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Plants and river morphodynamics: The emergence of fluvial biogeomorphology

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Abstract

In this article, we track the evolution of fluvial biogeomorphology from the middle of the 20th century to the present. We consider the emergence of fluvial biogeomorphology as an interdisciplinary research area that integrates knowledge drawn primarily from fluvial geomorphology and plant ecology, but with inputs from hydrology and landscape ecology. We start by assembling evidence for the emergence of the field of fluvial biogeomorphology with a keyword search of the Web of Science and a detailed analysis of papers published in two scientific journals: a geomorphology journal—Earth Surface Processes and Landforms; a multidisciplinary river science journal—River Research and Applications. Based on this evidence, we identify three distinct time periods in the development of fluvial biogeomorphology: the ‘early years’ before 1990; the transitional decade of the 1990s; and the period of rapid expansion and diversification in themes, methods and investigation scales since 2000. Because the literature is vast, we can only summarize developments in each of these time periods, but we refer to recent in-depth reviews and conceptual perspectives on relevant topics. Thus, rather than a full and deep review, we present an annotated bibliographic overview of the development of fluvial biogeomorphology, whereby the text describes broad trends but is supported by tables of citations that can deliver greater detail. We end with a brief consideration of likely future developments.

KEYWORDS
biogeomorphology, fluvial geomorphology, modelling techniques, monitoring techniques, physical ecosystem engineers, plant ecology, time and space scales

1 | INTRODUCING FLUVIAL BIOGEOMORPHOLOGY

Until the middle of the 20th century, research on the vegetation and geomorphology of river corridors developed largely independently.

Geomorphologists focused on the landforms, overall morphology and integrated style of river-floodplains, with vegetation simply being a feature of areas of negligible physical disturbance. Thus, the middle decades of the 20th century saw increasing geomorphological research on river flows and sediment transport processes and how these processes constructed river channel systems of different character supporting different landform assemblages in different environmental settings. In particular, numerous research papers by Lane, Leopold, Maddock, Miller, Wolman and many others during the 1950s led to completely new perspectives on the processes and forms of fluvial systems (summarized by Leopold et al., 1964). This research was then extended and developed in new directions by Schumm and colleagues during the 1960s (summarized by Schumm, 1977). Of

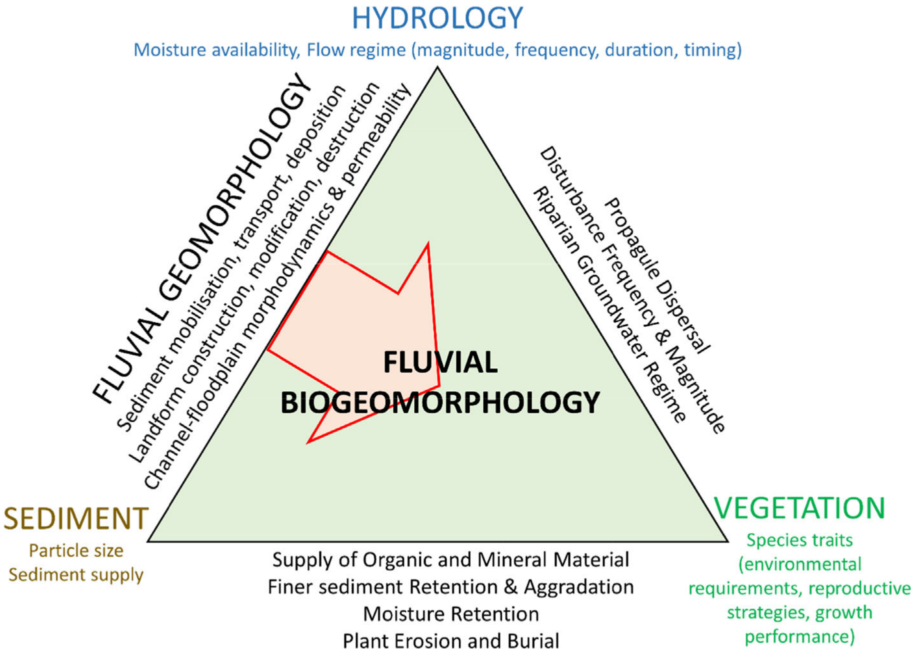

FIGURE 1 The context for fluvial biogeomorphology focusing on vegetation. The arrow indicates the evolutionary trajectory of fluvial biogeomorphology from fluvial geomorphology (interactions among water and sediments, particularly within river channels and corridors) to gradually incorporate vegetation responses and effects. [Color figure can be viewed at wileyonlinelibrary.com]

particular importance to the present review was the recognition that multiple physical styles of river exist, reflecting variations in valley gradient, river flow magnitude and frequency, sediment calibre and supply; and displaying different levels of stability and dynamics (summarized by Church, 2006) and that such variations in river morphodynamics drive floodplain morphodynamics and the construction of different styles of floodplain (summarized by Nanson & Croke, 1992). Furthermore, researchers were recognizing the importance of river size and the fact that individual channel roughness elements have an increasing impact on river channel morphodynamics as river channels become smaller (summarized by Church, 1992).

Egerton (2013) reviewed the development of the discipline of plant ecology in detail. He revealed that Warming (1895), Clements (1907) and Drude (1913) produced early textbooks that referred to plant ecology and the early to middle decades of the 20th century saw the contributions of Tansley (1923, 1939), Lindeman (1942), and Odum (1953) in developing the concept of an ecosystem as the fundamental underpinning of the discipline. Given the enormous spatial and temporal variability in the physical environment in and around river systems, it is hardly surprising that plant ecologists adopted a strong ecological approach to understanding river corridor vegetation from the middle decades of the 20th century.

In this article, we specifically consider 'fluvial biogeomorphology' as a distinct sub-discipline of fluvial geomorphology that is built on the 'historical' research in geomorphology and plant ecology described above. In other words, we focus specifically on 'fluvial (plant) biogeomorphology'. We aim to describe the development trajectory of the sub-discipline since the middle of the 20th century from early, mainly physically based, fluvial geomorphological research at the interface between hydrological and sediment-related processes through the gradual incorporation of plant-related processes (Figure 1).

To achieve this aim, we first consider evidence for the emergence of the sub-discipline of fluvial biogeomorphology revealed by searching the published literature (Section 2). We then track this emergence through three time periods: before 1990 (Section 3), through the 1990s (Section 4), and during the first two decades of the 21st century (Section 5). We end with our thoughts on possible future developments (Section 6).

The relevant literature is vast and there are many recent reviews of different aspects of fluvial biogeomorphology research. Therefore, we do not attempt a comprehensive review but rather an annotated overview focusing on plants. To achieve this, we provide tables that cite selected review, conceptually integrative, and fundamental research papers to support a commentary on broad research trends and how these have evolved over the three selected time periods.

2 | EVIDENCE FOR THE EMERGENCE OF A SUB-DISCIPLINE

Based on our personal experience, we believe that the sub-discipline of fluvial biogeomorphology has gradually emerged over at least the last 50 years, but that it has only become the focus of widespread research, using an increasingly diverse set of research tools, since the beginning of the 21st century. This section reports on literature searches that aimed to check our pre-conceptions.

