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Review

Soil Properties, Processes, Ecological Services and Management Practices of Mediterranean Riparian Systems

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Abstract

Riparian zones, located at the interface between terrestrial and aquatic systems, are among the most dynamic and ecologically valuable landscapes. These transitional areas play a pivotal role in maintaining environmental health by supporting biodiversity, regulating hydrological processes, filtering pollutants, and stabilizing streambanks. At the core of these functions lie the unique characteristics of riparian soils, which result from complex interactions between water dynamics, sedimentation, vegetation, and microbial activity. This paper provides a comprehensive overview of the origin, structure, and functioning of riparian soils, with particular attention being paid to their physical, chemical, and biological properties and how these properties are shaped by periodic flooding and vegetation patterns. Special emphasis is placed on Mediterranean riparian environments, where marked seasonality, alternating wet–dry cycles, and increasing climate variability enhance both the importance and fragility of riparian systems. A bibliographic study, covering 25 years (2000–2025), was carried out through Scopus and Web of Science. The results highlight that riparian areas are key for carbon sequestration, nutrient retention, and ecosystem connectivity in water-limited regions, yet they are increasingly threatened by land use change, water abstraction, pollution, and biological invasions. Climate change exacerbates these pressures, altering hydrological regimes and reducing soil resilience. Conservation requires integrated strategies that maintain hydrological connectivity, promote native vegetation, and limit anthropogenic impacts. Preserving riparian soils is therefore fundamental to sustain ecosystem services, improve water quality, and enhance landscape resilience in vulnerable Mediterranean contexts.

Keywords: carbon sequestration; conservation practices; ecosystem functioning; land degradation; nitrogen cycling; nutrient retention; pedogenesis; vegetation-soil interactions

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1. Introduction

Riparian areas, derived from the Latin word "*riparius*" meaning riverbank, refer to lands next to freshwater bodies like rivers. First appearing in scientific literature in the 1970s, the term is now widely used, with equivalents in Greek as "*παραποτάμιο*" and "*παρόχθιο*". These areas are also known as riparian forests, buffer zones, floodplain forests, and meadows, playing a crucial role in ecosystem health and biodiversity [1]. While the term "*riparian*" has been introduced relatively recently in scientific literature, the interaction between humans and riparian areas has a long-established history [1,2].

Riparian zones are interface areas where terrestrial and freshwater systems meet, marked by unique physical and biological traits that are heavily shaped by the influence of water [3,4]. They facilitate the connection between water bodies and adjacent uplands through surface and subsurface hydrology, and are generally referred to as *ecotones* [5]. Especially abundant in temperate and tropical zones, these ecosystems can also be found in arid and Mediterranean regions, where they play a crucial role in maintaining local biodiversity and ecological functions [6,7]. The spread of riparian zones is extremely variable and not easily definable. In the western United States, riparian areas occupy less than 2% of land surface, about 1% in Europe and Africa up to 4% in south America [8]. These ecosystems typically host an assortment of plant species such as willow (*Salix* spp.) and cottonwood (*Populus* spp.), which provide habitat and food sources for numerous animals, including amphibians, birds, and small mammals [9]. Therefore, riparian zones are ecologically valuable, and ensure a broad spectrum of ecosystem services, such as water purification, flood control, nutrient cycling, habitat support, and also play a key role in maintaining biodiversity [10,11]. Moreover, they are included in the fifteen globally recognized terrestrial biomes [12].

In detail, water availability directly influences riparian plant communities, as it determines soil moisture levels, nutrient transport, and habitat stability [13,14]. Indeed, the depth and duration of soil saturation influence which species can establish and persist. Hydrophytes (e.g., willows, cottonwoods) thrive in saturated soils, whereas drought-tolerant shrubs dominate when water levels drop [15]. Fluctuations in water tables thus determine species zonation along riparian gradients [16]. Flowing water delivers nutrients from upstream areas into riparian soils. Regular flooding replenishes soil fertility, while reduced water availability limits nutrient inputs, leading to declines in productivity and shifts toward stress-tolerant vegetation [17]. Moreover, water flow shapes geomorphological processes (sediment deposition, erosion, bank formation). Stable water inputs maintain heterogeneous habitats that support diverse communities [18]. Conversely, water scarcity can destabilize soils, increase erosion, and simplify habitat structure [19].

Hence, riparian vegetation has a fundamental role in stabilizing soils by reducing erosion and regulating water dynamics [20]. However, this function depends on the type of vegetation, as different canopy species drive soil characteristics and nutrient cycling in many ways [4]. This contrast is evident in the study by Pérez-Corona et al. [21], which demonstrated that while native riparian forests help maintain soil fertility, plantations of *Populus hybrida* M.Bieb. result in lower nitrogen (N) and organic carbon (C) content, affecting microbial activity and nutrient availability. In addition to soil stability, the riparian buffers act as natural filters, reducing nutrient and pollutant loads before they reach aquatic systems, thus improving water quality and maintaining ecological balance [22,23]. Likewise, vegetation is significantly involved in water dynamics through multiple processes, e.g., evapotranspiration, which significantly shapes the hydrological cycles. Trees and shrubs along riverbanks transpire large amounts of water, directly affecting local balances. However, under climate change scenarios, increasing temperatures and prolonged droughts are expected to enhance evapotranspiration rates, leading to a reduction in water availability for both vegetation and groundwater recharge [24].

Beyond climatic factors, riparian ecosystems are also increasingly threatened by human-induced disturbances, altering natural vegetation dynamics and disrupting ecological processes [25]. In detail, northern Mediterranean regions seem to be more affected by urbanization, pollution, invasive species and flow regulation, while southern Mediterranean zones are affected more by water scarcity, desertification, overgrazing and climate vulnerability [26].

The frequent exposure of riparian soils to hydrological dynamics and their sensitivity to anthropogenic activities affect their structure, composition, and edaphic communities. Soils of riparian zones are highly dynamic, having properties that may vary due to the periodic flooding and subsequent sedimentation processes [27]. Understanding riparian soil formation, structure, and ecological functions provides insight into their critical role in both terrestrial and aquatic health. The importance of these ecosystems is even greater in Mediterranean regions, where water scarcity and seasonal variability shape their ecological dynamics [28]. Mediterranean riparian ecosystems provide essential ecological services (ESs), including climate regulation, water purification, and flood mitigation. In general, within the Millennium Ecosystem Assessment (2005) framework, ESs can be categorized as: provisioning, regulating, supporting, and cultural services. This categorization is focused on the different functions of the riparian ecosystems in relation to human and environmental well-being. The importance of riparian ESs is also reflected in the 2030 Agenda for Sustainable Development, with SDG 6 (Clean Water and Sanitation), SDG 13 (Climate Action), and SDG 15 (Life on Land) demanding the work not formally published but available on unpublished workable protection and management of terrestrial ecosystems and water resources. Despite their importance, the cumulative impact of factors, e.g., anthropogenic stressors on soil and vegetation dynamics, remains insufficiently studied [21]. Therefore, this paper discusses the formation processes, properties, and vital functions of riparian soils, exploring the impacts of human activities, climate change, and outlining strategies for effective management and conservation of soil health.

