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Global overview of ecosystem services provided by riparian vegetation

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Abstract

Fluvial riparian vegetation (RV) links fluvial and terrestrial ecosystems. It is under significant pressure from anthropogenic activities and therefore, management and restoration of RV is increasingly important worldwide. RV has been investigated from different perspectives, so knowledge on its structure and function is widely distributed. An important step forward is to convert existing knowledge into an overview easily accessible, e.g. for use in decision-making and management. We aim to provide an overview of ecosystem services provided by RV by adopting a structured approach to identify the ecosystem services, describe their characteristics and rank the importance of each service. We evaluate each service within four main riparian vegetation types adopting a global perspective to derive a broad concept. Subsequently, we introduce a guided framework for use in RV management based on our structured approach. We also identify knowledge gaps and evaluate the opportunities an ecosystem service approach offers to RV management.

Keywords: riparian management, streams, rivers, restoration,

Introduction

Riparian vegetation (RV) of fluvial systems is a complex of vegetation units along the river network that is functionally related to the other components of the fluvial system and surrounding area (Naiman et al. 2005). It is a hybrid and open ecotone: hybrid because it results from co-construction by human and natural processes, and open because the land alongside fluvial systems interacts with the river and associated processes (Dufour et al. 2019). The riparian zone is therefore characterized by high spatial and temporal variability mainly driven by bioclimatic, geomorphological and land-use conditions, which all change over time under natural and human influences. Riparian vegetation in the context of this paper is defined as the vegetation established in the riparian zone, i.e. the portion of terrestrial landscape from the high-water mark towards the upland where elevated water tables influence vegetation and soil (Naiman et al. 1993).

Riparian vegetation offers a variety of ecosystem services (ES). The concept of ES has become an important model for linking the functioning of ecosystems to human welfare, which is critical for a wide range of decision-making contexts (Fisher et al. 2009). Equally there is a plethora of definition of ES, but they are generally defined as the 'the benefits people obtain from ecosystems' or 'the contributions that ecosystems make to human well-being' after the Millennium Ecosystem Assessment (MEA 2005) and the Common International Classification of Ecosystem Services (CICES) report (Haines-Young and Potschin 2013), respectively. The ES concept, which introduced a new framework for analyzing social–ecological systems, has been advocated as a useful tool that provides a holistic and transparent assessment of impacts on human well-being (e.g. MEA 2005, Fischer et al. 2018), allowing decision-making to take proper account of the value of services from ecosystems (Haines-Young and Potschin 2009). Nevertheless, our ability to draw general conclusions remains limited due to sparse information, among others (Carpenter et al. 2009).

There is a consensus that there should be a distinction between 'final' ecosystem services and supporting or 'intermediate' services. This distinction is well illustrated in the ecosystem service cascade framework of Potschin and Haines-Young (2011) to highlight the position of the Common International Classification of

Ecosystem Services (CICES) classification (Figure 1). Here we focus on final ecosystem services, which are the outputs of ecosystems (whether natural, semi-natural or highly modified), that most directly affect the well-being of people (Haines-Young and Potschin 2013) (Figure 1).

Riparian vegetation has the capacity to deliver a disproportionately high amount of ecosystem services relative to their extent in the landscape (e.g. Sweeney and Newbold 2014) because of their ecotone characteristics and the ecological functions of RV (Capon et al. 2013). However, riparian vegetation is under high pressure from a range of anthropogenic activities, such as streamflow regulation by dams, pollution, land-use change, timber harvesting, water diversion, mining, and deforestation and from invasive species (e.g. Goodwin et al. 1997, Poff et al. 2011). In Europe, it has been estimated that 80% of natural riparian habitats has disappeared during the past 200 years (Naiman et al. 1993). The loss of riparian vegetation is generally immense in developed countries, for example, it has declined by 85–95% in California, Arizona, and New Mexico US, with most losses attributed to grazing (NRC 2002). Conversely, increasing effort is being undertaken to recover RV with varying success depending on the restoration (e.g., hydrogeomorphic, active plant introduction, floodplain conversion, invasive species and grazing control (González et al. 2015).

Riparian zones and their vegetation have been investigated from a range of perspectives covering multiple scientific and applied disciplines such as hydrology, biology, geography, remote sensing, management and restoration (e.g. González et al. 2015). Thus, knowledge on structure and function of riparian vegetation is distributed among a wide range of fields and disciplines (see Dufour et al. 2019). Several studies have documented how RV is key for specific ecosystem services, but few have attempted to document the full range of ecosystem services it provides. An important step forward is therefore to convert the existing knowledge into an overview more easily accessible and directly applicable for decision-making and management of riparian vegetation - a task undertaken in this article.

The general objective of this paper is to make an overview of ecosystem services provided by RV. More specifically, we adopt a structured approach to 1) identify the range of ecosystem services, 2) describe their characteristics, and 3) rank the importance of each service. We evaluate each service within four main riparian vegetation types within a global perspective to derive a broad concept. The key tasks in this paper were therefore, to firstly compile a comprehensive checklist of ecosystem services provided by RV, and secondly to synthesize the knowledge on these ES from the literature. Based on the structured approach we introduce a guided framework for use in riparian vegetation management. We also seek to identify key knowledge gaps and conclude the paper by evaluating the opportunities an ecosystem service approach offers to riparian vegetation management and restoration.

Study approach

In this paper, we used the groups of final ES described in Maes and colleagues (2016); provisioning, regulating and maintenance, and cultural ES. Provisioning services are the physical products directly obtained from the RV (e.g. timber, seeds and harvestable genes), regulating and maintenance services incorporate those that both directly (e.g. pollutant capture, carbon sequestration) and indirectly (e.g. regulation of decomposition, climate and hydrology) sustain environmental quality. Cultural services include tangible recreational uses (e.g. walking along a river) or less tangible benefits such as aesthetic, spiritual benefits and educational values. In fact, the most recent version of CICES (ver.5.1; Haines-Young and Potschin 2018) stresses that all ES have an inherent cultural value, but cultural services should be treated as an independent group, as was also undertaken in this review.