2.1 | Web of Science

The Web of Science (WoS, https://www-webofscience-com) provides a near-comprehensive database of published literature, especially of research papers published in international journals. Many terms have been used to categorize research at the interface of geomorphology and ecology (Wheaton et al., 2011), which makes literature searches challenging. We repeated the search conducted by Coombes (2016)

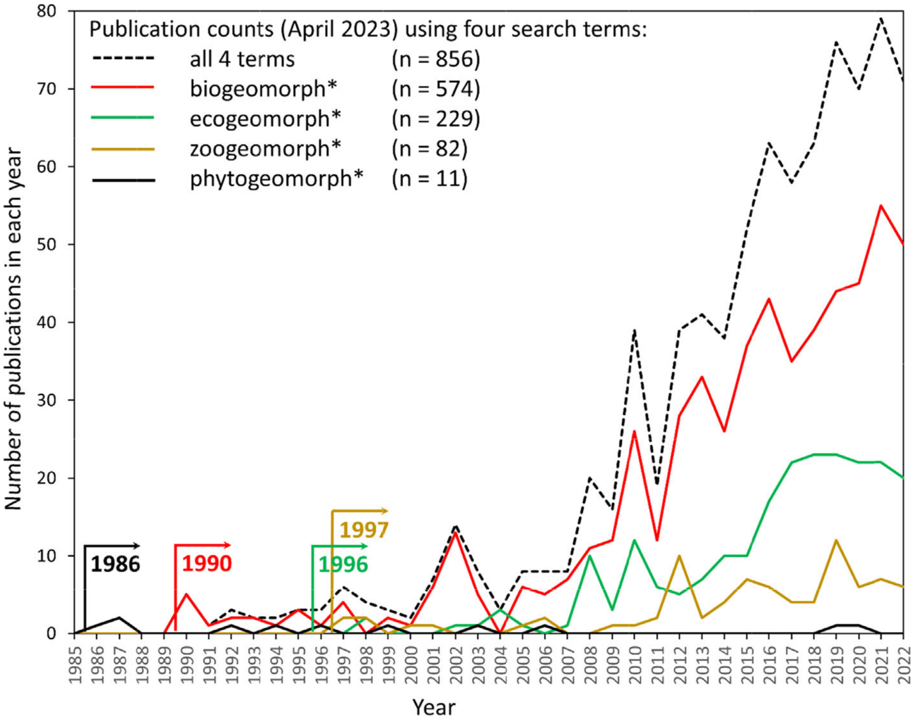

FIGURE 2 Results of a Web of Science search using four keywords individually and in combination. The graph shows the number of publications in each year. There were no relevant publications before 1986. The four arrows with dates indicate the year in which each keyword was first found (i.e., phytogeomorph*—1986, biogeomorph*—1990, ecogeomorph*—1996, zoogeomorph*—1997). [Color figure can be viewed at wileyonlinelibrary.com]

for his review of biogeomorphology, which used four search terms: biogeomorph*, ecogeomorph*, zoogeomorph*, phytogeomorph*. Using these terms, we identified a total of 856 publications within the WoS database, with biogeomorph* being by far the most commonly used. We also found a notable uplift in the number of publications from the beginning of the 21st century, especially from 2005 (Figure 2). While this search of WoS sets the scene for the present review, the number of identified publications was small. In addition, defining acceptable combinations of additional key words to reveal the trajectory of fluvial biogeomorphology proved challenging, so we adopted an alternative approach.

2.2 | Earth Surface Processes and Landforms and River Research and Applications

We selected two scientific journals that we expected to include relevant articles but from different scientific perspectives. Earth Surface Processes and Landforms (ESPL) is a geomorphology journal that provides an obvious place to track the evolution of a geomorphology sub-discipline. River Research and Applications (RRA) publishes papers on all aspects of river science and so has the potential to identify the trajectory of all sciences in areas relevant to fluvial biogeomorphology. We looked at every paper (excluding editorials, book reviews, newsletters, and announcements) published in these journals from their first issues in 1976 (ESPL) and 1987 (RRA) to the end of 2022, identifying those that in the view of one author (AMG) addressed research that was relevant to fluvial biogeomorphology. The small number of papers focusing on animals were excluded, so our analysis entirely reflects research involving plants as the 'bio' element in biogeomorphology, with animals as an occasional additional element. We identified all articles where vegetation was a central/key component in the research, either controlling or responding to fluvial and sub-surface hydrological processes (impacts of vegetation on interception and infiltration were excluded). We also identified articles where aspects of physical habitat and/or physical processes were considered in relation to the presence/impact of vegetation. Although the focus was on the river channel, margins and floodplain, articles on hillslopes were included where they explored relationships between vegetation and subsurface hydrology or rill-gulley flows. Such an analysis is clearly subject to some personal bias but a systematic approach was adopted that considered the title, keywords and abstract of every publication and, where these were insufficiently informative, the whole paper. This approach allowed publications that had content of notable relevance to fluvial biogeomorphology to be identified and classified.

Figure 3a illustrates that 532 relevant publications were identified from these two journals alone, and that the number of relevant papers identified in each calendar year has been steadily rising since the launch date of each journal. The broad biogeomorphological nature of the reported research is represented in Figure 3b, where brown bars highlight publications that predominantly focus on the way physical processes, physical habitats and landforms affect plants and/or wood; green bars focus on the ways plants and/or wood affect physical processes, physical habitats and landform development; and blue bars emphasize two-way interactions among physical forms and processes and plants. All bars represent the proportion of the total biogeomorphologically relevant papers in each journal that fall within each of these three categories in each decade. The bars prior to 2000 are based on small numbers of publications (the numbers are shown