To reach this aim, a bibliographic study was carried out through Scopus and Web of Science (WoS). We found that most of the papers on riparian area published over the last 25 years (2000–2025) critically discussed water dynamics, soil formation process, soil properties, ecosystem services and management and conservation strategies. We summarized these aspects of riparian ecosystems focusing on Mediterranean area and organized the following work accordingly.

2. Hydrological Dynamics of Riparian Ecosystems

The hydrological regime of riparian areas is defined by seasonal fluctuations in water availability, with alternating periods of high flow, typically resulting from rainfall or snowmelt, and low flow during dry seasons. These natural variations are central to riparian ecosystem functioning, as they regulate sediment deposition, groundwater recharge, and the structure of plant communities [13]. In this sense, hydrology is a key driver of riparian ecosystem dynamics, shaping multiple ecological functions such as nutrient cycling, sediment transport, and habitat availability for both aquatic and terrestrial species [1].

Among its many roles, riparian hydrology supports critical ESs including water regulation, biodiversity maintenance, nutrient cycling, climate resilience, and the modulation of river discharge [13]. Riparian vegetation significantly influences these processes by regulating water balance, thus affecting the performance of hydrological models and shaping regional water budgets. For example, Lupon et al. [24] demonstrated that incorporating riparian zones into hydrological models substantially improves their accuracy, particularly under dry conditions, by accounting for the water fluxes associated with riparian evapotranspiration. Moreover, the dynamic interplay between hydrology and habitat heterogeneity is fundamental to biodiversity. The spatial and temporal variability in water availability creates a mosaic of microenvironments that support diverse and often specialized plant and animal communities. Fernandez et al. [29] highlighted that riparian ecosystems harbor plant species uniquely adapted to repeated cycles of flooding and drying, a trait that enhances the overall resilience of these ecosystems to disturbance.

Riparian hydrology also plays a central role in water quality regulation and nutrient retention. Riparian forests act as natural buffers, filtering pollutants, especially nitrates, from runoff and reducing nutrient leaching into adjacent aquatic systems. Poblador et al. [22] observed that riparian zones adjacent to streams exhibit high transpiration rates and effective nutrient retention, contributing to improved water quality. Similarly, Castellano et al. [30] found that riparian buffer zones in the Iberian Peninsula were able to reduce nitrate and sulfate concentrations in groundwater by up to 79% and 41%, respectively. These findings confirm the importance of similar vegetation in mitigating pollution from agricultural uplands [31,32]. However, the capability of riparian systems to deliver these services is increasingly threatened by water quality degradation. Agricultural drainage often introduces excessive amounts of nutrients (e.g., phosphates and nitrates), sediments, and pesticides, while urban and industrial effluents contribute toxic substances such as heavy metals and persistent organic pollutants [33–35]. These contaminants compromise ecological function, reduce biodiversity, and promote harmful processes such as eutrophication.

Anthropogenic modifications further exacerbate these pressures. Activities such as dam construction, water abstraction for irrigation, and river regulation alter natural flow regimes, reduce flood frequency, and limit the river's capacity to dilute and export contaminants [36]. These changes not only weaken sediment and nutrient transport but also increase salinity in soils and water, particularly under climate change scenarios, adversely affecting vegetation structure and overall ecosystem performance.

Given these challenges, the need for integrated water management that safeguards both water quality and quantity is urgent. The degradation of riparian soils due to pollution and altered hydrology severely undermines their ability to sustain biodiversity, regulate nutrient cycling, and maintain soil structure [37]. Beyond their present-day functions, riparian systems are vital for climate change adaptation and mitigation. Mediterranean riparian ecosystems are especially vulnerable to hydrological alterations and prolonged droughts. Zaimes [2] underscores the importance of nature-based solutions, such as bioengineering techniques and ecological restoration, as effective strategies to restore natural hydrological connectivity and enhance climate resilience. Seasonal variations in flow regimes continue to shape riparian ecosystem dynamics. High-flow periods, driven by rainfall or snowmelt, lead to overbank flooding that deposits sediments and organic matter, replenishes groundwater, and triggers the germination of flood-adapted vegetation. Conversely, low-flow conditions, common in Mediterranean climates, result in reduced soil moisture and increased water stress among plant communities [13]. The cyclical balance between flooding and drought is thus critical for ecosystem stability. While floods renew habitats and distribute nutrients, drought periods facilitate sediment consolidation and support the establishment of drought-resistant, deep-rooted vegetation [1]. Yet, growing human intervention is disrupting these natural cycles. Dams and water diversions are fragmenting hydrological connectivity and impairing the ecological functioning of riparian zones [22]. In this context, sustainable water governance is imperative to conserve the integrity, resilience, and multifunctionality of riparian ecosystems.

3. Soil Origin and Dynamics at Water-Upland Interface

Soil formation in riparian zones shares many of the fundamental processes observed in other environments, such as weathering of parent material, organic matter accumulation, mineral transformations, and horizon development [38]. However, what sets riparian soils apart is their strong dependence on hydrological and geomorphological dynamics. Periodic flooding, sediment deposition, fluctuating water tables, and prolonged waterlogging distinguish their pedogenesis from that of upland soils [39]. Flooding plays a central role in riparian pedogenesis, governing not only the deposition of new materials but also the overall profile development of the soil. Floodwaters bring stratified layers of inorganic and organic material, resulting in highly layered soil profiles. Frequent overbank floods often reset soil development, impeding horizon differentiation, particularly in Fluvisols—minimally developed mineral soils formed on recent alluvial deposits. These are dominant in active floodplains like the Ebro (Spain), Po (Italy), and the Nile Delta (Egypt), supporting vegetation communities well adapted to disturbance [38–40]. In these environments, floodwaters sort particles by size, typically depositing coarser materials near river channels and finer particles further away [41]. This sedimentation not only shapes the soil structure but also contributes essential nutrients, creating fertile conditions that support high plant and microbial biodiversity [42]. Riparian vegetation, in turn, influences soil formation and stability as roots bind the soil, limit erosion, and promote water infiltration, while decaying litter continuously adds organic matter, improving both soil structure and fertility [10].

The extent and functioning of riparian zones vary widely, ranging from narrow 10–50 m strips to expansive floodplains extending hundreds of meters, depending on factors such as topography, stream size, and inundation frequency [43]. This spatial variability is mirrored in the diversity of soil type present.

In Mediterranean regions, hydrological regimes are especially variable, marked by long droughts interspersed with sporadic, intense floods [1]. These conditions create unique pedogenetic dynamics. Drought can cause salt accumulation and microbial dormancy, while flash floods may induce erosion and nutrient loss. The resulting soils, often categorized as Fluvisols (FAO-WRB) or Entisols (USDA), are typically young, stratified, and fertile with high water retention capacity, though with limited horizon development due to continuous disturbance. Where flooding is seasonal or water saturation persists, other soil types emerge. Gleysols, common in floodplain depressions and wetlands like the Camargue (France), Doñana (Spain), and parts of the Nile Delta (Egypt), form under anaerobic conditions, showing redoximorphic features. In zones with prolonged saturation and reduced decomposition, Histosols may develop, as observed in marshes like the Albufera de Valencia (Spain) and the Nile Delta (Egypt), characterized by thick organic layers [44]. In contrast, more stable riparian terraces, such as those along the Tagus (Portugal/Spain), Tiber (Italy), and Moulouya basin (Morocco), where drainage is improved and flooding less frequent, host Cambisols and Arenosols. These soils exhibit moderate development, with some horizon differentiation due to less frequent resetting of soil formation [39]. Stagnosols, meanwhile, occur in areas with seasonal surface water stagnation, influencing both hydrology and plant dynamics.

