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The Role of Non-Native Plant Species in Modulating Riverbank Erosion: A Systematic Review

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ABSTRACT

Riverbank erosion is a naturally occurring process that influences riparian zone habitats. However, anthropogenic activities are increasing rates of riverbank erosion. Climate change and hydrological and physical modifications drive riparian zone perturbations. Whilst native riparian vegetation can reduce riverbank erosion, the proliferation of non-native riparian plant species has been linked to riverbank instability, with marked changes in fluvial erosional regimes attributed to invasion by species such as *Impatiens glandulifera* (Himalayan Balsam) or *Tamarix* (Tamarisk) into riparian zones. Yet, the role of non-native plant species in modulating riverbank erosion remains unclear, in part due to the lack of investigations that quantify geomorphic change. We systematically assessed the relevant ecological and geomorphological literature to determine current understanding and to offer recommendations for future research on non-native plant—riverbank erosion. Included articles focused on a limited number of non-native plant species across a restricted range of habitats types, with dependency on topographic change and generally short study duration obscuring potential causal links or feedback cycles. It is critical in the face of parallel rapid proliferation of riparian non-native plant species and climate change effects, that we improve mechanistic understanding of their role in riverbank erosion.

1 | Introduction

Riverbank morphology is a product of opposing processes acting on riverbank structure, chiefly riverbank erosion and sediment deposition (Thorne and Tovey 1981; Simon et al. 2000; Church 2006). The erosion of riverbanks (defined as a topographic surface from the channel bed to the bank-full stage, where water begins to spread over a floodplain Florsheim, Mount, and Chin 2008) can be conceptualised as the balance between fluvially, and gravitationally, exerted shear stresses and geotechnical resistance forces acting predominately on the riverbank toe and to a lesser extent the riverbank face, controlling the loss of sediment (Darby and Thorne 1994; Church 2006; Langhorst and Pavelsky 2023).

Riverbank erosion is an important process in driving habitat creation. The constant disturbance and reworking of sediment and the dynamic nature of fluvial environments promotes the creation of new habitats throughout the riparian zone, an ecotone consisting of terrestrial and aquatic habitats. Native vegetation growing in the riparian zone can play an important role in modulating riverbank erosion, particularly at a reach scale (Gurnell 2014). Native vegetation above-ground biomass can deflect near bank flows and trap sediments during flood events (Vesipa, Camporeale, and Ridolfi 2017). Similarly, below-ground rhizome structures can provide marked hydrological and mechanical reinforcement (Pollen-Bankhead and Simon 2010; Nilsson et al. 2010; Figure 1). However, there is often a disconnect between the geomorphological and ecological controls on

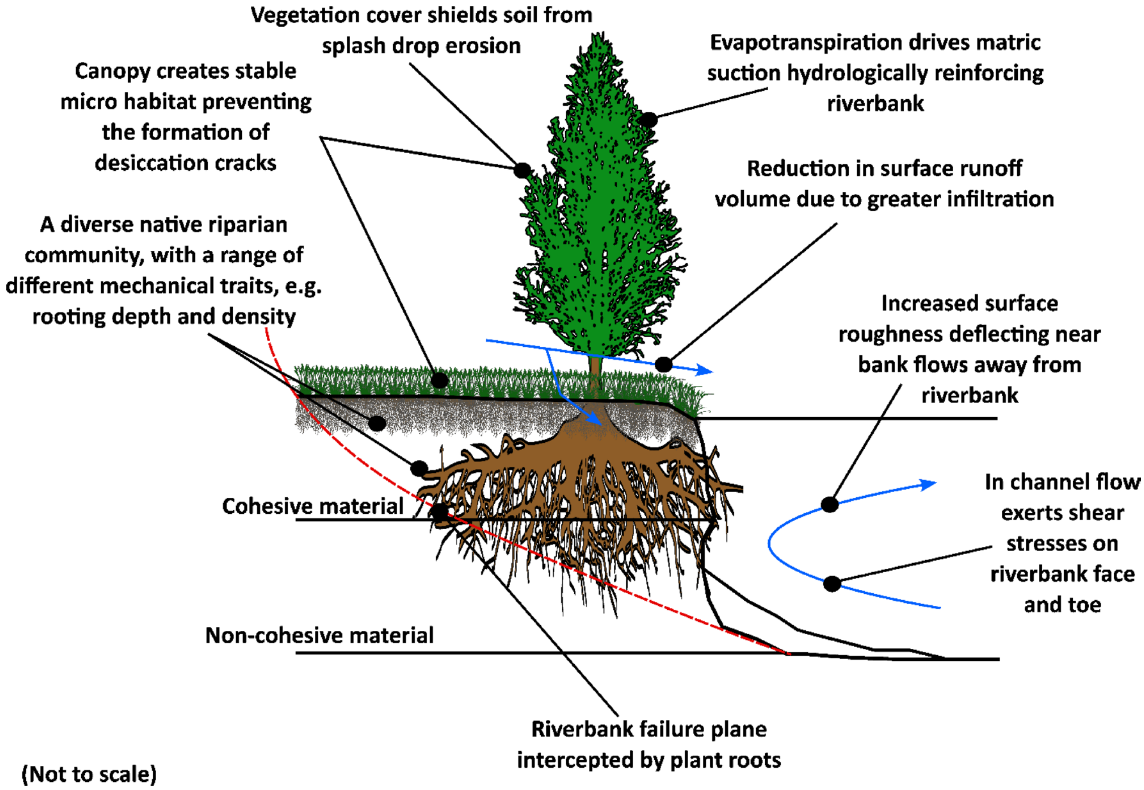

FIGURE 1 | Diagram depicting the influence of vegetation on riverbank erosion. [Color figure can be viewed at wileyonlinelibrary.com]

riverbank erosion that in a time of anthropogenically forced extreme global change, has substantive implications for riverbank restoration and management.

Globally, riparian zones face numerous anthropogenic pressures including flow regulation, encroachment of agriculture (Maracahipes-Santos et al. 2020; Wohl 2020), climate change induced changes to flood regime intensity and magnitude (Wasko et al. 2021), riverbed sediment extraction (Hackney et al. 2020), urbanisation (Wohl 2020) and introduction of non-native species (Pattison et al. 2017; Emery-Butcher, Beatty, and Robson 2020). These factors may directly impact the magnitude and timing of fluvial erosion. For example, increasing flood magnitude and frequency increase the ecological disturbance regime (Wohlgemuth, Jentsch, and Seidl 2022) acting on riparian vegetation, leading to plant communities experiencing greater abiotic and biotic stresses (Gurnell and Downs 2021; Henriques et al. 2022).