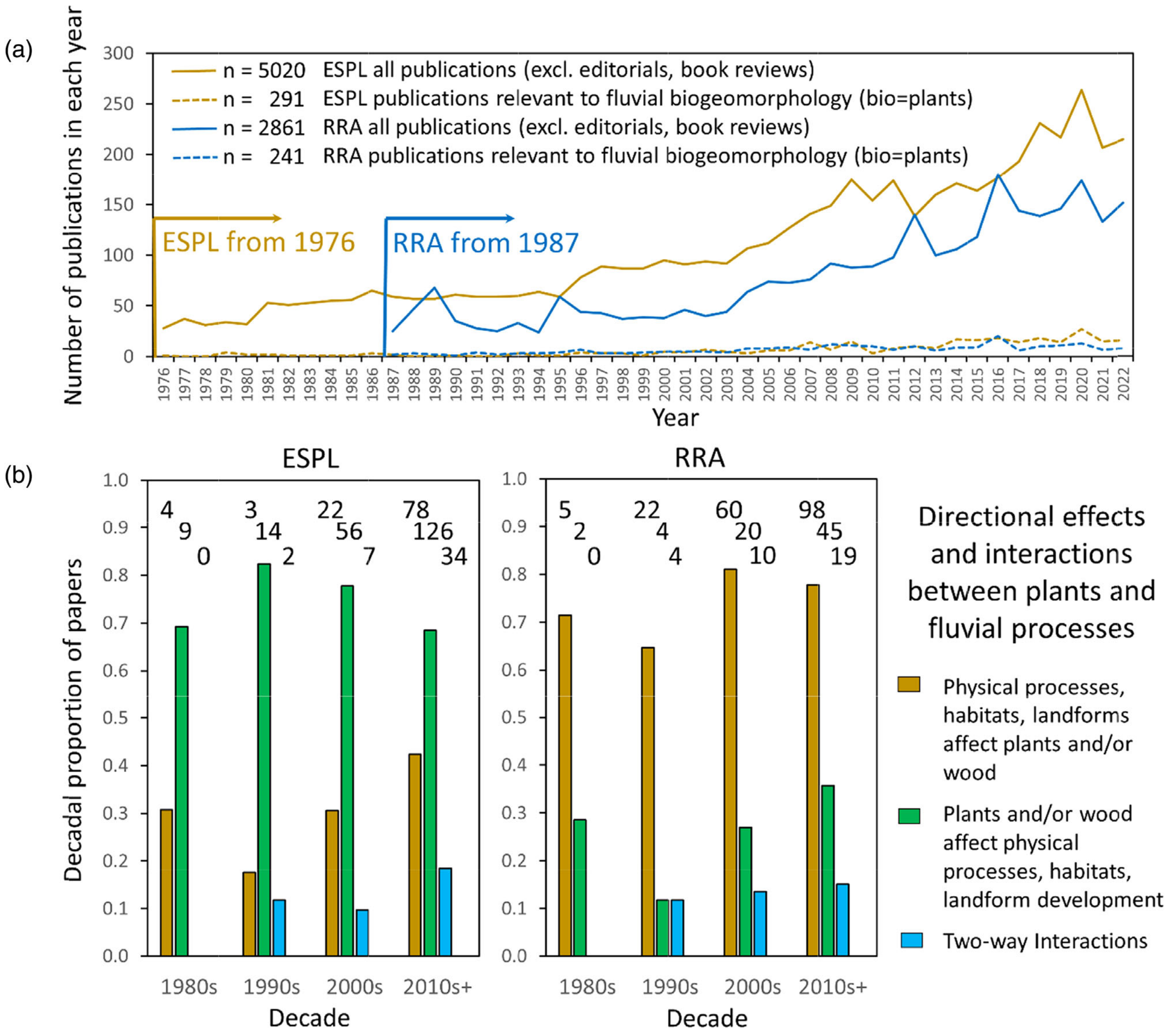

FIGURE 3 (a) The total number of publications considered and the number deemed relevant to the subdiscipline of fluvial biogeomorphology in the journals Earth Surface Processes and Landforms (ESPL, first issue in 1976) and River Research and Applications (RRA, first issue in 1987). (b) The proportion of the relevant publications in each journal within each decade that emphasized the impact of physical disturbances or habitat characteristics on plants and/or wood; the impact of plants and/or wood on physical processes and/or landform development; two-way interactions among physical processes and/or landforms and plants and/or wood (the numbers of publications are inserted above each bar). [Color figure can be viewed at wileyonlinelibrary.com]

above each bar), so pre-2000 patterns should be treated with caution. Nevertheless, there is a clear contrast between the geomorphologically focused papers in ESPL, which emphasize plant effects of physical forms and processes, and the broader river science papers in RRA, which emphasize the impacts of physical forms and processes on plants. Furthermore, papers on two-way interactions only start to appear in the 1990s in both journals.

Figure 4 presents evidence that the 1990s formed a transitional decade in fluvial biogeomorphological research. The upper part of Figure 4 confirms the emergence of papers on two-way interactions in the 1990s, with the exception of one early paper in ESPL (Keller & Swanson, 1979). Figure 4 also indicates the time spans in publication dates encompassed by papers emphasizing particular vegetation types and characteristics; considering different categories of physical habitat and physical disturbances; employing different research methods; and concerned with different time scales and spatial locations or scales. Publications in both journals show increasing diversity in research themes, methods, time and space scales through recent decades, but the geomorphologically focused papers in ESPL show particularly sharp transitions in the 1990s, illustrating an abrupt increase in the interest of geomorphologists in the physical role of vegetation. These trends are reflected in the broader literature on fluvial biogeomorphology and provide the structure for the rest of this review, which considers the 'early years' before 1990, the transitional decade of the

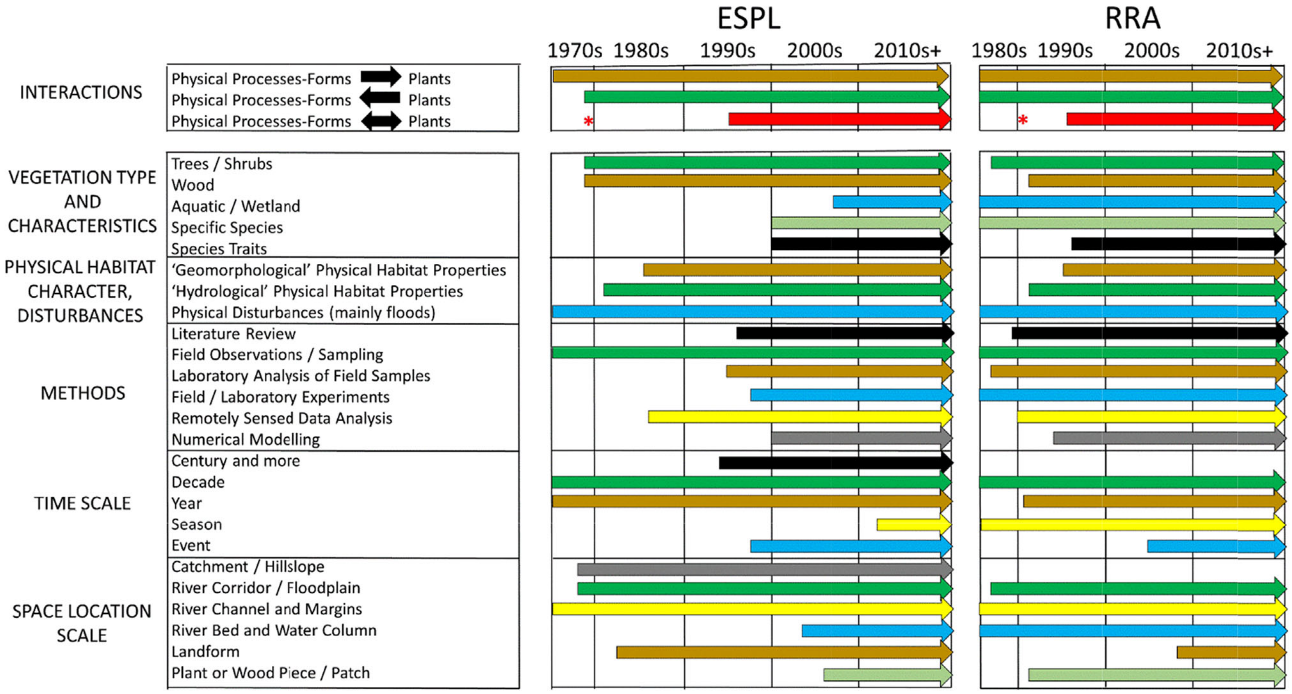

FIGURE 4 The time span (from the first paper to the present) of publications addressing different aspects of physical process-form and plant (including wood) interactions; vegetation types and characteristics; physical habitat characteristics and disturbances; research methods; predominant time scale; and space location/scale of the research. In the case of two-way interactions, the red asterisks indicate single, anomalously early publications (i.e., at least five years in advance of the next publication relevant to this theme). [Color figure can be viewed at wileyonlinelibrary.com]

1990s, and the rapid expansion of research outputs (Figures 2, 3a) and diversification in themes, methods and scales of research since 2000.