In arid and semi-arid riparian landscapes, such as southern Spain, Sicily (Italy), the Nile Valley (Egypt), and coastal plains in Tunisia [45] and Algeria, intense evapotranspiration and saline groundwater conditions promote the formation of Solonchaks and Solonetz. These salt-affected soils exhibit altered chemistry and host halophytic plant communities, presenting major challenges for both natural ecosystem functioning and agriculture [1,46]. Also, the expansion of urban environments and land associated with agriculture and grazing, as well as forest loss, may also have profound effects on soil formation processes in the riparian zone, affecting the frequency and intensity of flooding [2,47].

3.1. Soil Physical Characteristics

Riparian soils exhibit a wide range of physical properties, reflecting the complexity and dynamic nature of their formation sites [27]. Physical properties (i.e., texture, structure, porosity, and bulk density) often differ from those of non-riparian soils, as riparian soils are subject to regular cycles of saturation and sediment deposition [47].

Soil texture varies considerably among alluvial deposits. In riparian areas subject to frequent flooding, soils tend to contain higher amounts of finer sediments such as clay and silt. In contrast, riparian zones that are more stable or located near high-energy river channels often have coarser fractions, such as sand and gravel [35,48]. This textural variability significantly influences soil water retention, permeability, and nutrient availability. For example, while clay soils can retain more water than sandy soils, they typically have lower permeability. Conversely, sandy soils drain quickly but retain less water. Consequently, variability in soil water retention affects not only water availability for vegetation but also the transport of solutes within the soil. Riparian soils may have a stratified structure, indicative of successive sedimentary deposits, where the fine texture retains moisture but has limited infiltration capacity [49]. The stratified structure of these soils, combined with frequent organic inputs, can result in high porosity and low bulk density compared to upland soils. This structure facilitates water retention, air circulation, and root development, which are essential for sustaining plant life and microbial communities [50]. In riparian soils, organic inputs from vegetation and alluvial pulses are responsible of creating a complex and stable structure that influences porosity and controls erosion [10]. Similarly, the root systems of riparian plants contribute strongly to stabilizing aggregates, both through the mechanism of physical trapping and through the production of exudates [50].

3.2. Soil Chemical Characteristics

As well as soil physical features, the chemical characteristics are easily influenced by frequent wetting and drying cycles, reflecting significant variations in moisture content, creating anaerobic conditions during flooding events, and more aerated conditions when water recedes. Each time there is flooding, there will be anaerobic conditions that develop, but once the water recedes, and there is air in the soil, the plant roots are then able to access the oxygen. The change in moisture impacts not only microbial respiration and root respiration, but also nutrient availability. Indeed, soils are generally recognized by their relatively high soil organic matter (SOM) content, especially in the surface horizons. These soils generally accumulate SOM in relation to flooding events and decay of terrestrial plants nearby [40,51]. The high SOM content is key for riparian soil fertility and health. Recent research on riparian soils within Mediterranean regions have found a considerable variation in SOM content, likely driven by hydrology, vegetation and land use characteristics. Zheng et al. [52] stated the specific composition and biomass of riparian vegetation can affect the rate of SOC decomposition and the amount of soil available nutrients. Proximity to rivers often positions riparian forests as substantial C sinks in contrast to their upland counterparts [53], potentially attributed to flood dynamics in C accumulation [54]. Significant reductions in litter production, soil C stocks, nutrient cycling, and decomposition can be related to higher inundation frequency and intensity [39]. Many authors agree in giving riparian soils an important sedimentary function and greater C pools than adjacent uplands [55–57]. In this frame, C turnover is strictly associated with abiotic processes such as hydrolysis, mineral transformation and chemical oxidation by reactive oxygen species (ROS) [57–59]. Different C fractions, such as particulate and mineral-associated organic carbon (POC and MAOC, respectively), can be released with different amounts and time rates. Consequently, ROS may play differentiated roles in the transformation of different forms of SOC in the riparian zone [57,60]. In addition, the dissolved organic matter (DOM) produced by the decomposition processes of animal and plant residues can represent an important energy source and electron transfer intermediate between terrestrial and aquatic element cycles. Unfortunately, C, N and P content of DOM may cause eutrophication of water bodies [61]. However, modest amounts of such macronutrients, including potassium (K), contribute to high plant productivity and microbial activity, consequently boosting the riparian ecosystem's resilience and biodiversity [27]. Nonetheless, variations in these nutrients over time may lead to differential losses from soil that can alter their concentrations and ratios also in the water system, being more dynamic [62,63]. In the case of N, inputs and losses can be highly variable in riparian areas as flood cycles can affect the impact of plant species and soil characteristics [24]. Bernal et al. [64] emphasize the role of Mediterranean riparian areas as N sink with reduced N_2O emissions and organic N accumulation in the litter and forest floor especially in plane tree forests. Lupon et al. [65] report that Spanish riparian zones show a higher rate of the overall N cycle, including mineralization, net nitrification, and potential nitrate losses. In detail, for the denitrification rates, many authors report changes in this pathway in the soil during different phases of hydrological pulsing with a decline of the process over a drying phase, followed by an increase after a reflooding [66,67]. According to Ye et al. [68], the NO_3^--N content plays an important role, varying during the drying and rewetting phases and positively correlating with the denitrification rate. The removal of N from riparian ecosystems through denitrification is a faster process than plant uptake and microbial immobilization and is considered a solution to the eutrophication of watersheds in agricultural, forestry and urban systems [69,70]. At urban riparian sites, denitrification and microbial biomass can be particularly high, especially at spill sites or with specific vegetation cover (as common reed—*Phragmites* spp.), stating a close relationship between N fate and the C cycle [69,71]. Soil C dynamics and accumulation in disturbed riparian area seem to drive N mineralization and nitrification, inorganic N pools and denitrification particularly for surface soil. In fact, in an urban environment, surface run-off is more important than infiltration phenomena. Evaluation of this aspect is crucial in urban riparian management systems [71]. The fate of other nutrients such as P and K may also change depending mainly on the duration and extent of flooding. Shen et al. [72] reported that alternating dry and wet conditions increased P release in the soil and showed a particularly significant reduction in the P available fraction for riparian soils covered by shrubs.

Furthermore, the variations in nutrient dynamics caused by flooding contribute to the high cation exchange capacity (CEC) of these soils, indicating their strong ability to retain both pollutants and nutrients. The CEC values are generally due to high SOM content and other physical (e.g., soil texture) and chemical (e.g., pH) soil characteristics [73]. In Mediterranean riparian areas, a particularly important parameter related to CEC is soil salinity [30]. Higher ionic strength from dissolved salts promotes flocculation and lowers the solubility of dissolved organic carbon (DOC), thereby limiting labile C availability in Mediterranean riparian zones. However, saline ions can shift pH through cation exchange and alkalinization, which modulates microbial community activity via changes in base saturation and cation exchange capacity [74].