Native riparian plants exposed to these high stress states are at greater risk of biological invasions by non-native plant species (NNPS) (Zelnik, Haler, and Gaberščik 2015). Here NNPS are defined as species introduced outside their native range with impacts occurring at any stage of the invasion process (see Soto et al. 2024). NNPS can outcompete and replace native riparian vegetation, reducing diversity and the abundance of native plant species (Richardson et al. 2007; Pattison et al. 2017; Pattison, Whytock, and Willby 2018). Whereas native riparian vegetation has developed a range of morphological and phenological adaptations suited for specific river dynamics the colonisation of NNPS along riparian zones is likely to have different effects on erosional processes due to contrasting phenological and morphological traits (Greenwood and Kuhn 2014; Stover et al. 2018). This may result in the destabilisation or stabilisation of riverbanks. Indeed, NNPS have also been translocated by humans for riverbank erosion control projects (Chew 2009), providing an added dimension to the complexity of native vegetation responses to NNPS invasion. Given the important role of riparian vegetation in modulating riverbank erosion, understanding how NNPS may potentially alter this process is a critical area of understudied research needed to guide river management. Especially in the context of rapid global proliferation of NNPS (Seebens et al. 2021), who is effect on riverbank stability has not yet been determined.

A series of widely accepted assumptions regarding the role NNPS play in erosional processes are imbedded within current river management policy (e.g., Scottish Environmental Protection Agency 2020); for example, that *Impatiens glandulifera* increases overwinter riverbank erosion. The evidence based to support this relies on just three studies (Greenwood and Kuhn 2014; Greenwood et al. 2018; Greenwood, Gange, and Kuhn 2020) and anecdotal evidence from a few study sites. NNPS presumed role in modifying riverbank vulnerability to erosion, has been linked to a range of biotic factors including more limited vertical and lateral root systems compared to native species, and over winter dieback leaving riverbanks 'bare' during periods where flows are typically higher in temperate latitudes (Greenwood and Kuhn 2014; Greenwood et al. 2018; Greenwood, Gange, and Kuhn 2020; Matte, Boivin, and Lavoie 2022). Previous research suggests the influence of NNPS on erodibility of riverbanks is not unidirectional (González et al. 2020a; Matte, Boivin, and Lavoie 2022). For example, it has been shown that the NNPS *Tamarix* can provide riverbank reinforcement through increased rooting depths and above ground biomass that increases riverbank surface roughness, deflecting near riverbank flows thereby reducing riverbank shear stress (Pollen-Bankhead et al. 2009; González et al. 2019). However, these multi-faceted impacts of NNPS, increasing and decreasing the erodibility potential of riverbanks have not yet been comprehensively assessed at a global scale, despite its crucial importance in riparian zone restoration and management.

Despite the development of linkages between riparian vegetation and riverbank erosion (e.g., Gurnell 2014; Finotello et al. 2024), the specific impacts of NNPS on riverbank erosive processes, are largely unexplored (e.g., Fei, Phillips, and Shouse 2014; Emery-Butcher, Beatty, and Robson 2020; O'Briain, Corenblit, and Gurnell 2023). Synthesising current knowledge of NNPS in modulating riverbank erosion is necessary to understand the underlying mechanistic role NNPS play and to ensure a sufficient evidence base to facilitate policy decisions for both NNPS and riverbank erosion management. This systematic literature review synthesises current understanding of the role of NNPS in modulating riverbank erosion relative to native vegetation. Its key objectives are to (i) collate and synthesise evidence on how NNPS and native vegetation influence riverbank erosion and the relative significance of their roles; (ii) assess the methodologies used and the range of NNPS investigated and (iii) evaluate the bias that exist in NNPS riverbank erosion studies.

2 | Methods

To identify the role NNPS play in modulating riverbank erosion, we reviewed peer-reviewed and grey literature following a systematic review protocol conforming to the Collaboration for Environmental Evidence Guidelines (Pullin et al. 2022). The term NNPS was used to account for variability in the definition of what classifies as an invasive non-native species (see Soto et al. 2024).

2.1 | Search Strategy

To guide the Scoping Phase of this systematic review, our primary research question was disaggregated according to the PICO principles (Pullin et al. 2022). The PICO principles consist of four statements, which in this study are defined as:

Population: Any riverbank in any physiogeographic setting (i.e., a geographic region with a particular set of physical variables, e.g., altitude and rainfall, which are distinct from surrounding regions and any fluvial morphological type [Church 2006]).

Intervention: Any non-native plant that colonises riverbanks.

Comparator: Any non-vegetated or native riparian vegetated riverbank.

Outcomes: Any riverbanks showing a/no morphometric change (i.e., erosion or deposition).

Ten peer-review articles that captured the scope and range of terminology used (Appendix 1) were selected as benchmark articles to guide the Scoping Phase. The keywords used in the initial scoping test search strings were extracted from the benchmark articles (Appendix 1). Each search string was developed and tested in Web of Science, with the minimum combination of keywords used initially to maximise the retrieval of relevant results. The search string was made more generalised with additional terms, especially in reference to the range of terminology used to describe NNPS (see Golebie et al. 2022; Stevenson et al. 2023; Soto et al. 2024). During the iterative development of the final search string, the comprehensiveness of each search string was tested against its ability to return the benchmark articles in Web of Science (Foo et al. 2021). The final search string returned 100% of the benchmark articles:

(River or riverbank OR channel OR bank or stream) AND (non-native species OR invasive* OR alien OR exotic OR introduced OR non-indigenous OR non-native) AND (erosion OR stability OR 'factor of safety' OR destabilisation OR failure OR 'sediment loss') AND (vegetation* OR plant* AND riparian).

All searches were performed in English. Therefore, English language articles or articles translated into English were included in this review. We acknowledge that the exclusion of non-English language articles will introduce bias (Morrison et al. 2012; Hannah et al. 2024). We used Web of Science Core Collection (Clarivate 2024), SCOPUS (Elsevier 2024) and CABI abstracts (CABI 2024b) to collate peer-reviewed studies. To collate grey literature-Google Scholar, Google Search Engine and CABI Abstracts were searched for non-peer reviewed conference papers and proceedings, dissertations and theses (i.e., MSc, MRes, MPhil and PhD), whilst government and non-governmental organisations were searched for official and technical reports, for example, UK Environment Agency, United States Geological Survey and Parks Canada, and working papers. Searches included all years up to the end of March 2024.