3 | THE EARLY YEARS

Before 1990 several research themes emerged that provided a foundation for fluvial biogeomorphology. These themes are discussed below and are listed in Table 1, where reference is made to a more substantial body of literature than appears in the text.

Much early research was concerned with the physical environmental requirements of plant species and communities or the impacts of physical processes on plants. This led to the recognition that valley bottom vegetation was often constrained by subsurface soil moisture and groundwater dynamics (Table 1, theme 1, e.g., Featherley, 1940; Graf, 1982; Rutter, 1955) and the magnitude and frequency of flood inundation (Table 1, theme 2, e.g., Barnes, 1978; Bedinger, 1971; Leitman et al., 1984). At the same time, some hydrologists and geomorphologists were considering the role of plants as indicators of physical environmental processes, including soil moisture and overland flow regimes (Table 1, theme 1, e.g., Gurnell, 1981; Gurnell & Gregory, 1987), and the elevation and timing of major past flood events (Table 1, theme 2, e.g., Sigafoos & Sigafoos, 1966).

A logical extension of research on the impacts of hydrological processes on plants (Table 1, themes 1 and 2) is the recognition that characteristic plant communities may exist on different river channel and corridor landforms (Table 1, theme 3). Fluvial landforms exhibit differing sedimentary structures as well as moisture and inundation dynamics, that provide specific environmental conditions to support a vegetation cover with particular species composition, age structure and following characteristic successional patterns (e.g., Hupp, 1983; Nanson & Beach, 1977; Osterkamp & Hupp, 1984; Pautou et al., 1985; Shelford, 1954; Wistendahl, 1958). Furthermore, river channel changes such as narrowing, induced by shifts in fluvial processes, may be indicated by vegetation colonization of channel margin landforms (e.g., Martin & Johnson, 1987).

Within the field of plant ecology, texts such as Grime et al. (1988) and Haslam (1978) appeared well before 1990, providing invaluable semi-quantitative syntheses of the physical habitat preferences of individual plant species and their susceptibility to disturbances. Such reference texts provide a firm foundation for research within themes 1 and 2.

In addition to recognizing vegetation as an indicator of fluvial processes and forms, some early research also recognized vegetation as a control on physical forms and processes. Although not strictly fluvial form-process research, engineers working on channel-floodplain hydraulic prediction, design and management started to incorporate vegetation into their computations (Table 1, theme 4). This hydraulics research typically treated vegetation as having a fixed temporal effect and to be spatially invariant (e.g., Cowan, 1956), or to consist of blocks of given shape, height and density (e.g., Klassen & van der Zwaard, 1974). It was also typically concerned with assigning

TABLE 1 Selected publications prior to 1990 illustrating early research relating to several fluvial biogeomorphological research themes.

Research themes	Authors and dates
1. Soil moisture and groundwater affect plants	Featherley (1940), Rutter (1955), Gurnell (1978, 1981), Graf (1982), Gurnell and Gregory (1987).
2. Flood disturbance affects plants	Sigafoos (1964), Sigafoos and Sigafoos (1966), Bedinger (1971, 1978), Barnes (1978), Williams (1979), Leitman et al. (1984), Bren and Gibbs (1986), Streng et al. (1989).
3. Fluvial forms and processes affect plants	Shelford (1954), Wistendahl (1958), Gregory (1976), Nanson and Beach (1977), Hupp (1982, 1983), Osterkamp and Hupp (1984), Hupp and Osterkamp (1985), Pautou and Décamps (1985), Pautou et al. (1985), Salo et al. (1986), Amoros et al. (1987), Harris (1987), Martin and Johnson (1987).
4. Plants affect flow hydraulics	Fredenhagen and Doll (1954), Cowan (1956), Li and Shen (1973), Kouwen and Unny (1973), Klassen and van der Zwaard (1974), Petryk and Bosmajian (1975), Kouwen et al. (1981), Arcement and Schnelder (1987).
5. Wood affects fluvial processes and forms	Lobeck (1939), Heede (1972), Megahan and Nowlin (1976), Swanson and Lienkaemper (1978), Swanson et al. (1976), Beschta (1979), Keller and Swanson (1979), Vannote et al. (1980), Heede (1981, 1985), Mosley (1981), Nanson (1981), Bisson et al. (1982), Likens and Bilby (1982), Marston (1982), Megahan (1982), Bilby (1984), Sedell and Froggatt (1984), Triska (1984), Gregory et al. (1985), Keller et al. (1985), Harmon et al. (1986), Hogan (1986), Kochel et al. (1987), MacDonald and Keller (1987), Gregory and Gurnell (1988), Sedell et al. (1988), Bilby and Ward (1989), Sedell et al. (1989).
6. Riparian plants affect fluvial processes and forms	Zimmerman et al. (1967), Wilson (1973), Smith (1976), Graf (1978, 1979), Page and Nanson (1982), Murgatroyd and Ternan (1983), Hickin (1984), Kondolf and Curry (1984, 1986), Gray and MacDonald (1989).
7. Aquatic plants affect fluvial processes and forms	Dawson (1978), Hamill (1983), Dawson and Robinson (1984), Watson (1987), Losee and Wetzel (1988), Sand-Jensen et al. (1989).

Note: Publications are listed in chronological order with respect to each research theme; underlined publications highlight a notable focus on two-way interactions.

appropriate roughness coefficients to different vegetation cover types (e.g., Arcement & Schnelder, 1987), although some research also considered sediment dynamics (e.g., Li & Shen, 1973). This research was based on combinations of theory, field and flume measurements (e.g., Kouwen et al., 1969), with some emphasis on vegetation flexibility as research progressed (e.g., Kouwen et al., 1981).

The impact of large wood on fluvial forms and processes (Table 1, theme 5) has long attracted interest from geomorphologists. For example, Lobeck (1939, p. 428), in a chapter on organisms and geomorphology, discussed a ‘timber raft’ that completely blocked the Red River, Louisana, for several centuries, gradually evolving in size and location and inducing the formation of floodplain lakes. From the 1970s, the physical impacts of large wood in river systems started to attract significant attention from ecologists as well as geomorphologists, with much early work emanating from the Pacific Northwest of the United States. This early research was largely confined to dead wood retained in steep headwater streams. Using observations on streams where wood was present or had been removed, research investigated how log steps increase channel roughness, retain enormous quantities of sediment, dissipate flow energy (e.g., Beschta, 1979; Heede, 1972; Marston, 1982; Megahan, 1982; Megahan & Nowlin, 1976; Mosley, 1981; Swanson et al., 1976), attenuate flood waves (e.g., Gregory et al., 1985), and induce pool, riffle and bar development (e.g., Bilby, 1984; Hogan, 1986; Macdonald & Keller, 1987). The diversity of geomorphological impacts of wood was also recognized (e.g., Bisson et al., 1982; Gregory & Gurnell, 1988; Harmon et al., 1986; Keller et al., 1985; Swanson & Lienkaemper, 1978). Although most of the research at this time was concerned with small streams, a number of papers considered how wood and related physical features changed with stream size (width) and gradient (e.g., Bilby & Ward, 1989; Keller & Swanson, 1979; Likens & Bilby, 1982; Sedell et al., 1988; Vannote et al., 1980), with a notable evaluation of the complex mosaic of wood and fluvial forms that can develop on large, lowland river-floodplain systems (e.g., Sedell et al., 1989; Sedell & Froggatt, 1984; Triska, 1984). Some research also captured two-way interactions between wood and fluvial processes. For example, Keller and Swanson (1979) considered how wood is transferred through lower and higher gradient systems and how that wood then influences channel form and processes in distinctive ways. Nanson (1981) described how flood-deposited trees can form the core of scroll bars that then provide a stable substrate for tree colonization, sediment trapping and further scroll bar development. Kochel et al. (1987) revealed how floodplain trees that had been undermined and transported during a flood became trapped and stacked against standing trees, retaining sediment to create new elevated areas above floodplain level that could support tree colonization.