We used the CICES framework (CICES version 5.1; Haines-Young and Potschin 2018) to identify the ES provided by RV. We described the characteristic of each ES and included the underlying processes underpinning the ES delivery. We also described the goods and benefits provided by each ES. The characterization of each ES was derived from relevant scientific literature and complemented with empirical information. A search of the peer-reviewed literature was undertaken using the web of science employing the following combinations of search terms; riparian, vegetation, ecosystem services ('*' truncation to include similar versions of the same word such as singular/plural):

A key task of this paper was to rank the importance of each ES provided by RV based on the spatial and temporal extent of each ES – that is, how widespread is the ES provision and how often is it occurring. In order to acknowledge that the importance of each ES may vary substantially depending on the type of RV, we ranked the ES importance within each of four broad groupings of RV. The two criteria used for defining these four RV groups were the woodiness of the dominant vegetation (whether herbs/grass or woody-shrubs and trees) and local soil moisture (Figure 2). The importance of woody and non-woody RV for ES was discussed by Sweeney and Newbold (2014), with a differential provision of services depending on species woodiness. The importance of local soil moisture in structuring RV is well described (e.g. Nilsson and Svedmark 2002), and the selected types capture a representative gradient of conditions from permanently dry aerated soil to temporarily water-logged soil, to temporary wetlands with surface water till permanent riparian wetlands (Figure 2). The four extreme RV types along the two gradients are thus herbs/grass, dry forest, wet forest and riparian wetland (Figure 2). We have focused on four points in the two-dimensional space characterized by woodiness and local soil moisture, being aware of all intermediate occurring vegetation communities that may differ in ES provision. For example, fluvial geomorphology, hydrologic regime, width of the RV and climatic context all would be important but are not separately included in this framework.

We derived the relative importance for each provisioning, regulating and maintenance ES within each RV groups by using relevant scientific literature and expert opinion of the authors of this paper. For cultural ES we did not assign relative importance due to lack of data to support such assessment. A description of each ES is given below, while a synthesis of the ES characterization and ranking is given in Table 2.

Provisioning Services from Riparian Vegetation

Biomass

Biomass production in riparian areas for fuel for heating and green biogas production can be substantial. For example, in the Pacific North-West USA a range of riparian tree species in a lowland floodplain had a density production of 27,000 stems/ha in active floodplains and biomass as high as 540 t dry weight ha^{-1} over a 3-year period (Balian and Naiman 2005). Lower values of 54.4 t ha^{-1} (above- and below-ground biomass) have been reported under optimal conditions from a riparian forest in south-east Asia, dominated by *Populus euphratica* Oliv. (Thevs et al. 2012). Biomass production from shrubby vegetation such as certain willow species can be equally significant. Walczak and colleagues (2018) refer to figures from the UK, Poland and Sweden that range from 8-12 t ha^{-1} (fresh mass) and up to 20 t ha^{-1} under favorable conditions. Grassy biomass (residual) from managed riparian areas is also considered a provisioning service. Residual biomass from publicly managed floodplains of the Dutch Rhine tributaries was estimated at 370,953 t dry mass of biomass, of which 87% was grassy biomass (Bout et al. 2019). According to the authors, this was equivalent to an estimated 353 TJ of heat from the woody biomass and 15 million m^3 of green biogas from grassy biomass. Taller grasses such as *Phragmites* or *Arundo* are harvested in some areas for biomass (i.e. paludiculture; e.g. Brix et al. 2014) and their stems have been used for thatching and guide agricultural seedlings in many parts of the world.

Food outputs from riparian zone include herbs, berries (elderberries, blackberries, huckleberries and saskatoon) and to lesser extent mushrooms. Here again, these are alluded to in the literature but do not appear to be widely used, so their importance is limited at local scale and is therefore assessed to be low (see Table 1 and Table 2).

Genetic Resources

Genetic resources in RV include any genetic material, such as seeds and spores that could be harvested, wild plants used for crop breeding and genetic information from plant material used to extract genes.

Among the wild crop relatives in riparian vegetation, two climber species, grape vine and hops are used globally in the production of economically and culturally emblematic wine and beer, respectively. In both cases, wild populations are being used and are increasingly recognized for breeding commercial varieties of these species (Patzak et al 2010). In fact, *Vitis vinifera* L. ssp. *sylvestris* (Gmelin) Hegi, the European wild grape and ancestor of cultivated grapevine varieties (*V. vinifera* L. ssp. *vinifera*) is the sole wild grapevine species existing in Europe. Wild hops (*Humulus lupulus* L.) in riparian areas are potential new germplasms to expand the variability of genetic resources for hop breeding (Patzak et al. 2010).

As a complementary benefit, the genetic resources of crop-wild relatives also have the potential to improve disease resistance of cultivated species. In the case of wild grapevine, comparative inoculation studies with several grapevine pathogens revealed relatively high levels of resistance in some of the *Sylvestris* spp. accessions (Schröder et al. 2015). Similar application has been developed in the production of *Rubus* spp. berries. Wild *Rubus idaeus* germplasm from riparian areas could potentially be used against raspberry cane disease, which is amongst the most devastating problems for raspberry production (Hall et al. 2009).