2.2 | Article Screening and Eligibility Criteria

The title, keywords and abstracts of articles and grey literature identified were collated into EndNote 20 bibliographic software (The EndNote Team 2024). Duplicates were removed using EndNote's 'find duplicate' tool. The unique references were exported from EndNote and imported into Rayyan for screening (Ouzzani et al. 2016).

2.2.1 | Screening Process

All articles were screened by members of the review team in three stages: (1) title, (2) abstract, and (3) full text (Appendix 2). At stage 1, articles were assessed against the eligibility criteria below. However, if there was insufficient evidence to exclude a study at title level (stage 1), it was screened again at stage 2 abstract level, and thereafter stage 3 full text. A record was kept of all studies excluded at full text level ($n=31$).

Screening was conducted by one reviewer. To ensure consistency in the exclusion process, a random 20.0% subset of articles was selected for second review. Any disagreements were discussed between reviewers to reach a consensus.

Additional collation of articles was undertaken at full text level, each included article reference list was used to identify other possible articles that met the inclusion criteria below; often termed 'snowballing' (Greenhalgh and Peacock 2005).

The following defined criteria were used to assess the inclusion of each article at all levels of screening:

1. Population
   a. Study investigates vegetated (NNPS and/or native) or non-vegetated riverbanks across any physiogeographic region and fluvial morphology.
2. Intervention
   a. Study investigates the impacts of one or more NNPS, as listed by the CABI Invasive Species Compendium (CABI 2024a), on riverbank erosion.
3. Comparators

   For one or more of the following, the study compares:
   a. The differences in riverbank erosion between native and NNPS field site/sites.
   b. Changes in riverbank cross sectional riverbank profile of an invaded riverbank over time, for example, yearly or monthly.
   c. Invaded riverbank evaluation changes pre- and post-flood events.
   d. The differences in river channel morphology, for example, narrowing or widening, pre- and post-invasion of NNPS.
   e. The differences in channel morphology pre- and post-NNPS management, for example, whole plant removal or chemical treatment.
4. Outcome
   a. Studies present evidence of changes in riverbank morphology, indicative of erosional processes.
5. Study Design

   For one or more of the following the study is designed as:
   a. Direct field observations of riverbanks
   b. In-direct remote sensing methods (e.g., aerial photography and satellite imagery)

2.3 | Data Coding and Extraction

A standardised data extraction template (Appendix 3) was developed to extract key variables from each article included at the full stage text. Data were coded into four broad categories: (i) bibliographic information, (ii) study scope, scale, and geographical location, (iii) NNPS interventions and (iv) riverbank erosion comparators (Appendix 3).

3 | Results

Keyword searches returned cumulatively 2778 articles: 1435 articles from SCOPUS; 395 articles from Web of Science; 427 articles from CAB abstracts; 500 from Google advance searches and 21 from snowballing, published between 1978 (first article found) and March 2024. Removal of duplicates left 2723 articles. After all three screening stages, 31 articles satisfied the eligibility criteria and were included for review. Only 1.1% ($n=31$) of the total collated articles directly linked riparian non-native vegetation to riverbank erosion processes through empirical field/remote sensing-based investigations. The excluded articles did not directly measure or test for NNPS modulated riverbank erosion. Despite this, 18.0% of excluded articles claimed to be testing this.

Both ecological geomorphology and environmental journals were represented across the included articles; *Geomorphology* (9.7%), Ecohydrology (9.7%), River Research and Applications (9.7%) and Journal of Soils and Sediment (6.5%).

3.1 | NNPS Role in Modulating Riverbank Erosion

The majority of included articles (90.3%) reported that NNPS played a significant role in modulating riverbank erosion (Figure 2). Of these articles, the direction of NNPS impact on riverbank erosion varied, with 54.8% of studies reporting a decrease in erosion, and 45.2% reporting an increase. In addition, the rates and direction of erosion reported differed amongst studies depending on the NNPS studied (Table 1), from 0.014 m a^{-1} with *I. glandulifera* (Greenwood and Kuhn 2014) to 1.85 m a^{-1} following *Tamarix sp* removal (Pollen-Bankhead et al. 2009). Whilst reporting a significant effect (p-value based statistical testing), some articles ($n=6$) report uncertainty regarding the magnitude of geomorphic change that NNPS directly contributed to riverbank erosion. For example, Arnold and Toran (2018) could not distinguish the NNPS erosional signature from native vegetation in terms of water turbidity change due to overprinting, that is, greater sediment flux from other sources, in response to peak flows. However, for most NNPS investigated there is limited evidence from which to draw conclusions regarding the contribution of NNPS to riverbank erosion (mean articles per NNPS $n=2$).

3.2 | Plant Species Investigated

Overall, 38 NNP and 61 native species were studied across included articles. NNPS were predominantly deciduous shrubs (37.1%) such as *Tamarix* (25.4%) and *Elaeagnus angustifolia* (7.9%), thereafter the perennial herb *Reynoutria japonica* (4.8%) and annual herb *I. glandulifera* (6.3%) (Figure 3). Species level identification of NNPS and native riparian vegetation varied across included articles, with 54.8% undertaking species level vegetation surveys to characterise the riparian plant community. Remaining articles characterised riverbank vegetation structure and community by genus level or growth form. For instance, vegetation surveys were simplified to denote the bulk community composition by the dominant native plant species, for example, *Salix* in Cadol, Rathburn, and Cooper (2011) to compare with *Tamarix* dominated stands. Similarly, Greenwood and Kuhn (2014) identified the most abundant native ground cover species to genus, for example, *Urtica* and *Ranunculus*, to compare with *I. glandulifera*. In contrast, some studies examined the effects of NNP management on riverbank erosion by comparing managed riverbanks to invaded sites (Jaeger and Wohl 2011). Matte, Boivin, and Lavoie (2022) also compared plant cover