During this early period, environmental scientists started to consider the aggregate effect of riparian vegetation on fluvial forms and processes (Table 1, theme 6) focusing on river channel initiation (e.g., Graf, 1979), size (e.g., Graf, 1978; Murgatroyd & Ternan, 1983; Zimmerman et al., 1967), recovery and stability (e.g., Gray & MacDonald, 1989; Kondolf & Curry, 1984, 1986; Wilson, 1973), and migration (e.g., Smith, 1976). Page and Nanson (1982) provided an early proposition of two-way interactions between vegetation and fluvial forms and processes when they noted that sediment retention by colonizing trees promoted the development of counter-point bars.

Similarly, research started to investigate the aggregate effects of aquatic vegetation on fluvial forms and processes (Table 1, theme 7) including the impact of seasonal aquatic plant growth and senescence on flow resistance and stage-discharge relationships (e.g., Dawson, 1978; Dawson & Robinson, 1984; Watson, 1987) and the time of travel of flood waves (e.g., Hamill, 1983). A more detailed, mechanistic understanding was developed regarding the movement of water through aquatic vegetation stands (e.g., Losee & Wetzel, 1988), the deformation of plant canopies by flowing water, and the retention of sediment as a result of flow velocity reduction within plant stands (e.g., Sand-Jensen et al., 1989).

In conclusion, early research was wide-ranging but addressed coarse spatial and temporal scales; was based heavily on field observations linked to specific, often simple concepts; and also frequently considered vegetation in a highly simplified way. Nevertheless, some research considered individual processes, landform types and species, and in a few cases two-way interactions between plants and fluvial forms and processes. During this early period, there was one particularly important conceptual contribution to fluvial biogeomorphology from Hickin (1984). He presented his ideas on the theme 'vegetation and river channel dynamics' and he noted that 'the physical science of fluvial geomorphology is flawed because it ignores processes that are not easily quantifiable and physically or statistically manipulable' (p. 111). He went on to describe some of these processes and emphasized five mechanisms by which vegetation may have a significant controlling influence on fluvial forms and processes: flow resistance; bank strength; bar sedimentation; log jam formation; and concave-bank bench deposition. While many of these mechanisms had been individually explored before 1990, their integration in Hickin's (1984) paper was an important influence on subsequent fluvial biogeomorphological research.

4 | A TRANSITIONAL DECADE

The 1990s marked a transition during which research reinforced the themes that had been investigated in earlier decades but also introduced new research directions and was frequently supported by a range of methodological advances.

The beginning of the decade saw the publication of two edited books (Thornes, 1990; Viles, 1988) that illustrated how research at the interface of geomorphology, hydrology and biology was providing a foundation for the emerging field of biogeomorphology with fluvial biogeomorphology as a very prominent component. Two symposia extended this integration; the 26th Binghampton Symposium on 'Biogeomorphology, terrestrial and freshwater' (Hupp et al., 1995) and 'Floodplain forests: structure, functioning and management' (Brown et al., 1997a), with Hughes et al. (1997) review of 'Floodplain biogeomorphology' appearing towards the end of the decade.

Many reviews, conceptual models and frameworks were published that organized and synthesized earlier research and in some cases, implicitly or explicitly, indicated new research directions (Table 2). For example, Maser and Sedell (1994) extended well beyond the reach and small catchment scale to synthesize and conceptualize the environmental role of wood through entire river systems into and across the oceans. Phillips (1995) extended the time scales over which vegetation–landform interactions could be considered by proposing some time scale-specific, theoretical research approaches. In relation to management-relevant space and time scales, Pautou et al. (1997) proposed space–time units to aid in understanding of patch dynamics on floodplains. Biggs (1996) formalized a simple way of grouping aquatic plants (periphyton, bryophytes or macrophytes) to consider how physical processes, especially flow velocity, might be expected to control their broad distributions along river systems. Following their earlier work, Johansson et al. (1996) placed the process of hydrochorous seed dispersal into context by asking the question 'Do rivers function as corridors for seed dispersal?'. Lastly, Sand-Jensen (1997) built upon the concept of organisms that act as ecosystem engineers (Jones et al., 1994) by considering the role of macrophytes as stream biological engineers. These are all examples of research contributions that built on early work to provide important frameworks and directions through the 1990s into the beginning of the 21st century.

TABLE 2 Selected publications from the 1990s reviewing earlier research and proposing conceptual frameworks relevant to some of the pre-1990 research themes listed in Table 1.

Research theme	Authors and dates
2. Flood disturbance affects plants	Bren (1993), Johansson et al. (1996), Hughes (1997).
3. Fluvial forms and processes affect plants	Hupp (1990), Higler (1993), Malanson (1993), Nilsson et al. (1993), Hupp and Osterkamp (1996), Scott et al. (1996), Naiman and Décamps (1997), Pautou et al. (1997), Tabacchi et al. (1998).
4. Plants affect flow hydraulics	Gippel (1995).
5. Wood affects fluvial processes and forms	Gregory (1992), Maser and Sedell (1994), Fetherston et al. (1995), Gurnell et al. (1995), Keller and MacDonald (1995).
6. Riparian plants affect fluvial processes and forms	Thorne (1990), Gurnell (1995, 1997), Gregory et al. (1991), Phillips (1995).
7. Aquatic plants affect fluvial processes and forms	Pitlo and Dawson (1990), Biggs (1996), Sand-Jensen (1997).

Note: Publications are listed in chronological order with respect to each research theme.

Much research extended pre-existing themes, particularly themes 2, 4, 5, 6 and 7 (see Table, 3 for examples). It revealed greater detail of the character of wood and plants, fluvial forms, fluvial processes and, increasingly, interactions among them. It also delivered observations from a widening range of environmental settings, including arid environments and ephemerally flowing water courses (e.g., Jacobson et al., 1999).

Several new research trends emerged during the 1990s. The study of interactions among plants and/or wood and fluvial processes

TABLE 3 Selected publications from the 1990s relevant to some of the pre-1990 research themes listed in Table 1 and some emerging themes.

