. (2010) and Bateman et al. (2012) provided detailed estimates of costs of different control methods, but they did not report cost-effectiveness or cost-benefit ratios. More recently, Albers et al. (2018) used bioeconomic modelling to consider the trade-off in terms of costs and positive effects on the ecosystem between controlling invasive *Tamarix* and restoring habitats with native species. All these examples show that, in the *Tamarix* control case, indirect and simulated market methods are underutilised and that the ES concept has been rarely, if ever, invoked. We believe a more systematic use of the ES cascade concept in cost-effectiveness, cost-benefit analyses and damage assessments would facilitate the comparison of results across studies.

Not all ESs and related benefits can be valued economically. While conceptual and methodological developments in economic valuation have aimed to cover a broad range of ESs, including cultural ESs, it can be argued that socio-cultural values (symbolic, aesthetic, ethical, relational etc.) cannot be fully captured by economic valuation techniques (Schröter et al. 2014). Socio-cultural values in invasive species management can be represented in more simple terms by the degree of satisfaction of different interested parties. For example, the aesthetic appreciation of the ecological condition of riparian zones by different groups of people has been evaluated with photo-elicitation surveys (e.g. Le Lay et al. (2013); Chin et al. (2014); Arsénio et al. (2020)). Other methods for understanding preferences or social values for ESs, such as deliberative valuation methods, preference ranking methods and multi-criteria analysis methods (Harrison et al. 2018), have been used in the evaluation of invasive species management planning more often than for monitoring outcomes (e.g. Liu et al. (2011); Japelj et al. (2019)). Perceptions and preferences of different interested parties are important because even the perceptions of success by environmentally-informed sectors of the population such as restoration practitioners do not necessarily align with abiotic and biotic parameters measured in the field (Jähnig et al. 2011) and public acceptance of outcomes is key for restoration success (Heldt et al. 2016). There is currently a dearth of studies that describe and quantify public opinion about *Tamarix* control and what society perceives as successful riparian ecosystem restoration along rivers in the American West. We are unaware of any studies of this kind. Only Sher et al. (2020) have explored how the human component (manager characteristics and decisions) may help explain *Tamarix* control outcomes in terms of vegetation structure and composition. Clark et al. (2019) previously showed the high degree of collaboration between restoration practitioners and scientists in *Tamarix* control contexts.

Finally, the value of ecosystems also has an ecological component that may be represented by fundamental properties of ecosystems, such as resilience, stability, health, complexity and integrity (De Groot et al. 2010). These are ecological values (or intrinsic values of nature) that cannot be expressed in economic or socio-cultural terms because they are not based on human preferences or principles, as they go beyond the anthropocentric approach of ESs (Kretsch and Stange 2016; Potschin and Haines-Young 2016). The quantification of these critical ecosystem properties and the subsequent integration into the evaluation of natural resources management, is still in its infancy and is subject to intense debate and study in academic circles (Jaunatre et al. 2013; Moreno-Mateos et al. 2020; Rohwer and Marris 2021; Dakos and Kéfi 2022; Ren and Coffman 2023). No efforts to value such fundamental ecological properties of systems responding to invasive species management, including *Tamarix*-dominated systems, have been made. Functional traits can be used to value resilience and stability of plant communities through measurable properties, such as functional redundancy, dispersion and response diversity (Laliberté et al. 2010). Other approaches to measure ecological values include ecological networks (Raimundo et al. 2018) and genome sequencing that incorporates eco-evolutionary processes in ecosystem recovery (Moreno-Mateos et al. 2020).

## The importance of determining a relevant spatial scale in the application of the cascade model for *Tamarix* control

An important consideration when assessing ESs and associated benefits in the context of *Tamarix* control is the definition of the smallest spatial scale at which ESs will be examined (i.e. the grain of the spatial scale, Turner et al. (1989)). For example, to quantify the contribution of river restoration to ES provision, Vermaat et al. (2013)

determined that the grain should be forest patches or fluvial features (e.g. sand or gravel bar, secondary channel, terrace) no larger than 100 $m^2$. Cassiano et al. (2013) also used a 100 $m^2$ resolution to assess the contribution of remnant riparian forest patches to water-related ESs in an agricultural landscape of south-eastern Brazil. Rather than determining an optimal value for the grain size, Riis et al. (2020) defined ESs provided by riparian systems using study units based on a classification of four different vegetation types. Determining a spatial scale that can discriminate between *Tamarix*- and native species-dominated units, possibly the forest patch or fluvial features (see, for example, Scott et al. (2022) for criteria to determine relevant geomorphic units), will be key for a fair socio-economic valuation of *Tamarix* control projects using an ES approach. It will also be critical to determine the ecosystem biophysical structure, processes and functions of riparian systems (pre- or post-*Tamarix* control) that constitute the first two steps of the cascade model.