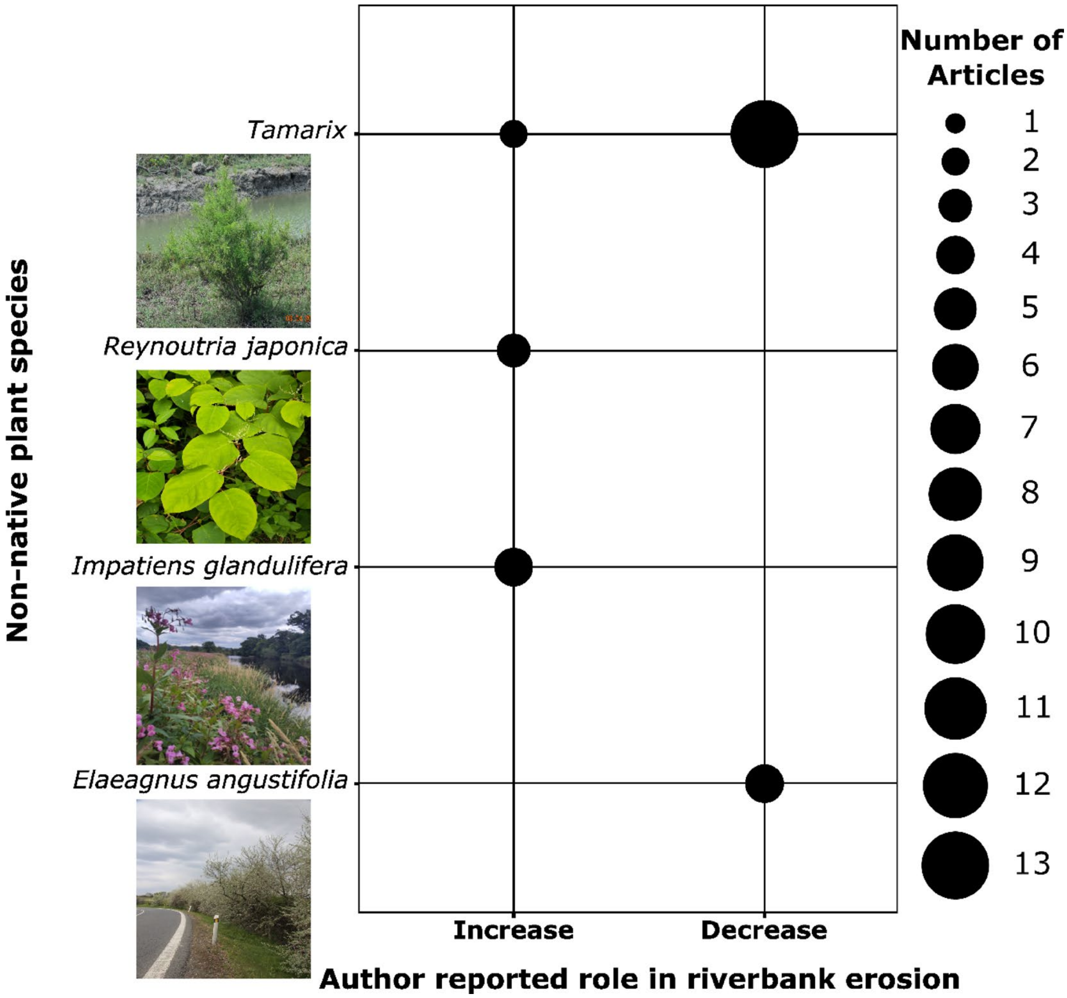

FIGURE 2 | Author reported erosional significance of non-native plants (NNPs). Erosion significance is a binary variable either increasing or decreasing riverbank erosion. Only those NNPs with > 3 articles have been included. The points are scaled to the number of articles in each grouping. Additional photos provided kindly by: *Tamarix*—Chayan Kumar Giri and *Elaeagnus angustifolia*—Jan Pergl. [Color figure can be viewed at wileyonlinelibrary.com]

along an abundance gradient to establish the role of *R. japonica* on erosion rates.

When comparing NNPS to native vegetation, studies focused on specific native plant species rather than whole community assemblages. For example, Greenwood and Kuhn (2014) compared the NNPS *I. glandulifera* to the native annual herbs *Urtica* and *Ranunculus*, while Birken and Cooper (2006) compared the deciduous trees *Populus deltoides and Salix exigua* to the NNPS *Tamarix* The native plant species selected for comparison generally had the same phenology and growth form as the NNPS. Exceptions to this include Stover et al. (2018) who compared the perennial grass NNPS *Arundo donax* to the native deciduous tree *Salix*.

3.3 | Methodologies Used to Investigate NNPS Role in Riverbank Erosion

Overall, a range of methodologies have been used to determine the role of NNPS in modulating riverbank erosion with variable effectiveness (Table 1). Methodologies are classified into two distinct groupings: field-based methods (61.0%) and remote sensing (39.0%). Channel surveying methods that directly measure sediment loss (e.g., erosion pins and terrestrial LiDAR scanning), as opposed to riverbank profile change, were infrequently employed (only 18.6% of articles). Channel surveying methods enabled direct measurement of topographic change from which rate/volume of riverbank erosion could be determined over small areas when investigating NNPS impact at reach scale. Remote sensing was used where historical and contemporary aerial imagery enabled authors to track planform morphological change over extended periods of time. Cadol, Rathburn, and Cooper (2011) tracked the effect of the NNPS *Tamarix* on planform morphology over ~70 years using historical aerial imagery (spatial resolution 1–4 m). They found that up to 75% of the channel had narrowed by 2004, relative to 1935, coinciding with a 45% expansion in NNPS, though concluded that this was co-occurring in response to wider environmental change not driven by *Tamarix*. Wieting, Friedman, and Rathburn (2023) also used aerial imagery (resolution 0.2–1 m), demonstrating that *Tamarix* removal was associated with significant channel widening. Some methods were infrequently used ($n = \sim 1$) for instance Arnold and Toran (2018) used turbidity sensors to determine sediment flux from riverbanks invaded by *R. japonica*, but these were unable to distinguish between the effect of NNPS and geomorphic effective flows.

TABLE 1 | Summary of the reported riverbank geomorphic change attributed to non-native plant species given methodologies used, study length and comparison with native vegetation.