Research theme	Authors and dates
Expanding knowledge on established research themes (from Table 1)	
2. Flood disturbance affects plants	Baker (1990), Hughes (1990), Johnson-Gottesfield and Gottesfeld (1990), Bayard and Schweingruber (1991), Birkeland (1996), Gottesfeld (1996), Cordes et al. (1997), Blanch et al. (1999), Ferreira and Stohlgren (1999).
4. Plants affect flow hydraulics	Gurnell and Midgley (1994), Sand-Jensen and Mebus (1996), Sand-Jensen and Pedersen (1999).
5. Wood quantities and impacts on fluvial processes and forms	McDade et al. (1990), Robison and Beschta (1990a, 1990b), Harmon and Hua (1991), Shields and Smith (1992), Evans et al. (1993), Gregory et al. (1993, 1994), Nakamura and Swanson (1993), Montgomery et al. (1995), Richmond and Fausch (1995), Thompson (1995), Hedman et al. (1996), Ruediger and Ward (1996), Beechie and Sibley (1997), Hilderbrand et al. (1997), Myers and Swanson (1997), Wohl et al. (1997), Gurnell and Sweet (1998), McHenry et al. (1998), Buffington and Montgomery (1999), Elosegi et al. (1999), Jacobson et al. (1999).
6. Riparian plants affect fluvial processes and forms	Davis and Gregory (1994), Dunaway et al. (1994), Madej et al. (1994), Friedman et al. (1996), Davies-Colley (1997), Dwyer et al. (1997), Huang and Nanson (1997), Trimble (1997), Abernethy and Rutherfurd (1998), Burckhardt and Todd (1998), Rowntree and Dollar (1999).
7. Aquatic plants affect fluvial processes and forms	Petticrew and Kalff (1992), López and Garcia (1998), Sand-Jensen (1998).
New research directions	
8. Wood and Plant Traits	Brewer and Parker (1990), Nielsen and Sand-Jensen (1991), Nilsson et al. (1991b), Rowntree (1991), Thebaud and Debussche (1991), Reyes et al. (1992), Sand-Jensen and Vindbæk Madsen (1992), Spencer and Ksander (1992), Johansson and Nilsson (1993), Mallik and Rasid (1993), Kubitzki and Ziburski (1994), Décamps et al. (1995), Danvind and Nilsson (1997), Bekker et al. (1998), Bornette et al. (1998), Mahoney and Rood (1998), Bilby et al. (1999), Friedman and Auble (1999), Greulich and Bornette (1999), Robertson and Augspurger (1999).
9. Vegetation–fluvial process interactions along low-gradient, large and multi-thread rivers	Abbe et al. (1993), Harwood and Brown (1993), Pautou and Arens (1994), Marston et al. (1995), McKenney et al. (1995), Abbe & Montgomery (1996), Brown et al. (1997b), Piégay (1997), Piégay and Bravard (1997), Van Coller et al. (1997), Wende and Nanson (1998), Edwards et al. (1999), Kollmann et al. (1999), Tooth and Nanson (1999)
10. Vegetation–fluvial process interactions: Insights from channel recovery	Simon and Hupp (1990), Hupp and Simon (1991), Shields and Gray (1992).
11. Vegetation–fluvial process interactions: Insights from flow regulation	Nilsson et al. (1991a), Garcia de Jalon et al. (1994), Johnson (1994, 1997), Rood and Mahoney (1995), Scott et al. (1997), Dominick and O'Neill (1998), Kranjcec et al. (1998), Cooper et al. (1999), Scott et al. (1999).

Note: Publications are listed in chronological order with respect to each research theme.

developed well beyond the confines of predominantly single-thread streams and headwater rivers to include larger and/or lower gradient rivers of both single and multi-thread styles (Table 3, theme 9). This research investigated interactions among wood and/or riparian vegetation and distinctive landforms associated with particular river styles and transitions between styles (e.g., Abbe et al., 1993; Abbe & Montgomery, 1996; Harwood & Brown, 1993; Piégay & Gurnell, 1997) as well as river channel dynamics and floodplain connectivity (e.g., Piégay, 1997; Piégay & Bravard, 1997). One particular focus was how wood and riparian vegetation were linked in systems where fragments of the riparian tree species could sprout and help to initiate landforms such as scroll bars (McKenney et al., 1995) and small (pioneer) islands (Edwards et al., 1999). Some researchers gained further insights into interactions among plants and/or wood and fluvial processes from studying rivers recovering from morphological modifications (Table 3, theme 10) and flow regulation (Table 3, theme 11). Building on the flood pulse concept (Junk et al., 1989), changes to the flow regime, whether flow reduction, augmentation or changes in the magnitude and frequency of flow extremes, produced a very fertile area for gaining biogeomorphological knowledge. Fluvial process impacts on propagule dispersal, germination, and growth performance of riparian trees and their significance for the structure of riparian woodlands and landforms gained particular attention (e.g., Cooper et al., 1999; Cordes et al., 1997; Kranjcec et al., 1998; Rood & Mahoney, 1995; Scott et al., 1997, 1999). This research supported the creation (Mahoney & Rood, 1998) and subsequent developments of the 'Recruitment Box' model that links flow regime characteristics to riparian tree recruitment. A further new research theme considered plant and wood traits (Table 3, theme 8) focusing on seed and seed bank characteristics and dispersal processes (Bekker et al., 1998; Danvind & Nilsson, 1997; Hughes & Cass, 1997; Johansson & Nilsson, 1993; Nilsson et al. 1991b); the growth performance, architecture, strength and flexibility of the above- and below-ground biomass of different plant species and growth stages (e.g., Mallik & Rasid, 1993; Nielsen & Sand-Jensen, 1991); and the susceptibility of different species to environmental disturbances and competition (e.g., Brewer & Parker, 1990; Décamps et al., 1995; Friedman & Auble, 1999; Greulich & Bornette, 1999; Robertson & Augspurger, 1999).

The final important characteristic of fluvial biogeomorphology research in the 1990s was the increasing use of methods that improved and complemented field measurements. For example, methods for quantifying wood in field surveys were improved (e.g., Beschta & Robison, 1990; Ringvall & Stahl, 1999; Thevenet et al., 1998). Field experiments (i.e., manipulations of the field environment, e.g., Assani & Petit, 1995; Brueske & Barrett, 1994; Crowl & Covich, 1990; Dudley et al., 1998; Greulich & Bornette, 1999; Smith et al., 1993; Wilcock et al., 1999) and laboratory experiments, including flume and mesocosm studies (e.g., Braudrick et al., 1997; Gippel et al., 1996; Hughes et al., 1997; Wu et al., 1999; Young, 1991), were conducted to test hypotheses developed from theory and field observations. Researchers increasingly used historical maps and aerial images to consider information covering longer time periods and larger areas than was otherwise possible (e.g., Johnson et al., 1995; Marston et al., 1995). Following the launch of the first Landsat satellite in 1972, the 1990s saw increasing use of multi-spectral data sets obtained from satellite platforms (e.g., Kalliola et al., 1992; McCarthy et al., 1993; Mertes et al., 1995), although the typically coarse spatial resolution of the available data and difficulties in linking ground measurements to spectral signatures limited the nature and reliability of obtained outputs (Mertes, 2002). Researchers also developed new process-based models that emphasized mechanisms affecting the nature and functioning of plants and wood in and around rivers, including further advances in modelling impacts on flow resistance and channel conveyance (e.g., Auble et al., 1994; Bragg & Kershner, 1997; Darby, 1999; Kirkby, 1995; Mahoney & Rood, 1998; Stromberg et al., 1993; Van Sickle & Gregory, 1990).