The genetic pool of wild populations of riparian trees such as the black popular *Populus nigra* provides economically relevant outputs for the development of commercial native trees and for advanced, molecular breeding of these species. Wild populations of *P. nigra* are also being studied to obtain bioenergy from lignocellulosic feedstocks that has the potential to develop as a sustainable source of renewable energy (Allwrigth et al. 2016). Finally, seeds provided by riparian species are extremely important as genetic material for ex-situ conservation of the native genetic resources.

Overall, at the European scale the relative importance of this ecosystem service is reported as unknown (e.g. Vidal-Abarca et al. 2013).

Regulating and Maintenance services

Filtration of pollutants and chemical conditions of freshwaters

Riparian filtration services refer to the control of sediments, nutrients and pollutants inputs to adjacent water (Lowrance et al. 1984). A large body of scientific literature demonstrates the important role of riparian zones in regulating and improving water quality in streams and rivers (e.g. Jordan et al. 1993, Kuusemets et al. 2001) involving both physical and biological mechanisms. Physical processes comprise filtering and deposition of sediments and sediment-bound pollutants by root and stems such as pesticides (Naiman et al. 2005). As much as 75% of sediments transported from uplands to streams has been reported to be physically retained by RV (Cooper and Gilliam 1987). As recently reviewed by Feld and colleagues (2018), the key to efficient reduction of surface runoff of soil particles is to have grass strips acting as mechanical filters.

Riparian zones are also effective sinks for dissolved inorganic nitrogen (N) and phosphorus (P) from surrounding agricultural and/or urban areas (Naiman et al. 1997), providing thus a high potential in controlling eutrophication of waterbodies. One major mechanism for N removal is denitrification (Cooper and Gilliam 1987), occurring in riparian microsites with anaerobic conditions and decomposing organic substrate. Plant and microbial assimilative uptake also contribute significantly to inorganic N and P removal within land-water interface environments. Inorganic P is removed by soil adsorption and deposition of P-bounded sediments. The efficiency of inorganic N and P removal in riparian zones varies due to a number of hydro-geomorphological, chemical and biological factors (e.g. Groffman et al. 1992, Hefting et al. 2003) but denitrification rates up to 295 kg N ha^{-1} yr^{-1} have been measured in riparian zones (Lowrance et al. 1984). Sabater and colleagues (2003) reported that 5 to 30 % of nitrogen was removed by meter of buffer strip but with no differences between climate or vegetation type (trees vs herbaceous). In terms of inorganic P, values of 70% to 90% removals have been estimated in vegetated riparian buffer strips (Gascuel et al. 2010). Finally, pesticides and other contaminants can also be effectively removed in riparian zones by attachment to vegetation matter, biological assimilation and accumulation (sequestration), or by metabolic degradation processes (Aguiar et al. 2015).

Carbon sequestration

Carbon (C) sequestration refers to the capture and long-term storage of carbon that would otherwise be emitted to or remain in the atmosphere. Riparian forests and wetlands are important carbon sinks, with potential for long-term storage (e.g. Cierjacks et al. 2010, Suftin et al. 2016; Table 2). Given the importance of soil and plant C sequestration to ameliorate changes in atmospheric chemistry, conserving undisturbed riparian areas could be an effective strategy to enhance climate change mitigation in rivers (e.g. Lal 2005). Sequestration rates vary along environmental gradients and for different vegetation types (e.g. Suftin et al. 2016). Research on riparian C storage and sequestration is scarce and most studies are from South and North America while European studies are even more limited. The median C stock in riparian biomass was estimated to be 63 tC ha^{-1} with the highest values of 318-487 t C ha^{-1} from mature temperate forests in North and South America, and those values were considered to be comparable to the highest estimates for any forest biome (Dybala et al. 2019). From Europe, Cierjacks and colleagues (2010) reported C stocks of 474 t C ha^{-1} for mature riparian woods and 212 t C ha^{-1} for meadows and reeds in Danube floodplains. However, the relative importance of the distinct riparian compartments for C storage and the variations across scales, vegetation types, geological and climate settings are still unknown.

Erosion control

Erosion control refers to the reduction of the weathering away of soil and thereby the inputs of soil particles together with nutrients and carbon to water bodies. The soil-stabilizing effect of the plants is particularly relevant during events of intense rainfall and snowmelt (e.g. Larsen 2017). Species composition, root architecture and woodiness influences control of erosion and river bank stability (Simon and Collison 2002, Feld et al. 2018). The most effective erosion control seems to result from mixed stands of riparian woody and non-woody species (Simon and Collison 2002), but as recently reviewed by Feld and colleagues (2018), grass strips are the key to efficient reduction of surface runoff for soil particles.

The reduction and fragmentation of riparian forests, particularly in mountainous areas, endangers the ES of prevention and control of landslides (Larsen 2017). As an extreme example of the importance of keeping riparian zones forested is the La Purisima storm that hit the Panama at the end of 2010. The lack of bank-stabilizing effects of riparian tree roots due to riparian deforestation has been suggested to be one of the causes for more than 500 landslides during this event (Larsen 2017). Overall, this ES is of medium to high importance (Table 2).

Flow Regulation

Floodplains and riparian areas have long been recognized for delivering significant positive flow regulation services involving reduced frequency and magnitude of flooding, augmented low flows, and reduced stream flow and runoff (Thomas and Nisbet 2007, Rak et al. 2016, Table 2). Physically, as floodwater flows through a vegetated area, the plants resist the flow, reduce flow velocity and dissipate the energy, increasing the time available for water to infiltrate into the soil and be stored, which enhances groundwater recharge and results in a delay and reduction in magnitude of downstream flood peaks and reduced river bank erosion during heavy precipitation events. Increased hydrologic roughness due to vegetation and tree cover further reduces flood peaks. The potential importance is substantial as the damage cost of flooding or drying of urban or agricultural areas is high. For example, the costs for the flood damage caused by an intense rain event (cloudburst) in Copenhagen on 2^{nd} July 2011 amounted to 1 billion euros (Leonardsen 2012) and may have been significantly reduced by properly conserving upstream riparian areas. Furthermore, the slow release of water from riparian areas during dry periods is important for the ecological health of streams and downstream recipients, as well as for potential crop irrigation in the surrounding areas (Keesstra et al. 2018).