Study	Habitat/ river type	NNPS	Native vegetation	Method	Site scale	Study length	Sediment loss/gain or geomorphic change	NNPS significance in modulating riverbank erosion
Matte, Boivin, and Lavoie (2022)	Temperate flood plains rivers	*Reynoutria japonica*	Yes, one homogenous unit	Differential GPS	Reach	1 year	0.03 cm a^{-1}	Increased
Greenwood and Kuhn 2014	Temperate upland river	*Impatiens glandulifera*	Yes, one homogenous unit	Erosion pins	Reach	6 months	0.14 cm a^{-1}	Increased
Pollen-Bankhead et al. 2009	Xeric freshwater and endorheic basins	*Tamarix sp and Elaeagnus angustifolia*	Yes, authors picked out three species (*Populus fremontii*, *Salix gooddingii*, *Salix exigua*)	Channel topographic survey and aerial imagery	Reach	3 years	1.85 m a^{-1} (following *Tamarix* removal)	Reduced
Stover et al. 2018	Xeric freshwater and endorheic basins	*Arundo donax*	Yes, generally one homogenous unit apart from comparison with *Salix laevigata*	Aerial imagery	Reach	30 years	~ 200 m of channel widening	Increased
Greenwood et al. 2018	Temperate upland river/temperate flood plains rivers	*Impatiens glandulifera*	Yes, one homogenous unit	Erosion pins	Reach	4 years	~ 0.24 cm a^{-1}	Increased
Arnold and Toran 2018	Temperate flood plains rivers	*Reynoutria japonica*	Yes, one homogenous unit	In situ turbidity sensors, erosion pins	Reach	1 year	29.77 cm a^{-1}	Increased (though not fully conclusive)
Cadol, Rathburn, and Cooper 2011	Xeric freshwater and endorheic basins	*Tamarix and Elaeagnus angustifolia*	Yes, one homogenous unit	Aerial imagery	Catchment	~ 70 years	65% of channel across the catchment had narrowed	Reduced
Wieting, Friedman, and Rathburn 2023	Xeric freshwater and endorheic basins	*Tamarix*	Yes, one homogenous unit	Aerial imagery	Catchment	~ 10 years	Removal increased floodplain destruction rate by a factor of 1.9	Reduced

(Continues)

TABLE 1 | (Continued)

Study	Habitat/ river type	NNPS	Native vegetation	Method	Site scale	Study length	Sediment loss/gain or geomorphic change	NNPS significance in modulating riverbank erosion
Vincent, Friedman, and Griffin 2009	Xeric freshwater and endorheic basins	*Tamarix*	Yes, generally one homogenous unit apart from comparison with *Salix*	Aerial LiDAR	Reach	4 years	Removal increased channel width by 84%	Reduced
Kaehler 2023	Temperate flood plains rivers	*Reynoutria japonica*	Yes, full vegetation survey	Erosion pins	Reach	1 year	11.1 cm a^{-1} sediment loss	Increased
Graf 1978	Xeric freshwater and endorheic basins	*Tamarix*	Yes, one homogenous unit	Historical imagery	Catchment	107 years	27% reduction in channel width	Reduced
Faller 2018	Temperate flood plains rivers	*Impatiens glandulifera*	Yes, simplified vegetation classes	Erosion pins	Reach	2 years	−0.18 cm a^{-1}	Increased
Jaeger and Wohl 2011	Xeric freshwater and endorheic basins	*Tamarix*	Yes, one homogenous unit	Channel surveying	Reach	3 years	Removal increased channel width by 5%–15%	Reduced (though inconclusive)
González et al. 2019	Xeric freshwater and endorheic basins	*Tamarix*	Yes, one homogenous unit	Channel surveying	Reach	1 year	Channel widening especially in 20% of flood plain invaded by *Tamarix*	Increased (though inconclusive)
González et al. 2020b	Xeric freshwater and endorheic basins	*Tamarix*	Yes, one homogenous unit	Channel surveying	Reach	7 years	Channel widening coinciding with 75% reduction in *Tamarix* cover	Increased (though inconclusive)
Birkeland 1996	Xeric freshwater and endorheic basins	*Tamarix*	Yes, full vegetation survey	Channel surveying	Reach	~13 years	Coincident with narrower channels and larger point bars	No significance difference
Dean and Schmidt 2011	Xeric freshwater and endorheic basins	*Tamarix*	Yes, one homogenous unit	Historical imagery and channel surveying	Catchment	~108 years	0.17 to 0.22 m a^{-1} sediment deposition	Reduced

(Continues)

TABLE 1 | (Continued)

Study	Habitat/ river type	NNPS	Native vegetation	Method	Site scale	Study length	Sediment loss/gain or geomorphic change	NNPS significance in modulating riverbank erosion
Greenwood, Gange, and Kuhn 2020	Temperate upland river, temperate flood plain river	*Impatiens glandulifera*	Yes, one homogenous unit	Erosion pins	Reach	6 months	56% of patches analysed showed greater sediment flux from invaded plots	Increased
Birken and Cooper 2006	Xeric freshwater and endorheic basins	*Tamarix*	Yes, full vegetation survey	Channel surveying	Reach	63 years	1.50–2.25 m of sediment deposition between 1938 and 2001	Reduced
Moody and Schook 2023	Xeric freshwater and endorheic basins	*Elaeagnus angustifolia*	Yes, one homogenous unit	Channel surveying	Reach	~ 38 years (compares 1978 and 2016 only)	*Elaeagnus angustifolia* stand width controlled by point bar morphology	No significant difference
Dean et al. 2011	Xeric freshwater and endorheic basins	*Tamarix*	Yes, full vegetation survey	Channel surveying	Reach	~ 16 years	16–35 cm a^{-1} sediment deposition	Reduced
Durning et al. 2021	Xeric freshwater and endorheic basins	*Tamarix*	Yes, simplified vegetation units	Remote sensing	Catchment	11 years	Sediment deposition reported	No significant difference
Hecker, Meehan, and Norland 2019	Xeric freshwater and endorheic basins	*Bromus inermis*, *Poa pratensis*	Yes, full vegetation survey	Channel surveying	Reach	1 month	Invaded riverbanks at higher risk of erosion (erosion risk index: 0.40)	Increased
Shields Jr, Bowie, and Cooper 1995	Temperate flood plain rivers	*Pueraria lobata var. thomsonii*	Yes, simplified two invasive and native woody species	Channel surveying	Reach	10 years	Riverbank protection reported	Decreased

(Continues)

TABLE 1 | (Continued)

Study	Habitat/ river type	NNPS	Native vegetation	Method	Site scale	Study length	Sediment loss/gain or geomorphic change	NNPS significance in modulating riverbank erosion
Smith-Adao and Scheepers 2007	Tropical and sub-tropical flood plain rivers	*Rumex acetosella, Dittrichia graveolens, Conyza canadensis, Acacia mearnsii, Conyza bonariensis, Lolium perenne, Paspalum distichum, Setaria, Solanum nigrum, Tamarix, Distephanus angolensis, Verbena officinalis, Bidens Pilosa, Lactuca serriola, Commelina benghalensis, Convolvulus arvensis, Ipomoea purpurea, Cyperus esculentus, Fumaria officinalis, Plantago lanceolata, Pennisetum clandestinum, Populus × canescens, Tropaeolum majus*	Yes, full vegetation survey	Channel surveying	Reach	1 year	0.25 m a^{-1} sediment deposition	Reduced

(Continues)

TABLE 1 | (Continued)