3.3. Soil Biological Characteristics

Riparian soils host a high biological complexity with a variety of microorganisms, fungi, invertebrates, and root systems that all contribute to soil formation and ecological stability. This biological diversity is made possible by the interaction between land and water, as well as consistent disturbances from flooding and productive vegetative communities that provide a patchwork of habitats and multiple ecological niches. Because riparian soils are frequently submerged as a result of flooding, they experience intermittently anaerobic conditions, which affect chemical parameters such as pH and salinity, thereby influencing the structure and function of biological communities [75]. Burt and Pinay [76] highlighted how this unpredictable water regime fosters 'niche' plant and microbial communities adapted to spatio-temporal variations in moisture.

In semi-arid Mediterranean rivers, downstream salinity gradients significantly reduce riparian vegetation cover and diversity. Salinization imposes osmotic stress, selecting for salt-tolerant microbial taxa and suppressing sensitive ones, ultimately altering community structure and reducing soil respiration [77]. Shifts in pH, especially outside the neutral range of 5.5–7.5, can also inhibit enzymatic activities and nutrient transformations, such as those catalyzed by phosphatases and dehydrogenases [78]. For example, studies in Mediterranean coastal lagoons like Fogliano Lagoon (central Italy) demonstrated that salinity gradients profoundly shape microbial diversity and abundance, affecting both surface and deeper soil layers under different land uses [79].

The effects of hydrologic pulsing on riparian zones are now recognized as fundamental drivers of biogeochemical processes and microbial community dynamics [80,81]. In particular, denitrification, a key microbial process under anaerobic conditions, is highly sensitive to flooding regimes. Changes in denitrification rates can be directly linked to shifts in denitrifier community structure [82]. The abundance, activity, and composition of microbial communities are influenced by both the duration and frequency of submergence. Short-term flooding events may enhance microbial diversity, organic matter mineralization, and nutrient release. In contrast, prolonged inundation can decrease aerobic microbial diversity while favoring anaerobic taxa such as methanogens and sulfate-reducing bacteria [75].

Furthermore, community shifts induced by flooding can impact functional processes like N cycling and greenhouse gas (GHGs) emissions. Microbial communities following short inundations tend to be diverse and rich in functional groups involved in SOM turnover. Conversely, extended anaerobic conditions reduce community heterogeneity by selectively promoting low-oxygen-adapted microorganisms. These changes can reduce overall microbial diversity but may increase the abundance of functional types suited to specific environmental conditions. Ye et al. [83] demonstrated that plant succession significantly shapes microbial diversity and C cycling in coastal riparian zones. Similarly, Ye et al. [68] found that denitrification rates vary significantly with vegetation type and flooding phase, reporting at least tree soils showing 11-fold increases during re-flooding compared to dry phases. Molecular markers such as nirS and nirK (encoding for different nitrite reductases) also varied under different hydrologic regimes. Notably, nirK-type communities exhibited greater resilience to water stress, indicating a potential selection mechanism driven by natural drying and rewetting cycles.

In Mediterranean riparian soils, microbial biomass and bacterial composition are shaped by seasonal water availability. Generally, aerobic microbial processes such as nitrification and organic matter mineralization are typically enhanced during moist but aerated conditions, when taxa like certain Proteobacteria and Actinobacteria may become more active. Although summer droughts typically increase soil oxygenation, certain spore-forming anaerobic taxa such as *Clostridia* spp. may persist in a dormant state and become active when anaerobic microsites re-emerge, for instance following rewetting events [84]. Under these circumstances, denitrification—mediated by genera like *Pseudomonas* and *Paracoccus*, becomes essential to mitigate N loss and prevent nutrient leaching into surface waters. Microbial nutrient demand and ecosystem functioning are also governed by elemental stoichiometry and soil nutrient availability, strictly influenced by vegetation [85]. Indeed, microbial activity is affected by SOM depletion driven by vegetation degradation [86,87] and in this context, the abundance of ammonifiers, nitrifiers, and cellulolytic microbes decreases with increased plant degradation, affecting C, N, and P fluxes [88].

The production of ROS is also linked to microbial diversity. Zhang et al. [89] and Chen et al. [90] reported that upstream riparian soils showed higher ROS levels compared to downstream areas, coinciding with higher SOC and DOC contents. River soils, frequently exposed to oxygen, exhibited elevated ROS production, likely due to the abundance of iron-reducing bacteria, which play a central role in redox dynamics [57].

However, soil microorganisms in toto or their specific metabolic pathways, including specific organic compounds and proteins, are used as useful bioindicators of natural or anthropogenic changes in riparian ecosystems. Among the wide use of these biological parameters, soil microbial activity and enzymes act as key components of soil biochemistry, actively participating in nutrient cycling and SOM decomposition [35,91]. In riparian zones, the activity of N- and P-acquisition enzymes is generally higher than that of carbon-related enzymes, and significantly increases in areas with vegetative cover [92].

Finally, biologically, riparian zones support several habitats, shaped by vegetation type and land use, which influence biodiversity [35,69,75,93]. These zones provide great habitat resources for different taxa, not only plants but also animals, thus reinforcing their role in landscape connectivity and ecological resilience [63,93,94].

3.4. Role of Vegetation on the Overall Soil Properties

There is a complex interaction between vegetation, soil, and microbes that is critical to the functioning and resilience of riparian ecosystems. This strict net contributes to nutrient cycling, C sequestering, and resistance to possible invasions of alien species. Riparian root systems are fundamentally structural and functional for the stability and health of river ecosystems. As mentioned above, roots stabilize soils, reduce erosion, and decide the sediment transport within riverbeds and riverbanks, which promotes the hydro-morphological resilience of watercourses [10,95]. Roots also improve water infiltration and soil porosity which allows for gas exchange; they can also create microhabitats suitable for diverse microbial communities important for biogeochemical cycles [41].

Mediterranean riparian zones have high vegetation heterogeneity of trees, shrubs, and herbaceous taxa according to topography, soil type, water availability, and disturbance frequency [1,96]. This high biodiversity is partly supported by the root structure of pioneer species, often called "bank stabilizers", including *Salix* spp., *Populus* spp., and *Platanus orientalis* spp., along with herbaceous species like *Phragmites australis* (Cav.) Trin. ex Steud. and *Juncus* spp., that effectively colonize disturbed areas, producing distinguishable vegetative belts different from the surrounding terrestrial communities (Figure 1). The roots of these species extend deeply (taproots) or laterally depending upon the microhabitat, are dependable for mechanical support, and provide access to water beyond their immediate availability corporate during drought periods to assure ecosystem function [2].

Among these species, *Salix* spp. is usually dominant in wetter and more frequently flooded habitats because of their higher tolerance to flooding, whereas *Populus* spp. and *P. orientalis* L. are dominant in more stable, less flood-prone zones [2,95]. Other frequent riparian species, e.g., *Alnus glutinosa* (L.) Gaertn., *Fraxinus angustifolia* Vahl and *Tamarix* spp. contribute to soil formation and nutrient cycling by the production of litter and their root architecture [96].