Pollination and seed dispersal

Plant regeneration is essential for maintaining biodiversity and ecosystem functioning in ecosystems, but may be threatened by human disturbance. Pollination and seed dispersal are the most threatened processes of plant regeneration because any disturbance such as habitat fragmentation or modification by an invasive plant species is likely to change the patterns of seed movement and recruitment. Riparian vegetation provides important nesting and foraging sites (nectar and pollen) for pollinators, and proximity to such habitats has been found to increase pollinator species richness, crop visitation rates and pollination success (e.g. Garibaldi et al. 2014, Petersen and Nault 2014). Vegetated riparian areas and wetlands support generally higher richness and diversity of pollinator species than dry adjacent lands, especially those dominated by monoculture (e.g. Ricketts 2004, Munyuli et al. 2013). Riparian vegetation may also play a role in seed dispersal across landscapes. However, the significance of this ecosystem service provided specifically by riparian vegetation is largely unknown (Table 2).

Maintenance of nursery populations and habitats

Riparian areas can host highly valuable natural habitats and act as nursery areas. A nursery is defined as a habitat that contributes more than the average, compared with other habitats, to the production of individuals of a particular species that recruits to adult populations (Beck et al. 2001).

Several species of small and large flagship mammals are specialized to inhabit and reproduce in riparian areas (e.g., otter*;* Prenda et al. 2001), and represent important foraging areas for insectivorous bats (Grindal et al. 1999). Riparian vegetation also provides habitat for resident and migratory birds (e.g., waders, ducks and herons; e.g. Gillies and Clair 2008), and many species of reptiles and amphibians. Nearly 70% of vertebrate species in a region will use riparian habitats in some significant way during their life cycle (e.g. Naiman et al. 1993). Undisturbed or well-conserved riparian areas also positively affect fish productivity (Tomscha et al. 2017) and the presence and spawning of target fish species with commercial and recreational interest such as salmonids (e.g. Bilby et al. 2003). In addition, RV subsidies as leaf litter are especially important for aquatic food webs and in the absence of autochthonous primary production, can be the major carbon source for aquatic biota (e.g. Pettit et al. 2012). Similarly, woody debris in the stream provides habitat and shelter for aquatic organisms and the exposed roots of riparian trees are the spawning substrate and larval habitat for some stream fish species (e.g. Pettit et al. 2013). Riparian vegetation also sustains benthic and riverine invertebrate richness (Malmqvist 2002), and many semi-aquatic organisms, such as salamanders, depend on both aquatic and terrestrial habitats to complete their life cycle and maintain viable populations (Semlitsch 1998).

Pest control

Natural control of plant pests in agro-ecosystems is provided by predators and parasitoids, such as birds, bats, spiders, ground beetles, lady beetles, lacewings, flies and wasps, as well as entomopathogenic organisms (e.g., fungi, bacteria, nematodes). Habitat requirements for natural enemies include several ecosystem properties often encompassed by riparian systems: (i) supplementary food resources, e.g., alternate hosts, or prey; (ii) complementary food resources, e.g., pollen, honeydew, nectar; (iii) microclimatic conditions; and (iv) overwintering/aestivation shelters and refuges (e.g. Jonsson et al. 2008). Riparian vegetation can provide refuges and other resources to natural enemies, and serve as corridors for their dispersion between other non-crop habitats and into crop fields (e.g. Luke et al. 2018). There are several examples worldwide providing evidence of the relevance of pest-regulating services by riparian vegetation. One study by Maisonneuve and Rioux (2001) found that the proportion of pest species decreased with the complexity of riparian vegetation structure, while insectivorous species increased in abundance in woody riparian strips. Stockan and colleagues (2014) reported the highest density and species diversity of generalist predators (Coleoptera, Carabidae) in unmanaged riparian margins. However, Gray and Lewis (2014) observed that 30–50 m width riparian forests adjoining oil palm plantations in Malaysian Borneo were unlikely to provide a pest control service. Clearly, the characteristics of riparian vegetation and associated environmental conditions that influence the pest control service require further study.

Regulation of microclimate

Riparian vegetation can exert considerable influence on the local microclimate (Chen et al. 1999) with dense, closed canopies reducing evaporation, reducing wind speed and maintaining high relative humidity. In riparian areas, the stream flow regime and groundwater will result in surface soils with high moisture content. Shading from RV canopies also results in lower air and water temperatures, therefore alleviating the heat stress, which is related with public health (e.g. Kristensen et al. 2014). Riparian vegetation is important for temperature and light control within streams (Capon and Pettit 2018). Trees on the river edge provide shade that can reduce instream primary production and water temperature, the latter with positive effect on dissolved oxygen. This microclimate regulation is especially evident in arid and semi-arid areas where the lushness of riparian trees and shrubs contrasts with the surrounding arid landscape where vegetation is scarce.

Fire effects mitigation

Riparian zones can act as a natural barrier to limit the spread and spatial extent of upland wildfires (Pettit and Naiman 2007). Riparian systems tend to differ from adjacent uplands in moisture regime, topography, micro-climate, soils and vegetative structure, resulting in higher fuel moisture content, relative humidity and lower wind speeds. Therefore, fires are generally less frequent and of lower intensity in riparian zones (e.g. Dwire and Kauffman 2003).