Study	Habitat/ river type	NNPS	Native vegetation	Method	Site scale	Study length	Sediment loss/gain or geomorphic change	NNPS significance in modulating riverbank erosion
Nsor, Mensah, and Agumenu 2021	Tropical and sub-tropical flood plain rivers	*Arthraxon hispidus, Chromolaena odorata*	Yes, full vegetation survey	Channel assessment	Catchment	6 months	Invaded plots correlate with higher riverbank erosion risk	Increased
Kui et al. 2017	Xeric freshwater and endorheic basins	*Tamarix and Elaeagnus angustifolia*	Yes, simplified vegetation units	Historical aerial imagery	Catchment	56 years	Two-fold decrease in Brading index compared to native vegetation	Reduced
Manners, Schmidt, and Scott 2014	Xeric freshwater and endorheic basins	*Tamarix*	Yes, simplified vegetation units	Historical aerial imagery	Reach	46 years	6% channel narrowing associated with increased *Tamarix* cover	Reduced
Londe and Silva 2014	Tropical and sub-tropical flood plain rivers	*Urochloa mutica, Urochloa eminii, Pennisetum purpureum*	Yes, single homogenous unit	Channel surveying	Reach	1 month	NNPS associated with reported higher erosion rates	Increased
Meier, Reid, and Sandoval 2013	Xeric freshwater and endorheic basins	*Lupinus polyphyllus*	Yes, single homogenous unit	Channel surveying	Reach	3 years	0.7–0.72 m sediment deposited between 2007 and 2010	Reduced
Mlamla, Kakembo, and Barasa 2022	Tropical and sub-tropical flood plain rivers	*Pteronia incana*	Yes, simplified vegetation units	Channel surveying	Catchment	6 years	Increased sediment loss (859 g/m^2) in invaded areas	Increased

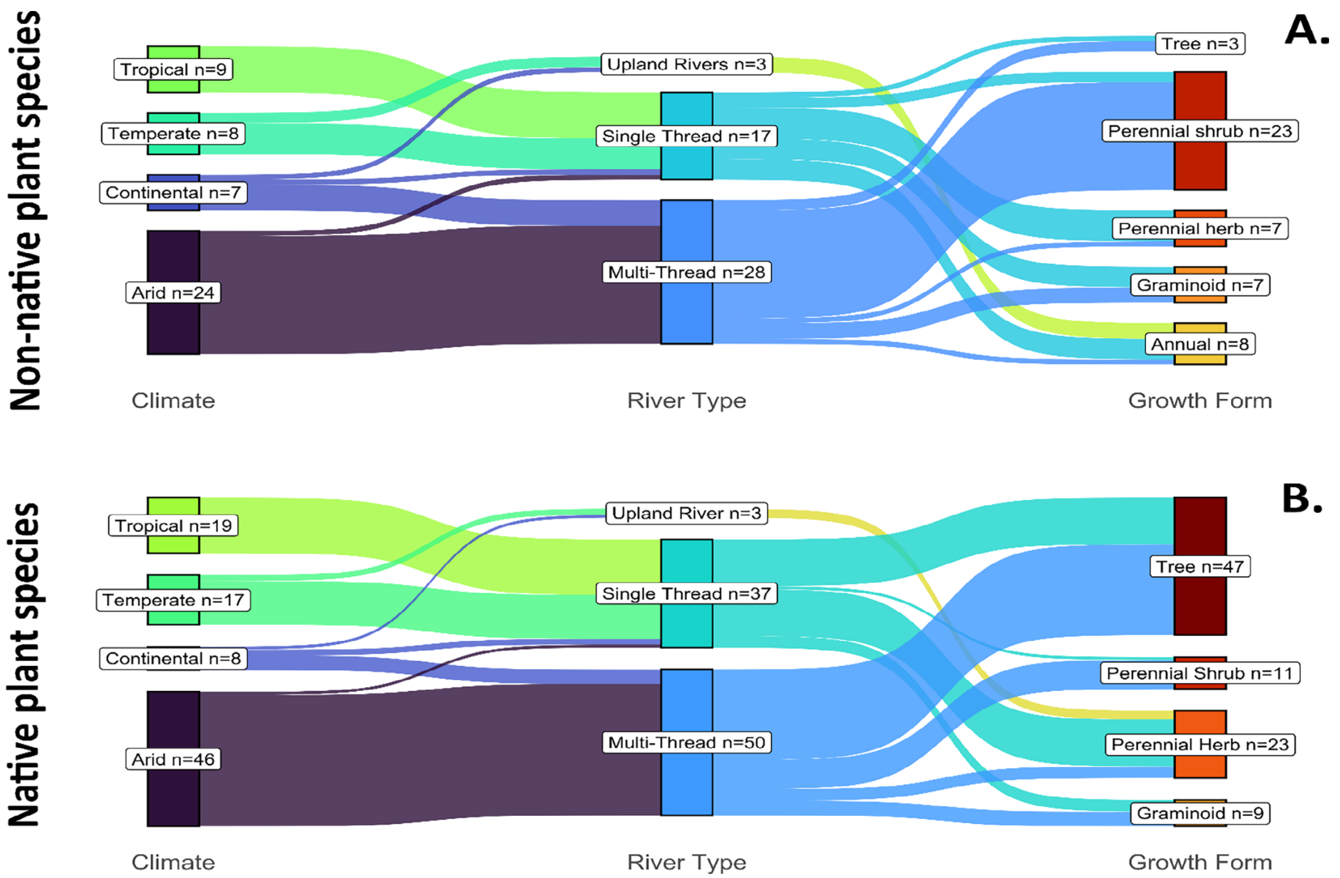

FIGURE 3 | Sankey diagram depicting the relationship between climate, river type and growth form for both (A) non-native plant species (NNPS) and (B) native plant species from each of the study rivers and plant species within the included articles ($n = 31$). The difference in growth forms is highlighted between NNPs and native vegetation, for example, native trees ($n = 47$) as opposed to NNPs ($n = 3$). A greater number of articles investigated arid multi-thread systems. [Color figure can be viewed at wileyonlinelibrary.com]

3.4 | Spatial and Temporal Study Design

Most included articles focussed on the reach scale (a variable length of channel within the same hydrological setting) (64.5% of articles) versus catchment scale (35.5% of articles), which corresponded with the channel surveying methodologies employed. The number of sampling sites varied considerably between included articles from one to 385, with the median number of study sites being eight. The area of these sample sites also varied for example, Greenwood and Kuhn's (2014) six sample sites occurred in the same 1 km of river, in contrast to 12 sample sites of Jaeger and Wohl (2011) over ~5 km of river channel. A range of channel widths were reported across the articles, from 2.5 to 300 m. Spatial distribution of study sites varied across the included articles and there was little assessment of spatial autocorrelation or other site level dependency that may skew the role NNPS play in determining the direction of riverbank erosion.