5 | EXPANSION AND DIVERSIFICATION: THE MAKING OF A SUB-DISCIPLINE

Since the turn of the century, the discipline of biogeomorphology has grown rapidly and the breadth and complexity of research have increased. The new research directions that emerged during the 1990s have expanded, subdivided and become increasingly integrated, making a simple development of the pre-2000 themes inappropriate. Research on the quantities and geomorphological impacts of large (dead) wood alone (Table 3, themes 5 and 8) continues to attract a lot of research attention. At the same time, research on living (riparian and aquatic) plants has developed particularly rapidly. Indeed, the impact of floods and other disturbances on living plants, the impacts of living plants on fluvial processes and forms, and the various feedbacks and interactions (Table 3, themes 2, 4, 6, 7, 8, 9, 10, 11) are now the core focus in fluvial biogeomorphology. Within this core focus, there is an increasing emphasis on wood and plant traits (Table 3, theme 8) with 'living wood' (entire uprooted trees and wood fragments that can sprout) providing a crucial biogeomorphological link between wood and plants in their roles as physical ecosystem engineers (Gurnell, 2014). In part, these research developments can be attributed to insights gained from the analysis of new spatial data sets and the application of innovative field and laboratory methods. Therefore, after briefly summarizing some broad research trends (5.1), this section is organized into three further subsections, two of which provide integrative overviews of research involving large (dead) wood (5.2) and riparian and aquatic plants (5.3), while a final section summarizes advances in the techniques and data sources used to support research in fluvial biogeomorphology (5.4).

5.1 | Broad research trends

Advances in biogeomorphology have been addressed in several reviews. For example, Naylor et al. (2002), Dietrich and Perron (2006), Stallins (2006), Haussmann (2011), Osterkamp et al. (2012), Coombes (2016), Viles (2020) and Rice (2021) all provide reviews from different perspectives, with Rice (2021) specifically focusing on the role of animals. Furthermore, three particular perspectives have been emphasized: space and time scales and how to link them (e.g., Larsen et al., 2021; Wainwright et al., 2011; Wheaton et al., 2011); the fundamental importance of disturbances (e.g., Kent et al., 2001; Rice et al., 2012; Viles et al., 2008); and coupling and feedbacks among biotic and abiotic processes and forms with a specific focus on physical ecosystem engineering by organisms (e.g., Allen et al., 2014; Collins et al., 2004; Corenblit et al., 2010, 2011; D'Odorico et al., 2010; Jones, 2012; Jones et al., 2010; Murray et al., 2008; Phillips, 2016a, 2016b; Reinhardt et al., 2010).

Research in fluvial biogeomorphology has incorporated these three perspectives and has been informed increasingly by the disciplines of landscape ecology and hydrology in addition to fluvial geomorphology and ecology. For example, the flood pulse concept, which captured the ecological importance of a river's flow regime (Junk et al., 1989), has been expanded to incorporate the broader river landscape through considerations of lateral as well as longitudinal connectivity; spatio-temporal variability in connectivity driven by flow pulses of all magnitudes; and their consequences for habitat turnover, heterogeneity and biodiversity (e.g., Junk & Wantzen, 2004; Tockner et al., 2000). More broadly, spatio-temporal changes in river landscape processes (hydrological, chemical, geomorphological, biological) and habitats/landforms have become the foundation for river environment research in general (e.g., Amoros & Bornette, 2002; Gurnell et al., 2016a; Naiman et al., 2005; Parsons & Thoms, 2007; Stanford et al., 2005; Thorp et al., 2006; Ward et al., 2002a, 2002b) and fluvial biogeomorphology in particular.

TABLE 4 Selected publications on the fluvial biogeomorphological role of large (dead) wood research in the 21st Century.

Perspective	Authors and dates
Overviews and integrating concepts	
	Hassan et al., (2005a, 2005b); Wohl and Jaeger, (2009); Seo et al., (2010); Collins et al., (2012); Erskine et al., (2012); Wohl, (2013, 2017, 2020); Comiti et al., (2016); Ruiz-Villenueva et al., (2016b); Kramer and Wohl, (2017); Wohl et al., (2017, 2019b); Wohl and Scott, (2017); Shumilova et al., (2019); Gurnell and Bertoldi, (2022a); Swanson et al., (2021).
Wood quantities and dynamics	
Assessments of wood quantities	Gurnell et al. (2000a, 2000b), Hering et al. (2000), Rutherfurd et al. (2000), Diez et al. (2001), Deng et al. (2002), De Waal (2002), MacNally et al. (2002), Meleason et al. (2005), Wyżga and Zawiejska (2005), Chen et al. (2006), Comiti et al. (2006), Daniels (2006), Young et al. (2006), Morris et al. (2007), Pfeil et al. (2007), Czarnomski et al. (2008), Lassettre et al. (2008), Nowakowski and Wohl (2008), Angradi et al. (2009), Cadol et al. (2009), Warren et al. (2009), Cadol and Wohl (2010), Moulin et al. (2011), Wohl (2011), Wohl and Cadol (2011), Wohl et al. (2011, 2012, 2018a, 2018b), Chen et al. (2013), Costigan and Daniels (2013), Beckman and Wohl (2014), Wohl and Beckman (2014), Costigan et al. (2015), Jackson and Wohl (2015), Kim et al. (2015), Hough-Snee et al. (2016), Kitchingman et al. (2016), Lininger et al. (2017), Mao et al. (2017), Galia et al. (2018a, 2018b, 2020), Martin et al. (2018), Matheson and Thoms (2018), Rossetti de Paula et al. (2020), Picco et al. (2021), Guiney and Lininger (2022), Gurnell et al. (2022), Pavlowsky et al. (2023).
Wood accumulation types and patterns	Gurnell et al. (2000a, 2000b), Abbe and Montgomery (2003), Kaczka (2003), Wallerstein and Thorne (2004), Zelt and Wohl (2004), Pettit et al. (2005), Dunkerley (2014), Boivin et al. (2015, 2017a), Wyżga et al. (2015), Dixon (2016), Gurnell et al. (2022), Wohl (2022).
Wood mobility	Van der Nat et al. (2003), Pettit et al. (2005), Warren and Kraft (2008), Wohl and Goode (2008), Curran (2010), Fremier et al. (2010), Bertoldi et al. (2013), Chen et al. (2013), King et al. (2013), Dixon and Sear (2014), Iroumé et al. (2015, 2018, 2020), Ruiz-Villanueva et al. (2016c, 2016d, 2016e), Boivin et al., (2017b), Haga et al. (2017), Wyżga et al. (2017), Wohl et al. (2019a), Iskin and Wohl (2021), Picco et al. (2021), Guiney and Lininger (2022), Hortobágyi et al. (2024).
Wood budgets and budget components	Johnson et al. (2000), Hyatt and Naiman (2001), Martin and Benda (2001), Ott et al. (2002), Dahlstrom et al. (2005), Sobota et al. (2006), Arsenault et al. (2007), Elosegi et al. (2007), Latterell and Naiman (2007), Czarnomski et al. (2008), Jones and Daniels (2008), Seo et al. (2008, 2015), Seo and Nakamura (2009), Merten et al. (2013), Pettit et al. (2013), Wohl and Ogden (2013), Benda and Bigelow (2014), Lucia et al. (2015), Dethier et al. (2016), Hassan et al. (2016), Picco et al. (2016), Ruiz-Villanueva et al. (2014c), Boivin et al. (2017a, 2017b), Galia et al. (2017), Kramer et al. (2017), Piégay et al. (2017), Senter et al. (2017), Steeb et al. (2017), Tonon et al. (2017, 2018), Lucia et al. (2018), Stella et al. (2021).
Interactions among wood and fluvial processes	
Flow patterns and sediment storage	Daniels and Rhoads (2003, 2004, 2007), Hassan and Woodsmith (2004), Manners et al. (2007), Cadol and Wohl (2011), Short et al. (2015), Martin et al. (2016), Pfeiffer and Wohl (2018), Hinshaw et al. (2020), Ader et al. (2021), Grabowski and Wohl (2021), Livers and Wohl (2021).
Headwater (and mountain) rivers	Massong and Montgomery (2000), Rot et al. (2000), Baillie and Davies (2002), Hart (2002), Keim et al. (2002), Curran and Wohl (2003), Faustini and Jones (2003), Gomi et al. (2003), Jeffries et al. (2003), Kail (2003), Lancaster et al. (2003), May and Gresswell (2003), Webb and Erskine (2003, 2005), Dahlstrom and Nilsson (2004), Dufour et al. (2005), Kreutzweiser et al. (2005), Lancaster and Grant (2006), Andreoli et al. (2007), Cordova et al. (2007), Comiti et al. (2008), Mao et al. (2008), Oswald and Wohl (2008), Bendix and Cowell (2010), Sear et al. (2010), Ryan et al. (2014), Scott et al. (2014), Seixas et al. (2020), Welling et al. (2021), Danhoff and Huckins (2022), Gurnell and Hill (2022).
Floodplain rivers	Brooks and Brierley (2002), Collins et al. (2002), Hughes and Thoms (2002), Brooks et al. (2003), Montgomery and Abbe (2006), O'Connor et al. (2003), Klaar et al. (2011), Collins et al. (2012), Phillips (2012).
Linking wood to trees	
	Díez et al. (2002), Tabacchi and Planty-Tabacchi (2003), Marx and Walters (2008), Freschet et al. (2012), Collins et al. (2012), Orman et al. (2016), Ruiz-Villanueva et al. (2016a, 2016b), Iroumé et al. (2017), Kahl et al. (2017).