With changing climate follows increasing risk in many regions of catastrophic fires, so managing this risk while conserving biodiversity is a major challenge. Dense natural riparian vegetation in most cases creates a buffer zone to the stream, which will limit terrestrial fire spread and protect stream ecosystems from fire effects (Bisson et al. 2003). Riparian zones create refugia for fire-sensitive species in a matrix of more fire-prone uplands. The benefits of riparian areas for fire protection has been recorded in diverse climatic environments such as temperate forest in the USA where after a severe fire, tree mortality was 37% in the upland area while no trees were killed in the adjacent riparian zone, and there was no loss of diversity of riparian species (Elliot et al. 1999). In a tropical fire-prone savanna in Central American fire rarely penetrates far into the adjacent riparian forest, fire damaged trees are only found on gentler slopes near the savanna-forest boundary (Kellman and Tackaberry 1993).

Evaluation of the importance of provisioning, regulating and maintenance services

When we compared the importance of the provisioning and regulating ES across the four vegetation types given in Table 2, we found that out of the 16 services provided, 12 services had at least one high ranking across the four vegetation types, and six had medium or high importance across all vegetation types ('filtration/storage', 'chemical condition of freshwater', 'fixation storage', 'erosion control', 'flow regulation', and 'providing habitats'; Table 2). Three other services were mainly associated with two vegetation types that are forest and wet forest providing 'standing crop of woody biomass' and 'climate regulation', and dry woodland together with herbs/grass providing mainly 'pollination' (Figure 3). In Table 3, we ranked the ES provided by RV such that the highest ranked service is the service with highest importance in most of the four vegetation types. It is clear that presence of any of the four vegetation types in the riparian area will provide several ES, but also that forest and riparian wetland will provide more than herbs/grass.

Cultural Services from Riparian Vegetation

Cultural Services are considered "non-material benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences" (MEA 2005), which have extended the original categories 'Cultural' and 'Recreation' of Constanza and colleagues (1997). Despite being increasingly recognized as key to ecosystem conservation and unavoidable in the general valuation of ecosystem services, apart from recreation services, this broad category is frequently overlooked due to its intangible and subjective nature, and lack of methodological frameworks to quantify their value in monetary means (TEEB 2010, Daniel et al. 2012). The CICES framework stresses that all ES have an inherent cultural value, but these services should be treated as an independent section. CICES classifies cultural services into two broad divisions and respective categories: i) Direct cultural services, which cover outdoor interactions with living systems (Experiential and Physical use of plants, animals and landscapes; Scientific; Educational; Cultural heritage; Aesthetic), and ii) Indirect cultural services, which rely mostly on remotely indoor interactions with the environmental setting (Sacred and/or religious values; Symbolic values; Entertainment; Existence; Bequest). These services can involve individual species, communities, habitats, and whole ecosystems. In Table 4 the direct and indirect cultural services of RV are listed.

Direct and indirect cultural services

Riparian areas and vegetation provide opportunities for researching nature *in situ*. They can function as outdoor laboratories for students or local communities through the development of environmental education and citizen science projects by schools, research centers and local associations may be complemented by experiences in classrooms or science centers. The time scale in which this cultural service is provided can be quite varied, ranging from a single day (ex. guided visits or activities) to an entire year(s) (long-term education projects). The benefits of outdoor learning experiences have been documented in environmental education literature, and rivers and riparian areas are not an exception. Studies have reported increased environmental awareness and the integration of knowledge of different subject areas from outdoor studies (e.g. Bouillion and Gomez 2001, Overholt and MacKenzie 2005).

The inspiring aesthetic value of rivers and riparian areas are well documented in a comprehensive body of art works (e.g. paintings and drawings) dating back several hundreds of years, and in the numerous tourists that visit, e.g., the Camargue, the Danube delta and the Coto de Doñana to enjoy the beauty of nature. The near natural and most diverse sections of rivers are more attractive to people due to a high sense of wilderness (Brown and Daniel 1991, Bowker and Bergstrom 2017). These areas are often in the upper reaches of rivers and are connected to the cultural services associated with mountains and nearby forests (e.g., recreation or exercise in the form of forest walks, and cultural heritage and sense of place (Zandersen and Tol 2009).

Riparian vegetation can also provide a sense of continuity and understanding of our place in the universe, which is expressed through ethical and heritage-values (Arts et al. 2018). Many riparian areas provide strong religious significance for indigenous groups, such as waterholes or particular riparian trees (e.g. Nagajara et al. 2014). In few cultures from northwestern Europe, wetlands have a spiritual significance, being places where ghosts, witches and dwarfs live (e.g. Hauck et al. 2013).

Methodological framework to guide management

We have provided and discussed a list of ES provided by RV and ranked the importance across four main vegetation types. The compilation of the full list of ES in one paper can be used to guide decision making in riparian management and restoration. The framework including the full list of ES provided by RV allows the identification of synergies and trade-offs between ES across RV types. For example, regarding synergies, it is easy from a list of ES as given in Table 2 to identify any synergies obtained by choosing certain vegetation types in a given restoration. Regarding trade-offs it is clear that RV provides some services but it can also provide some disservices. For example, RV can decrease flood risk downstream by lowering the speed of flood wave propagation but it can also deliver logs downstream that can generate a notably risk for bridges. Again by having a list of ES any trade-offs become easier to identify and assess for RV management. Therefore, the ES and benefits obtained from RV can be maximized by directing management and restoration towards specific target ES or bundles of services when taken trade-offs and disservices into consideration.

In order to make the concept useful in local management, we aimed to provide a general framework for adopting the ES approach to riparian area management and restoration. We provide a flow chart outlining the steps required in guiding management and restoration using information on provisioning, regulating, maintaining and cultural services as targets (Figure 3). The first part is based on the ecosystem settings, which is the identification of local riparian vegetation and associated ES, and the classification of the importance of these services following Table 1. The second part is the decision-making process where managers need to decide if the target is a set of specific ES or if it is to reach a balance to maximize the range of ES benefits.