Included articles had a range of study durations from < 1 year (34.4%) to > 3 years (59.4%), resulting in variable coverage of flow regime. For example, Matte, Boivin, and Lavoie (2022) sampled winter and spring inclusive of two small flood events to explore the effects of *R. japonica* on riverbank erosion. In comparison, Kui et al. (2017) assessed the long-term riverbank morphological legacy of *Tamarix* over ~56 years, with numerous small flood events punctuated by large 1:100-year flood events. Whereas Dean and Schmidt (2011) used 108 years of historical imagery.

3.5 | Hydrological Metrics Utilised Across Studies

A variety of river hydrological metrics, for example, discharge and water level, were incorporated to contextualise analysis of riverbank erosion by NNPS or native vegetation. Over half of articles (64.5%) included discharge, and 22.6% of articles included water level. Some articles (15.0%) reported that either no gauge stations were available or that these had technical issues, for example, peak flows not recorded. However, 40.6% of included articles did not incorporate hydrology into their analysis. Most included articles (87.9%) also reported on geomorphologically relevant variables including grain size variation and underlying bedrock geology. Grain size variation was generally integrated into data analysis, for example Matte, Boivin, and Lavoie (2022) used soil texture class as an explanatory variable within their regression models. However, some articles (e.g., Greenwood and Kuhn 2014) despite recording grain size variation did not include this in subsequent analysis.

3.6 | Study Habitats and River Types

There was an unequal geographical distribution of articles between the Global North (88.0%) and South (12.0%). The dominance of *Tamarix* and *E. angustifolia* mirrors this with studies being primarily based in Southwestern USA (51.6% of articles). This bias is likely exaggerated by the exclusive use of English language or translated literature in this study. At a continental scale, Africa and Asia were the least represented within the included articles. When the Global North was disaggregated by country, the United States of America (USA) dominated with 69.0% of articles, compared to 10.3% for Switzerland and 6.9% for the United Kingdom. Broadly, there is poor representation of articles at the national scale outside of the United States of America.

This geographical publication bias is reflected in the stark contrast of habitat types represented (Figure 3). Most articles investigated xeric freshwater habitats ($n=17$) common to the southwestern North America (94.4%) and South America (5.6%). Temperate floodplain ($n=7$) and upland ($n=4$) rivers received some attention, especially across Europe (50.0%), North America (40.0%) and Oceania (10.0%). Tropical floodplain rivers ($n=5$) and other freshwater habitats, for example, polar or temperate coastal habitats, were poorly represented within the included articles.

4 | Discussion

The role NNPS play in modulating riverbank erosion is evidently understudied. Our results show that there is evidence of NNPS affecting riverbank erosion rates compared to native riparian vegetation and bare ground, though the extent and importance of this varied. Inferring changes in erosional processes is species and context specific, with a lack of data available to infer general patterns. Given the exponential rate of new plant invasions globally (Seebens et al. 2021), there is an urgent need to better understand the multifaceted role of NNPS in riparian ecosystems.

4.1 | Riverbank Erosion Response to NNPS

Attributing changes in erosional processes based on aspects of riparian vegetation is challenging given that other hydrogeomorphological variables (e.g., channel width, discharge and sediment heterogeneity) may override any NNP erosional signature. Our results show that certain variables such as channel width, had a greater effect on NNPS invaded riverbank erosion when compared to native vegetation. Jaeger and Wohl (2011) demonstrated that the magnitude of riverbank erosion in response to *Tamarix* removal was highly temporally and spatially variable in a controlled before and after field trial. They reported that reaches with *Tamarix* removal underwent channel widening (~0.54 m) compared to control reaches. Similarly, other studies found that erosion in *Tamarix*—invaded reaches were affected more by channel width than in native *Populus* dominated reaches (Kui et al. 2017; Bywater-Reyes et al. 2022). Matte, Boivin, and Lavoie (2022) also argue that whilst *R. japonica* increased riverbank erosion rates by ~3 cm a^{-1} along the river Etchemin River in Canada, this too was strongly influenced by underlying river channel morphology (e.g., mid channel bars and existing riverbank gradient). Thus, at broad spatial scales *R. japonica* has a marked effect on the erosional regime of the catchment but the rate is heterogeneous; dependent on local factors including stand distribution and morphology.

The erosional signature by wider catchment scale changes may also obscure the ability to quantify riverbank erosion by NNPS. Arnold and Toran (2018) could not clearly attribute changes in turbidity (proxy for sediment flux), to either *R. japonica* invasion or episodic storm events. Similarly, Dott et al. (2022) reported that the primary control of riverbank erosion was dam-induced water base level lowering, rather than the geomorphic effect of *Tamarix*. Currently, there is insufficient evidence to distinguish the role of NNPS in driving riverbank erosion within the context of larger scale drivers of riverbank erosion, such as dam induced bed level lowering or riparian land use change.

When compared to native vegetation, NNPS are considered largely antagonistic in their role in modulating riverbank erosion. Our results show that NNPS have been attributed to changes in erosion rates by either stabilising or further destabilising riverbanks. *Populus* within their native ranges of southwestern United States, (Pollen-Bankhead et al. 2009) facilitate high rates of riverbank erosion. However, certain *Populus* species are invasive in South Africa and have contributed to the stabilisation of riverbanks and local groundwater table variation, which has led to increased mortality of native riparian vegetation (Smith-Adao and Scheepers 2007). *Salix* species have a stabilising effect on riverbank erosion rates in their native range of Central Europe and Asia (GBIF Secretariat 2023) and in their invaded range of Australia (Zukowski and Gawne 2006; GBIF Secretariat 2023). However, in Australia, increased riverbank stability has reduced erosion, limiting sediment supply for downstream habitats thereby disrupting riparian ecosystem processes (Zukowski and Gawne 2006).