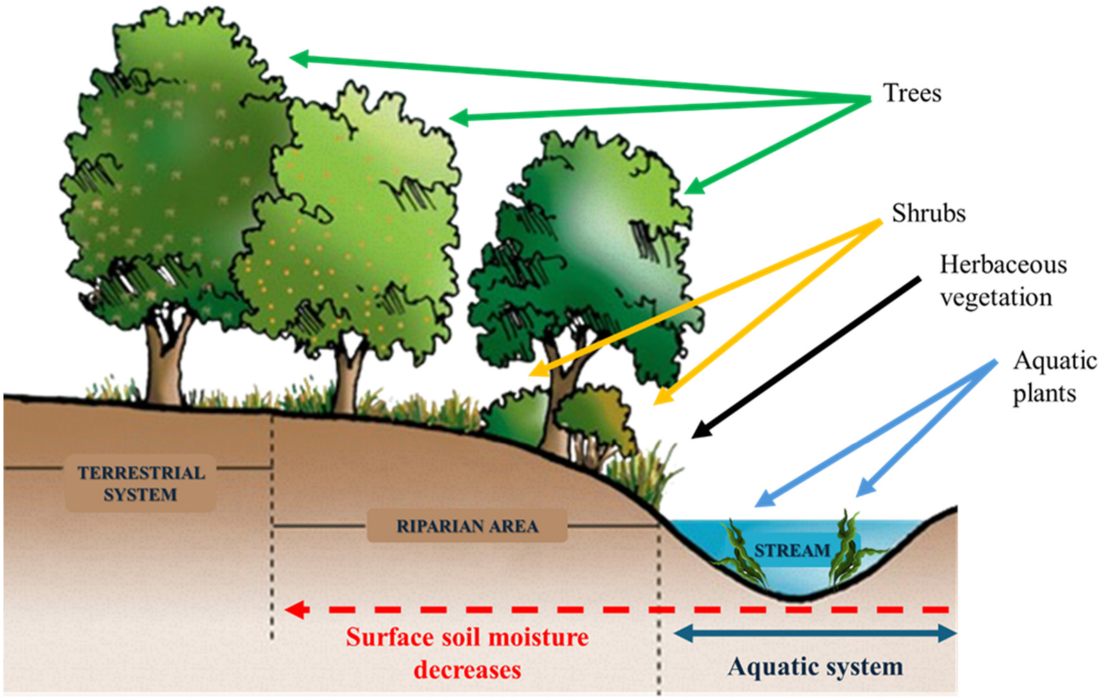

Figure 1. The location of riparian areas and common riparian vegetation of Mediterranean area (inspired by Zaimes et al. [1]).

The differences in root structure alongside litter type impact pedogenesis by influencing C turnover, soil structure and porosity, water retention, as well as nutrient dynamics within the soil. For example, deep taproots enhance soil porosity and aeration, while fine fibrous roots help bind surface soil particles, reducing erosion [97]. These plants also increase microbial activity in the soil which makes chemical reactions occur faster resulting in changes to pH value and CEC, altering soil fertility [10,96].

Nevertheless, Mediterranean riparian areas are severely affected by anthropogenic pressures such as agriculture, deforestation, river regulation, and urbanization, reflecting loss of vegetation and fragmentation, and degradation of root systems [95]. These impacts provide reduced vegetation continuity and altered floristic composition.

4. Ecological Functions of Riparian Soils

Riparian zones act as ecological engineers, particularly in Mediterranean environments where river systems are subjected to strong seasonal variability and anthropogenic pressures such as agriculture, urbanization, and water abstraction. The soils within these riparian corridors underpin many of the ecological functions attributed to these systems, serving as key interfaces between terrestrial and aquatic environments [10,43]. Their unique biogeophysical characteristics make them central to the delivery of several interlinked ESs that are critical to river health and landscape resilience (Figure 2). Among all, the most important services are water quality and hydrological regulation, erosion control and streambank stabilization, C sequestration, biodiversity and ecological connectivity, and temperature regulation.

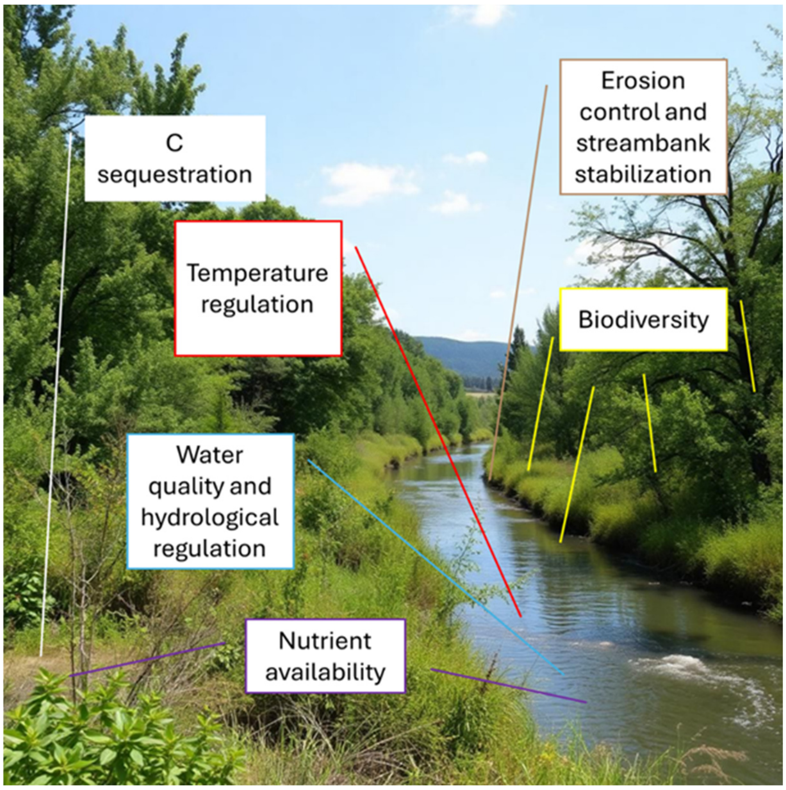

Figure 2. Riparian zones acting as the ecological engineers and reporting some of the most important ESs.

One of the most important services provided by riparian soils is water quality regulation. Acting as biogeochemical filters, riparian soils reduce nutrient and contaminant loads before they reach surface waters. This is particularly critical in Mediterranean catchments where agricultural runoff and diffuse pollution are prevalent. The combination of high organic matter, variable redox conditions, and active microbial communities allows for the efficient transformation and retention of N, P, heavy metals (HMs), and pesticides [10,38]. For example, studies in the Ebro basin have shown that forested riparian zones dominated by *Populus alba* L. and *Salix atrocinerea* Brot. can reduce nitrate concentrations by over 70% [98]. Riparian vegetation also contributes to this service by slowing overland flow, enhancing sedimentation, and providing additional surfaces for chemical and microbial processes [99]. These mechanisms are especially valuable in Mediterranean systems where traditional wastewater infrastructure fails to address non-point source pollution. Beyond this ES, riparian soils in Mediterranean landscapes are vital for hydrological regulation. Their texture and structure promote infiltration and subsurface flow, thereby reducing surface runoff, enhancing groundwater recharge, and maintaining baseflows during dry periods [10]. These regulating functions are amplified by the vegetation, which increases soil porosity and intercepts rainfall. In highly seasonal environments, such as the Tiber and Guadalquivir river basins, this function helps buffer against both drought and flash flooding, stabilizing the local hydrological regime and ensuring the continuity of aquatic and riparian ecosystems [100,101].