Knowledge gaps and perspectives

Several knowledge gaps can be identified based on the overview given in this paper. First, we need more knowledge on how the four main vegetation types and species traits specifically support different ES (Table 2 and 3). The ranking of the importance of each ES across vegetation types was based on expert opinion supported by the literature but in many cases further studies are needed to validate these rankings. Moreover, we have only considered the main vegetation types, but many intermediate vegetation types are present and might support differently. Second, seed and propagule dispersal, gene resources, and fire protection are highly understudied ES provided by RV. Third, a general issue across all ES is the matter of spatial scale. How much area is needed in order to support and optimize each of the ES? This is not only an unexplored issue in RV management but also in many other ecosystems when considering ES provision (e.g. Sutherland et al. 2016). Fourth, cultural services are important but currently it is difficult to quantitatively value the benefits, thus they are harder to include in management planning. And last, a better understanding of who is really benefiting from ES provided by riparian vegetation is also needed. Thus, more research on assessment, description, valuation and integration of cultural services into a decision context is needed (e.g. Vidal-Abarca Gutierrez and Suarez-Alonso 2013).

Conclusion

The severe degradation worldwide of freshwater ecosystems has posed a major threat to ES of riparian areas and their vegetation. This negative trend has continued to increase since 1950 even though the economic implications are serious (e.g. due flood damages), and in many places this negative trend might even be intensified due to climate change (e.g. Capon et al. 2013). Therefore, restoration of floodplain and RV would represent an important practice to mitigate the effects of such degradation and in many places, this is already occurring. Nevertheless, currently most water-related restoration projects just aim to improve habitat or water quality. In order to maximize the benefits of these restoration investments we suggest including an ES-based decision-making approach that includes RV. Therefore, if a broader perspective on ES of RV is included to help guide riparian management, the multi-functionality of freshwater ecosystems can be recovered and the provision of ES recovered or improved, and benefits to society would be enhanced.

In order to progress this approach more knowledge conversion is needed. However, as pointed out by Dufour and colleagues (2019), although there has been a continuous increase in the number of publications on RV since the 1990s, the integration of that knowledge across disciplines and socio-cultural aspects of RV are still very much understudied. In this paper we have listed and ranked ES provided by RV, and allocated the importance of each provisioning and regulating ES within each of four broad RV types. We also included cultural services, although we could not systematically assess their importance due to the highlighted knowledge gaps. Finally, we provided the first steps for a guided management framework for including ES in local restoration planning of RV. In order to move from the knowledge-based approach provided in this paper, to the policy tools for prioritizing restoration, we need to advance mapping of ES and perform assessments of their economic value. Despite the current limitations on available information, we believe this paper is a useful start for knowledge conversion and future implementation of the ES approach in restoration and management of RV.

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Table 1: Definitions of the categories of relative importance of ecosystem services based on the spatial scale at which an ES works (local to global), and the temporal scale of goods and benefits provided by an ES (uncommon to common). The definitions are based on expert opinion and use of scientific literature. The definitions are used to populate Table 2 and the color-coding is also used in table 3.

		Spatial Scale			
		Global	Regional	Local	Unknown
Temporal scale	Common	**High**	**High**	**Medium**	**Unknown**
	Less than common	**High**	**Medium**	**Low**	**Unknown**
	Uncommon	**Medium**	**Low**	**Low**	**Unknown**
	Unknown	**Unknown**	**Unknown**	**Unknown**	**Unknown**

Table 2. Provisioning, regulating and cultural ecosystem services (ES) and the main goods and benefits provided by riparian vegetation. For each service, we evaluate the relative spatial and temporal importance within four main riparian vegetation types (see methods and Figure 1 for more explanation). Ecosystem services and their main goods and benefits are derived from CICES (version 5.1; https://cices.eu/).

ES section	**ES division**	**ES category**	**Ecosystem service (ES)**	**Main goods and benefits**	**Herbs/ grass**	**Dry forest**	**Wet forest**	**Riparian wetlands**
Provisioning	Biomass	Standing crop	Standing crop of woody biomass	Biomass for fuel	Low	Medium	Medium	Low
			Standing crop of non-woody biomass		Low	Low	Low	Medium
		Wild plants and their outputs	Harvestable volume of wild berries or other	Food	Low	Low	Low	Low
	Genetic material	Genetic materials from all biota	Seeds, spores and harvestable genes	Extract genes for breeding, new products resisting disease	Unknown	High	Unknown	Unknown
Regulation and maintenance	Transformation of biochemical or physical inputs	Filtration/storage	Filtering/storage of particles	Reduction in sediment and toxic particles transport in streams	High	Medium	High	High
		Carbon sequestration	Fixation storage	Reduction in CO_2	Medium	High	High	High
		Chemical conditions of freshwaters	Removal of nutrient in runoff	Reduced pollution and damage costs of nutrient runoff	Medium	High	Medium	High
	Regulation of physical, chemical and biological conditions	Stabilization and control of erosion	Erosion control	Reduction of erosion and sediment loads in streams	High	Medium	Medium	High
		Buffering and attenuation of mass flows	Landslide	Protect human lives and infrastructure	Low	High	High	Low
		Hydrological cycles and water flow maintenance and flood protection	Flow regulation - The capacity of vegetation to retain water and release it slowly	Damage mitigation of extreme flows	Medium	Medium	High	High