Comparing NNPS with native vegetation in paired 'control' reaches is essential to unravel the extent to which NNPS modulate riverbank erosion. NNPS incur distinct changes in the riparian vegetation community structure (see Pattison et al. 2017) and the distribution of functional traits (Waddell et al. 2020). Most studies compare paired invaded and uninvaded reaches to determine relative differences in erosion rates (e.g., Matte, Boivin, and Lavoie 2022; González et al. 2019). However, some studies also choose single or a small group of native plant species with which to compare the NNPS erosional significance (e.g., Greenwood and Kuhn (2014) compare *I. glandulifera* to native *Urtica*; Birken and Cooper (2006) compare *Tamarix* to native *Populus deltoides* and *Salix exigua*). In part this is logical, as often the native plant species to which the NNPS is being compared forms the dominant native plant cover. However, this species centred approach may neglect the cumulative effect of whole community assemblages with a range of functional traits (Tisserant et al. 2024), and the subsequent changes of this with NNP invasion, when considering modulation of riverbank erosion.

4.2 | Methodological Bias in NNPS Riverbank Erosion Research

Various methods have been employed to investigate the modulating effects of NNPS on riverbank erosion, including remote sensing and field based. Our results suggest that methodologies used to understand the impacts of NNPS on riverbank erosion may be scale dependent. Remote sensing methods, for example, aerial photography, are valuable for detecting geomorphic and ecological change over both large spatial and temporal scales. For instance, Cadol, Rathburn, and Cooper (2011) reported 75% channel narrowing over 70 years associated with the spread of *Tamarix*. Similarly, Wieting, Friedman, and Rathburn (2023) use of aerial imagery indicated that Tamarix removal was associated with significant channel widening. However, a marked drawback of remote sensing-based observations is the homogenisation of vegetation units, with generally a simple binary NNPS or native unit—that may miss underlying ecological interactions that have a direct effect on bank erosion rates. Conversely, field-based methods support short-term high resolution data sets that can evaluate NNPS modulated riverbank erosion at the reach scale. Erosion pins have been used extensively in riverbank erosion research as they enable a standardised measure of sediment loss (Greenwood and Kuhn 2014; Arnold and Toran 2018). Greenwood and Kuhn (2014) used erosion pins to understand the influence of *I. glandulifera* on riverbank erosion. The use of erosion pins gives robust net erosion rates, but it is difficult to directly attribute sediment loss to NNP given other fluvial erosional processes. Arnold and Toran (2018) report that the erosional effect of *R. japonica* could not be distinguished from the effect of episodic storm events that drive most riverbank erosion. Thus, the scale of observation may influence the apparent significance of NNPS in modulating riverbank erosion. Bywater-Reyes et al. (2022) argue that effects of the NNP *Tamarix* are scale dependent. At reach scale *Tamarix* can reduce sediment loss, but this effect becomes insignificant at the catchment scale. Kui et al. (2017) also report that *Tamarix* results in a two-fold increase in riverbank erosion locally, but this is not reflected at catchment scale.

4.3 | Geographic Distribution of Studies

Despite NNPS being present in most river systems globally, the geographic distribution of articles investigating NNPS role in modulating riverbank erosion is limited. Most articles were restricted to North America, specifically the Arid Southwest, or Europe. This likely reflects the historical legacy of soil erosion control policy and financial resources available (Castillo and Smith-Ramírez 2018). The dominance of articles from southwestern USA contributes to broader assumptions about NNPS and native vegetation ecogeomorphological feedback that may not be valid. Hydrological process-based models such as HEC-RAS Riparian Vegetation Simulation Module (Zhang, Johnson, and Greimann 2019) are based on conditions (i.e., hydrology, vegetation) of the south-west USA. Unifying models of NNPS modulated riverbank erosion are currently lacking outside of USA arid systems (e.g., Bywater-Reyes et al. 2022), in part due to unreplicated region-specific insights and crucially numerous physical data gaps especially in under-represented habitats. In part, as our results show, there is severe under representation of many habitats, most notably tropical and to a lesser extent temperate rivers.

5 | Recommendations

We have identified four overarching knowledge needs to be addressed to increase our understanding of the role of NNPS in modulating riverbank erosion and further support river management policy.

5.1 | Improve Interdisciplinary Working Between Invasion Ecology and Fluvial Geomorphology

Understanding how NNPS modulate riverbank erosion requires interdisciplinary working between invasion ecology, plant sciences and fluvial geomorphology. Many invasion ecology and fluvial geomorphology specific investigations do not adequately incorporate theoretical frameworks of the corresponding disciplines into an integrated set of conclusions. For example, several studies did not incorporate the role of hydrology in driving riverbank erosion irrespective of the vegetation present. Equally, fluvial geomorphology focussed investigations often homogenise vegetation as single cohesive units rather than complex dynamic communities. These two examples highlight the need for closer interdisciplinary working to capture complementary perspectives on riverbank processes.

5.2 | Couple In Situ Measurements of Riverbank Erosion With Comprehensive Vegetation Surveys

Owing to a diverse range of functional traits at the species level, whole vegetation assemblages influence the relative rate and magnitude of riverbank erosion. Thus, investigations into the role of NNPS should incorporate the full vegetation assemblage into any analysis. For instance, there could be a series of thresholds that exist as a result of an invasion process that would likely be missed without a comprehensive vegetation survey. Similarly, coupling in situ measurements of riverbank erosion with comprehensive vegetation surveys may reveal temporal (e.g., seasonal) variation in the rate of riverbank erosion between invaded and un-invaded reaches that might help resolve underlying mechanisms.

5.3 | Broaden Range of NNPS and Habitat Types Studied

Developing a deeper conceptual understanding of NNPS modulated riverbank erosion requires broadening the range of NNPS studied. The potential geomorphic effects of many NNPS remain understudied, for example, *Salix* species in Australia, which constrains both scientific understanding and management. There are also marked knowledge gaps for a range of habitats, specifically tropical rivers, and temperate coastal rivers, which undermine management efforts as the evidence based is not sufficient to support policy.

5.4 | Increase Temporal Range of Studies to Reveal Legacy Effects and Feedback Loops

Longer duration investigations (> 3 years) would enable complex NNP—native plant species riverbank erosion feedbacks to be evaluated and legacy effects to identified that may have marked consequences for restoration and management efforts and their timing. Longer studies may more adequately incorporate long term hydrological data.

6 | Conclusions

The role of NNPS in modulating riverbank erosion remains unclear, with conflicting evidence. This reflects a range of factors including the limited array of NNPS and growth forms studied, methods used and a marked habitat and geographical bias. Presently, there is insufficient evidence to effectively mitigate or manage the potential impacts of NNPS on riverbank erosion. Further progress in mechanistic understanding and management can be achieved through the integration of ecological invasions, community dynamics, geomorphic processes and anthropogenic river disturbance in an invasion ecology—fluvial geomorphological interdisciplinary context.

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Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in The role of non-native plant species in modulating riverbank at https://zenodo.org/records/12819597.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.