Unfortunately, ESs provided by riparian corridors have usually been overlooked precisely because they have been quantified using an inappropriately large grain where ESs are assigned to general land-use categories, such as agricultural, urban and natural (e.g. Felipe-Lucía and Comín (2015)). Lumping natural areas into one category simplifies the heterogeneity of ecosystems and ignores important differences in dominant vegetation, which can strongly influence some attributes of ecosystem structure, such as biodiversity, that ultimately determine supporting functions and final ESs (e.g. wildlife use: *Tamarix*-dominated, native-dominated and mixed riparian forests can support different avian communities, Van Riper et al. (2008)). For example, the aesthetic appreciation (class service "3.1.1.1" in CICES v.5.1) of a mixed riparian forest dominated by healthy native cottonwoods (*Populus* spp.) may not be the same as the one provided by a defoliated *Tamarix* monoculture, even though they both may be designated as "natural forests" when compared to lands occupied by urban sprawl or agricultural fields. Evaluating the steps of the cascade model at the appropriate scales is important so that resource management actions are likewise implemented and monitored at the appropriate scale.

## Conclusion

The ES cascade model provides a research framework to define, quantify and value the services that ecosystems provide to society and we suggest it could be a valuable tool for integrating social-ecological outcomes more systematically in the evaluation of invasive species management, including *Tamarix* control. The ES concept (and, by extension, the cascade model) can be useful for measuring the socio-economic effects of management actions on human well-being as rigorously as the effects on biophysical structure have been measured thus far for *Tamarix* control (Goetz et al. 2024). This will ultimately increase effectiveness, accountability and transparency of both management and decision-making processes (Funk et al. 2014). However, the use of an ES approach and the linear structure of the cascade model do not necessarily imply that the final purpose of invasive species management must be to make an ESs/benefits valuation, especially in economic terms. This misconception has prevented more studies of ESs in restoration projects (i.e. fear of denaturalising restoration ecology's motivation to restore the Earth's natural capital, Matzek (2018)) and could risk having the same effect on invasive species management (see also Gómez-Baggethun et al. (2010) and Kallis et al. (2013) for criticisms of commodification of ESs). Each step of the cascade model is intrinsically valuable. The cascade model is intended to help conceptualise all the possible measures and indicators of ecosystem change and how they connect to each other, to provide an implementation framework and to identify knowledge gaps (Potschin-Young et al. 2018).

Implementation of the cascade model in the context of *Tamarix* control will require overcoming some challenges. For example, the current lack of information on responses to *Tamarix* control for most ecosystem components, processes and functions (Goetz et al. 2024) reduces the confidence of economic and socio-cultural valuations. In addition, the paucity of studies on ESs in the *Tamarix* control context indicates that more collaboration between biophysical and social scientists is needed. The comprehensive approach of the cascade model requires participation of multidisciplinary teams, which can be challenging to assemble depending on the capacity and resources of organisations involved. The good news is that there is evidence that land managers and scientists share information and communicate effectively when working on *Tamarix* control efforts (Clark et al. 2019).

With this paper, we hope to have provided clear guidelines and recommendations for how to achieve a comprehensive and holistic assessment of social-ecological outcomes of a prominent invasive species management case: *Tamarix* control in the American West. Further, we hope to stimulate discussion and consideration of applying the cascade model more broadly to invasive species management in a variety of contexts.

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### Author ORCIDs

Eduardo González-Sargas https://orcid.org/0000-0001-6485-0088

Patrick B. Shafroth https://orcid.org/0000-0002-6064-871X

Francesc Baró https://orcid.org/0000-0002-0145-6320

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## Supplementary material 1

### Supplementary data

Authors: Eduardo González-Sargas, Patrick B. Shafroth, Francesc Baró

Data type: docx

Explanation note: appendix S1 provides a list of references studying the functions of water cycling and evapotranspiration and biocontrol-related herbivory (trophic relationships). appendix S2 includes an extended list of ecosystem services and benefits provided by systems dominated by *Tamarix* and replacement vegetation such as native riparian forest and meadow vegetation that follows the CICES v.5.1 classification (Haines-Young and Potschin 2018). appendix S3 describes economic valuation methods.



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