		Pollination	Pollination	Contribution to yield of crops	High	High	Low	Low
		Seed and propagule dispersal	Seed and propagule dispersal	Maintain biodiversity in the region	Unknown	Unknown	Unknown	Unknown
		Maintaining nursery populations and habitats	Providing habitats	Nursery habitats; Sustaining populations (e.g. of iconic species, or threaten species)	High	High	High	High
		Pest control	Providing habitats for native pest control agents	Reduction in pest damage to crop	High	High	High	Unknown
		Climate regulation	Evaporative cooling by urban riparian trees	Temperature control in stream and air	Low	High	High	Low
		Fire regulation	The capacity of riparian vegetation to reduce frequency, spread or magnitude of fires	Reduction in fire damage costs	Unknown	Unknown	Unknown	High
Cultural (Biotic)	Direct: In-situ and outdoor interactions with living systems, that depend on presence in the environmental setting	Experiential and physical interaction	Ecological quality to support recreational use	Recreation, fitness; de-stressing or mental health; nature-based recreation; ecotourism and eco-awareness; bushwalking, birdwatching, orienteering. Also for rest, relaxation and refreshment.	*NA*	*NA*	*NA*	*NA*
		Scientific	Sites of specific scientific interest	Knowledge about the environment and nature	*NA*	*NA*	*NA*	*NA*
		Educational	Sites used for conservation activities	Skills or knowledge about environmental management	*NA*	*NA*	*NA*	*NA*

	Heritage	Sites of cultural importance	Tourism, local identity	*NA*	*NA*	*NA*	*NA*
	Aesthetic	Area of natural beauty	Artistic inspiration	*NA*	*NA*	*NA*	*NA*
Indirect: Remote, often indoor interactions with living systems, that do not require presence in the environmental setting	Sacred and/or religious values	Totemic species or settings of religious interest	Mental well-being. Many riparian areas provide strong religious significance for indigenous groups, such as particular riparian trees.	*NA*	*NA*	*NA*	*NA*
	Symbolic values	Species, habitats or landscapes that can be used as symbols	Social cohesion, cultural icon Conservation of riparian habitats and keystone species	*NA*	*NA*	*NA*	*NA*
	Entertainment	Artistic productions	Nature films, books, paints, draws	*NA*	*NA*	*NA*	*NA*
	Existence	Natural areas designated as wilderness	Mental/Moral well-being; valuing wilderness of rivers and riverine areas	*NA*	*NA*	*NA*	*NA*
	Bequest	Species and ecosystem settings	Moral well-being; promotion of the sustainability of bio-cultural identity and of the overall social-ecological system	*NA*	*NA*	*NA*	*NA*

Table 3. Ecosystem services provided by riparian vegetation, distributed across four main vegetation types, and ranked from high to low importance following definitions of high, medium and low given in table 1.

Ecosystem service	Herbs/grass	Forest	Wet forest	Wetlands	ES Importance High to Low
Providing habitats	High	High	High	High	
Filtering/storage of particles	High	Medium	High	High	
Fixation storage	Medium	High	High	High	
Erosion control	High	Medium	High	High	
Providing habitats for native pest control agents	High	High	High	Unknown	
Flow regulation - The capacity of vegetation to retain water and release it slowly	Medium	Medium	High	High	
Removal of nutrient in runoff	Medium	High	Medium	High	
Landslide	Low	High	High	Low	
Pollination	High	High	Low	Low	
Evaporative cooling by urban riparian trees	Low	High	High	Low	
Standing crop of woody biomass	Low	Medium	Medium	Low	
Seeds, spores and harvestable genes	Unknown	High	Unknown	Unknown	
The capacity of riparian vegetation to reduce frequency, spread or magnitude of fires	Unknown	Unknown	Unknown	High	
Standing crop of non-woody biomass	Low	Low	Low	Medium	
Harvestable volume of wild berries or other	Low	Low	Low	Low	
Seed and propagule dispersal	Unknown	Unknown	Unknown	Unknown	