Erosion control and streambank stabilization are also essential for riparian areas, particularly in Mediterranean basins characterized by steep slopes and episodic intense rainfall. Bank erosion can contribute up to 50% of the total sediment yield in some Mediterranean catchments [102], making this service indispensable. Root systems of native plants like *Salix* spp. and *Tamarix africana* Poir. mechanically bind soil particles, increase shear strength, and resist hydraulic stress [2,100]. At the same time, riparian vegetation enhances surface roughness, reducing flow velocities and encouraging sediment deposition along banks [41]. These combined effects reduce the risk of channel incision and help maintain geomorphic and ecological stability in river corridors affected by land use intensification.

Another key soil-based service in riparian zones is C sequestration, which contributes to both climate regulation and local soil fertility. Riparian soils receive periodic inputs of organic material from flooding, litterfall, and root turnover. These conditions, coupled with high microbial activity during wet periods, promote the accumulation and stabilization of SOC [65,76]. Studies have shown that riparian soils can store significantly more C than adjacent agricultural lands. The seasonally dynamic wet–dry cycles typical of Mediterranean climates further regulate microbial decomposition rates, producing episodic carbon fluxes and enhancing long-term carbon retention [2,40]. Mineral associations within these soils and the structural complexity provided by root systems contribute to carbon stabilization and aggregation processes [52].

In addition to regulating flows and storing carbon, riparian soils support biodiversity and ecological connectivity, especially in fragmented Mediterranean landscapes. Soil-mediated processes facilitate the establishment of diverse plant communities and create habitat mosaics for insects, amphibians, birds, and mammals. Vegetated riparian corridors are crucial for maintaining biological diversity in heavily altered catchments. Lind et al. [47] found that buffers wider than 24 m are required to sustain plant diversity, while vertebrate populations benefit from widths of up to 100–150 m. These zones also maintain trophic linkages through organic matter export to streams, supporting aquatic food webs and functional diversity [103].

Finally, riparian soils contribute indirectly to temperature regulation through the support of dense vegetation that shades streams and stabilizes microclimates. This is particularly important in Mediterranean regions where summer temperatures can exceed thermal tolerance limits for many aquatic species. Shaded streams with riparian cover can be up to 4 °C cooler than those without, providing thermal refugia for sensitive species such as *Luciobarbus* spp. and *Austropotamobius italicus* Faxon [104].

In Mediterranean regions, riparian soils represent multifunctional systems that deliver key regulating, supporting, and provisioning services fundamental to river health, landscape resilience, and human well-being. Their contributions to water purification, erosion control, carbon storage, hydrological buffering, and biodiversity support highlight the need for targeted conservation and restoration. Approaches such as the Ecologically Functional Riparian Zones (ERZ) framework [47] provide science-based guidance for optimizing riparian buffer width and structure based on soil type, vegetation, and hydrological context. Safeguarding these systems is essential for addressing current environmental challenges and ensuring the sustainability of Mediterranean river basins under future climatic and land use changes.

5. Anthropogenic Impacts, Biological Invasions and Climate Change

Although the riparian zone provides numerous benefits, its existence is strongly affected by human activities [105]. Riparian areas are subject to constraints on land use such as agricultural conversion, irrigation withdrawals [106,107] or dams construction (Figure 3).

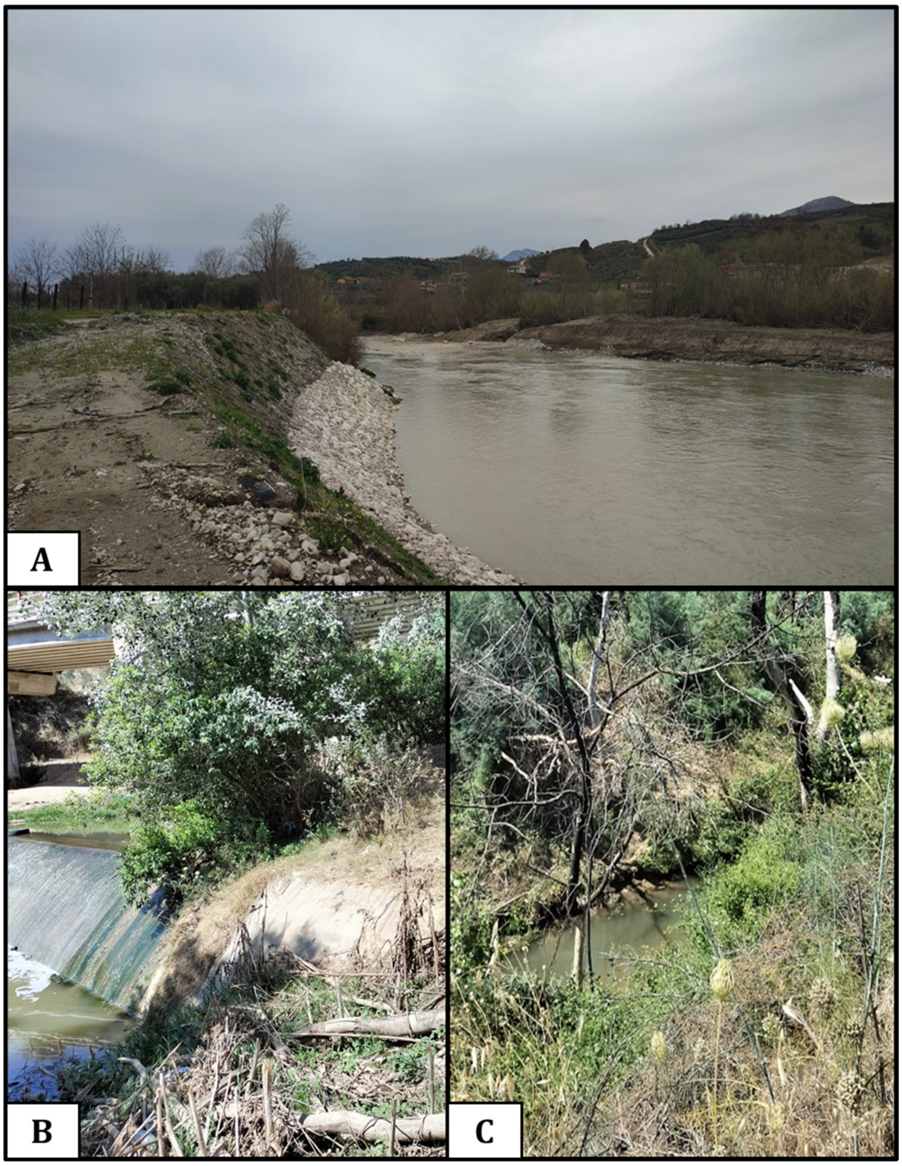

Figure 3. Landscapes of different Mediterranean riparian areas: (**A**) Medjerda river (Souk-Ahras province, north-east Algeria); (**B**,**C**) Calore river (Benevento province, southern Italy) (pictures shot by Prof. Dr. Anna De Marco in 2025).

Therefore, riparian ecosystems are extremely sensitive to land use changes [35,108]. Humans have occupied the Mediterranean for thousands of years and overexploited ESs of riparian areas, leading to their degradation [109]. The region, mainly in northern Africa (e.g., Egypt, Algeria, Tunisia, Libya, Morocco) and in the Eastern Mediterranean/Middle East (e.g., Lebanon, Syria, Jordan, Israel and Palestine), faces water scarcity coupled with rapid population growth [110].