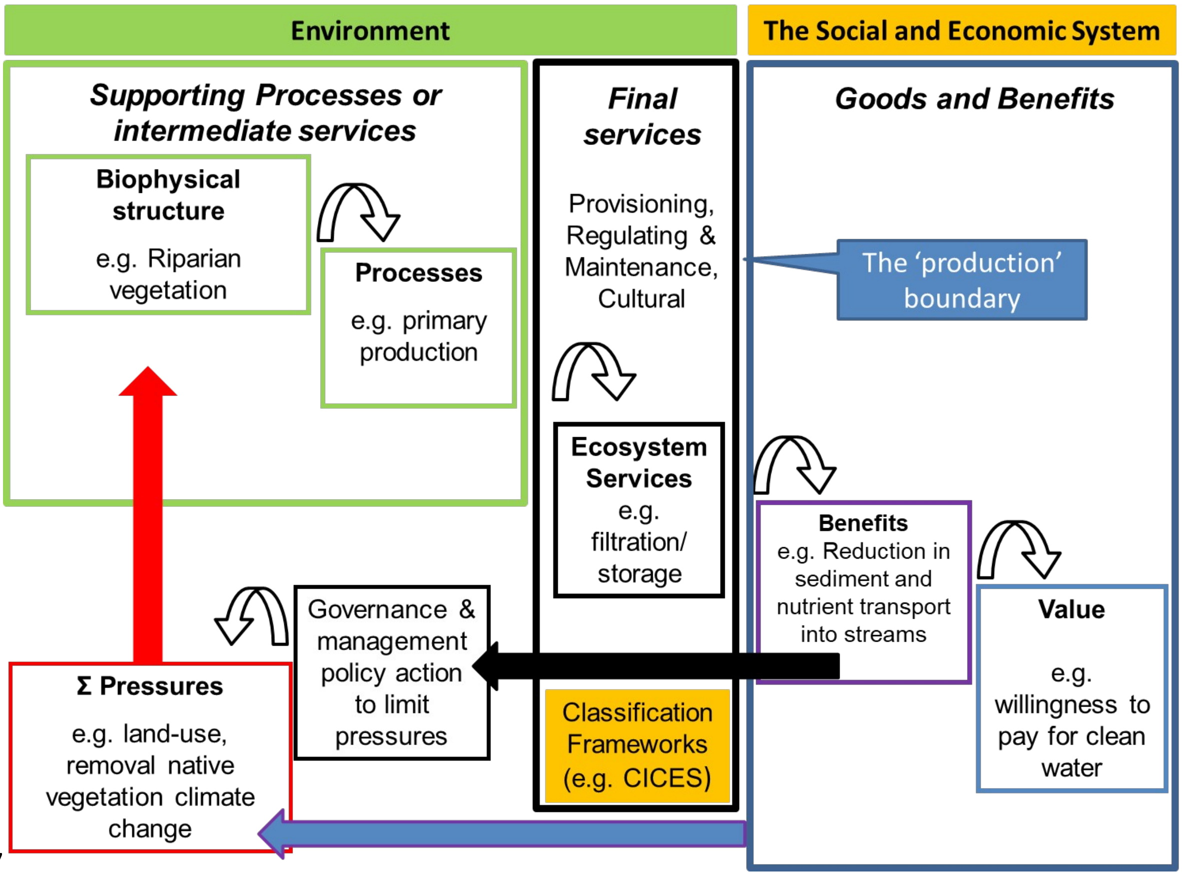

Figure 1: The ecosystems cascade model which highlights the role of supporting processes and intermediate services in the delivery of final services and the goods and benefits humans derive from riparian vegetation. Source: Modified after Potschin and Haines-Young (2011).

Figure 2: Diagram showing the four main riparian vegetation types structured along two main factors; cover of wood and local soil moisture.

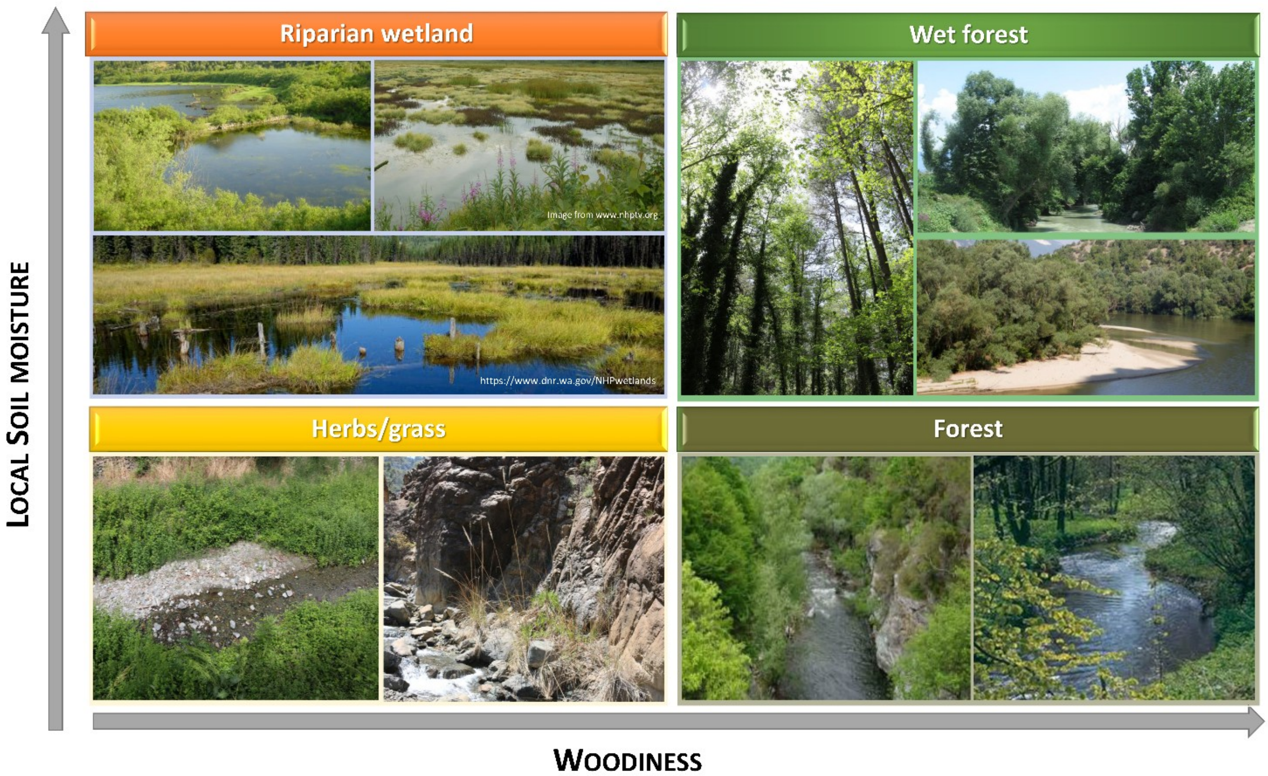

Figure 3. Management framework for determining the environmental settings for the riparian vegetation for a particular region (Ecosystem setting) by identifying (ID) local vegetation types, the relevant ecosystem services, and finally ranking the importance of the relevant ecosystem services in relating it to the different vegetation types (following Table 3). Second, based on the ecosystem setting we suggest subsequent steps for managers to make best decisions aiming either for target services or for maximizing the number of services provided by riparian vegetation. The steps include the identification of synergies and trade-offs between ecosystem services and the economical and non-economical valuation of the target single or bundle of ecosystem services provided by the riparian vegetation.