Since 2000, both agricultural land and human activities in the region have expanded significantly. In fact, in recent decades, human and agriculture activities have intensely impacted these areas resulting in an overall decrease in soil and water quality. Generally, the expansion of agricultural and urban land into riparian areas poses significant threats to riparian soils. Urbanization exerted an intensive pressure on riparian system resulting in vegetation trampling, soil compaction or erosion, pollution and eutrophication phenomena [111,112], reduced permeability due to the increase in impervious surfaces, altering water infiltration and flow patterns [38].

Amongst other factors the increasing number of industries, waste production and removal, population growth and consequent urban development in pristine areas led to changes in land use and impacted soil and water quality over time [30,36,37,65,98]. In particular way, the expansion of agriculture, considered to be the other culprit for the extreme degradation of riparian areas, emphasized the land use change and alteration of these ecosystems by impacting on several ecological processes [28,101]. With the rapid urbanization and with the increasing use of fertilizers and pesticides, soil HMs pollution has become an urgent environmental concern [106]. In the Mediterranean lowlands, these pressures have resulted in fragmented ecosystems, unlike in upland areas where farming remains comparatively limited, producing adverse consequences for the delivery of ESs [1].

The studies conducted by Napoletano et al. [35,63], in Algerian riparian soils, analyses how anthropogenic impacts increase the concentrations of heavy metals (Cd, Cu, Fe, Mn, Ni, Pb and Zn) in the riparian ecosystems of the Medjerda river. The results showed that when compared to non-urban areas, urban areas and peri-urban areas were richer in HMs which compromises soil quality in terms of different contents of SOM, carbonates, hygroscopic water and pH. Indeed, a long history of agricultural exploitation and the recent increase in the rate of urbanization have exposed the Medjerda river to pollution from agricultural and domestic sources [113]. The results from this study emphasize that the expected industrial and urban development of the study area, besides agriculture, could raise the HMs pollution worryingly.

Furthermore, studies by Richardson et al. [27] confirm that land use changes reduce organic matter turnover, nutrient levels, and biodiversity in riparian areas. Here, biological invasions pose significant threats, especially if the areas are already stressed by anthropogenic pressures. Invasive plant species such as *Ailanthus altissima* (Mill.) Swingle, *Arundo donax* L. and *Tamarix* spp. have become widespread in riparian zones, often forming dense monocultures that outcompete native vegetation, leading to biodiversity loss and changes in soil properties [21,104,105,114]. *A. donax* is known for its rapid growth and high water consumption, which can lead to decreased water availability for native species and increased fire risk due to its dry biomass [106]. In addition, the release of phytotoxins, accumulation of leaf litter, rhizomes, as well as shading and fast growth impact on foodwebs, inducing low nutritional value and toxicity to both plant and animal communities [104]. Similarly, *Tamarix* spp. have been shown to lower water tables and increase soil salinity, further hindering the establishment of native species. These changes in plant species composition are very often exacerbated by climate change [115–118].

In terms of fauna, non-native species such as *Linepithema humile* Mayr has disrupted local food webs and displaced native insect populations, leading to cascading effects on riparian biodiversity [119]. These invasions are often facilitated by human activities, including land use changes, water management practices, and the global movement of species through trade and travel [120]. The combined impact of invasive species and other stressors underscores the need for integrated management strategies to protect and restore the ecological integrity of riparian ecosystems in the Mediterranean basin.

In addition, another important factor threatening riparian ecosystems, often overlooked, is the increase in seasonal tourism in most Mediterranean countries, with an overall increase in the population in coastal regions during the summer [121,122]. However, in the decades ahead, water supplies and riparian ecosystems are expected to come under increasing strain as a result of expanding human interventions [35,63].

Crop expansion, uncontrolled grazing, increased demand for timber, illegal logging, and deforestation have reduced the areas of natural vegetation along rivers to narrow linear strips along their banks [121]. Removal of vegetation in riparian zones destabilizes the soil, increases erosion, and disrupts nutrient cycling. Without root systems to bind soil particles, riparian soils become more susceptible to erosion, which can lead to sedimentation in surrounding water bodies, damaging aquatic ecosystems [41]. Overgrazing and logging further exacerbate soil degradation by reducing organic matter inputs and compacting the soil, making it less hospitable to plants and microorganisms [25,82].

Climate change presents several challenges to riparian soil health, including altered precipitation patterns, increased frequency of droughts and floods, and shifting vegetation communities. The Mediterranean region is one of the most vulnerable to global change [2]. Regional projections indicate a strengthening of the hydrological cycle, driven by rising temperatures, more intense rainfall events confined to shorter periods of the year, reductions in summer precipitation of up to 50%, and an escalation in both the frequency and severity of droughts [123,124]. Forecasts also point to decreasing mean river discharges, higher water temperatures, and more frequent large-scale floods. In Mediterranean catchments, declining runoff has already been documented in rivers across Greece [125], the Balkans [126], Lebanon [127], Turkey [128] and Spain [36]. Since most Mediterranean basins are sustained by snow-fed mountain springs, rising temperatures are expected to diminish snowpack and accelerate snowmelt [2]. Combined with climate change impacts on hydrology and growing water demand from population increases, this is likely to accelerate the transition from perennial to intermittent streams, and from intermittent to ephemeral ones [129]. The mounting stress on diminishing freshwater resources will further aggravate impacts on rivers and their riparian zones [130]. Moreover, prolonged and irregular droughts, whether seasonal or multi-seasonal, are projected to intensify pressures on native plant and animal communities [131]. Consequently, riparian habitats along intermittent and ephemeral streams are predicted to expand in extent, while those tied to perennial streams are expected to undergo a marked decline [2]. According to Firoozi and Firoozi [132], changes in flood regimes may lead to soil erosion and reduce riparian zones' capacity to buffer water flows. Warmer temperatures may also affect microbial communities and nutrient cycling processes in riparian soils, leading to shifts in ecosystem dynamics and reduced soil C storage.

6. Conservation and Management of Riparian Soils

The challenges posed by anthropogenic activity and climate change can alter patterns and processes that support riparian functions and biodiversity [133]. Riparian ecosystem restoration is therefore increasingly recognized as critical to mitigating many environmental stressors. The main pressures and related changes and effects are shown in Figure 4.

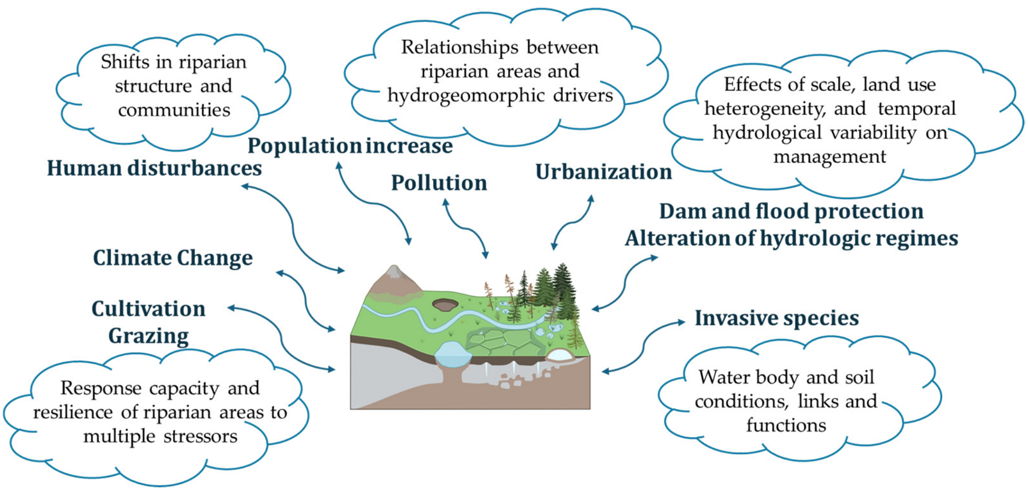

Figure 4. Dominant stress factors and their ecological variations (visualized in clouds) related to riparian ecosystems.

About 40% of Earth's natural terrestrial ecosystems have been converted to agriculture, with intensification and growing land demand driving habitat loss and reduced heterogeneity, following trends expected to worsen with rising population for food demand [134–136]. Against this backdrop of increasing pressure on natural ecosystems due to agricultural expansion, the conservation and restoration of riparian areas become particularly critical, especially in the Mediterranean region, where these habitats provide essential ecological functions and are internationally recognized for their environmental value. The importance of restoring riparian systems in the Mediterranean region is recognized, as many areas have been designated as protected under the Habitats Directive (92/43/EEC) and the Ramsar Convention [1]. The Water Framework Directive (WFD; 2000/60/EC) obliges European Union (EU) countries to assess the characteristics of their riparian areas [137]. Nevertheless, in numerous countries, regulations for the establishment and management of riparian buffer zones are still insufficient [138] leaving many riparian habitats vulnerable to human pressures that shrink their extent and compromise their ecological integrity. Efforts aimed at restoring these areas often achieve limited success in recovering the original biodiversity and structural stability characteristic of undisturbed riparian ecosystems [2]. On the other hand, a wide range of riparian restoration projects have attempted to enhance riparian ecosystem services and mitigate the impacts of agriculture [139]. However, adequate evaluation of restoration success is usually lacking [140,141]. Their outcomes depend on the objectives, previous conservation status, social acceptance, and techniques used [142]. In addition, riparian restoration is particularly important in semi-arid Mediterranean areas [143], where riparian forests are the most threatened ecosystems due to land use intensification and associated water abstraction [33].

The greatest habitat improvements occur when riparian management involves the planting of trees or remnant forest [144]. Riparian restoration focused on reforestation of degraded areas allows forest structure to recover rapidly and, although it may not become a true riparian forest, high levels of complexity, diversity and functionality can be achieved [145–147]. Furthermore, riparian management through planting is considered as a line of defense also to mitigate contaminants before they enter the watercourse and improve its quality. Among all, fencing livestock and withdrawing riparian margins from agricultural use are additional practices particularly important to improve water quality [144]. Riparian assessment on riparian vegetation and hydromorphological relationships is frequently conducted in at least 68 countries, from 1949 to 2015. The largest percentage of studies was conducted in north America (over 40%), followed by Europe (22%), and south America, notably the Amazon basin (12%). For the study of vegetation-hydromorphology relationships, Stella et al. [96] identified that the biomes studied most were temperate forest, followed by semi-arid and desert shrubland, and Mediterranean forest.

In the Mediterranean context, the success of reforestation and replantation is usually conditioned by the suitability and adaptation of plant species to survive under multi-stress conditions due to natural (e.g., drought and high salinity) and anthropogenic (e.g., agricultural intensification and alteration of the flow regime) stressors. The identification of the main stressors that determine plant survival and growth can help managers in selecting the most suitable species and river reaches for an economic riparian restoration in semi-arid Mediterranean areas [30]. Among the potential determinants of restoration success, groundwater depth and soil properties appear to play a prominent role in plant survival and growth [27,63] which could subsequently influence the scale and magnitude of the ecosystem service provided by riparian areas.

The study conducted by Castellano et al. [30], in two Mediterranean catchments nestled in the Flumen river basin (northern Monegros County, Iberian Peninsula), demonstrates that the main factors influencing the success of riparian reforestation in semi-arid

Mediterranean areas are environmental drivers such as water table depth, soil salinity and soil nutrients. Furthermore, it reveals that riparian restorations in agricultural landscapes can be effective in terms of improving the provision of ecosystem services such as water purification, habitat provision, microclimate regulation and soil C storage, compared to degraded riparian areas and agricultural crops. In particular, the study provides new insights for landscape managers on the interactive effects of water and soil variables that drive the survival and growth of planted vegetation, which should be taken into account to optimize the design of riparian restorations in Mediterranean agricultural landscapes. According to the authors, this approach will help increase the success of further riparian restorations.

In addition, to guide management plans, a better understanding of the relationships between riparian plant structure and their hydrogeomorphic drivers at the catchment scale [33] is needed. For the successful application of these strategies, it is essential to gather and evaluate knowledge from past restoration efforts throughout the Mediterranean. Actions should focus on restoring hydrogeomorphic processes to promote the long-term self-sufficiency of riparian ecosystems [142]. Additionally, further research is needed on the conditions, connectivity, and ecological roles of water bodies and riparian zones, considering how water management practices influence ecosystem service provision [148]. There are many physical models on the impacts of climate change on water scarcity, but such approaches are limited [2].

However, riparian management practices should be adopted according to the specific problems of the area and the "one size fits all" approach is not effective because the functions of riparian zones vary depending on the geography of the area [149]. For example, the management practice for a riparian zone dominated by intensive agriculture should be different from the riparian zone under the threat of urbanization [10].

Future pressures on Mediterranean riparian zones are expected to intensify, making it essential to implement strategies that safeguard ecosystem services for generations to come. These ecosystems possess inherent resilience, and with targeted interventions, their structure and function can be preserved and restored effectively [2].

7. Conclusions

Riparian zones represent ecologically vital interfaces between terrestrial and aquatic environments, playing a central role in landscape connectivity, water regulation, and soil development. The dynamic hydrology of these areas, marked by fluctuating water tables, periodic flooding, and moisture gradients, drives unique soil-forming processes (pedogenesis) that shape their physical, chemical, and biological characteristics. These include enhanced nutrient cycling, organic matter accumulation, and microbial diversity, all of which are deeply influenced by vegetation cover and root systems. Functioning as natural filters and carbon sinks, riparian soils provide critical ecosystem services, from water purification to erosion control. The soils, shaped by alternating wet and dry cycles, are particularly important for C storage and nutrient retention in these climate-sensitive landscapes. However, these functions are increasingly threatened by anthropogenic pressures such as land use change, pollution, and hydrological alterations, as well as by the growing impacts of climate change. These stressors compromise soil health and long-term ecosystem resilience, especially in Mediterranean catchments where water scarcity and extreme weather events are intensifying.

Recognizing the complexity and vulnerability of riparian soils, especially in Mediterranean contexts, is essential for their sustainable conservation. Unfortunately, existing research on Mediterranean riparian systems remains scarce, and further studies are urgently needed. Moreover, integrated management strategies that account for hydrological dynamics, vegetation patterns, and soil integrity are crucial to preserving the ecological functions of riparian zones and ensuring their continued contribution to both local and global environmental stability. Therefore, maintaining and restoring the health of riparian soils is not only an ecological priority but a key action necessary to uphold essential ESs and pivotal for safeguarding for future generations. Appreciating the irreplaceable contributions of riparian ecosystems, and acting accordingly, is vital for a sustainable future.

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