Note: Publications are listed in chronological order with respect to each perspective.

5.2 | Large wood

Numerous recent papers have reviewed and conceptualized the fluvial biogeomorphological role of large wood (Table 4). Furthermore, an edited book (Gregory et al., 2003) and three journal special issues (Gurnell, 2007a; Picco et al., 2017; Wohl & Iroumé, 2021) entitled 'Wood in World Rivers' have been published since 2000. Wood research remains quite heavily focused on streams and small rivers in forested mountainous areas of the US. However, since 2000, significant bodies of work have been undertaken on lower gradient, larger river systems, of differing geomorphological style and subject to varied river corridor land cover and management. Furthermore, the geographical range of wood research continues to expand with published research results emanating from Central and South America, Asia, Australasia and Europe and to a lesser extent from Africa. Although research papers on large wood frequently address several different research perspectives, this overview considers work that is largely centred on (i) wood quantities and dynamics; (ii) interactions among wood and fluvial processes and forms; (iii) linking wood to trees.

5.2.1 | Wood quantities and dynamics

Assessments of wood quantities

Researchers continue to provide information on the quantities of wood stored in and around river systems (Table 4). In forested systems, wood quantities vary with biogeographical setting (e.g., Lininger et al., 2017; Wohl et al., 2017), the age and species composition of the forest (e.g., Beckman & Wohl, 2014; Elosegi et al., 2007; Gurnell & Bertoldi, 2022a; Morris et al., 2007), the nature and recency of forest management (e.g., Gurnell & Hill, 2022; Mao et al., 2017; Nowakowski & Wohl, 2008), and the spatio-temporal distributions and severity of physical (wind, fire, extreme precipitation, landslides and floods) and biological (diseases, infestations) disturbances (e.g., Arsenault et al., 2007; Costigan et al., 2015; Dethier et al., 2016; Guiney & Lininger, 2022; Iskin & Wohl, 2021; King et al., 2013; Pavlowsky et al., 2023; Vaz et al., 2015; Wohl, 2022). The general trend of decreasing wood retention per unit channel area as river channel dimensions increase along forested systems has been confirmed (e.g., Kim et al., 2015; Wohl & Cadol, 2011; Wohl & Jaeger, 2009), but notable differences in wood storage have been identified among rivers of different gradient and geomorphological style (e.g., Daniels, 2006; Galia et al., 2018b, 2020; Gurnell et al., 2000a, 2000b, 2002; Lassettre et al., 2008; Martin et al., 2018; Moulin et al., 2011; Pettit et al., 2005; Wyżga & Zawiejska, 2005; Wyżga et al., 2017). In-channel wood storage is affected by local obstructions such as boulders, living trees, roots, fallen trees and wood jams and the presence of bank and bed irregularities (Dunkerley, 2014; Gurnell, 2003; Pettit et al., 2005), but as channels increase in size, such local irregularities decrease in relative importance and channel planform and cross-sectional characteristics increasingly dominate wood retention (Abbe & Montgomery, 2003).

Wood storage within the river corridor also varies with valley confinement, and thus the presence/absence, size, morphology and dynamics of any river margin or floodplain. Wood storage quantities and patterns on floodplains reflect the mix of local wood production; wood delivery from the river channel and valley side processes (e.g., Lancaster & Grant, 2006; Reeves et al., 2003); and the degree to which wood from these sources mixes and interacts (e.g., Wohl, 2020). Furthermore, large volumes of wood can be retained within floodplains for long periods following incorporation into floodplain sediments (e.g., Arsenault et al., 2007; Brooks & Brierley, 2002; Hyatt & Naiman, 2001).

Although most research has been concerned with lightly managed forested catchments or river corridors, the effects of other land cover types and any management interventions that modify land cover or reduce channel morphological complexity have been shown to markedly reduce wood storage (e.g., Brooks et al., 2003; Scott & Wohl, 2018).

Wood accumulation types and patterns

An important aspect of wood storage is whether wood is retained as individual pieces or within accumulations or jams. Some accumulations store enormous quantities of wood, such as the wood rafts that can develop on large complex river systems (e.g., Boivin et al., 2015, 2017a). The number of wood accumulations or jams is often recorded as an indicator of wood storage, and a variety of wood jam classifications have been devised to indicate likely hydraulic impacts. Following the simple classification of jams in small low-gradient streams proposed by Gregory et al. (1985, 1993), which discriminates jams according to whether they completely cross the channel and their relative flow resistance, several new classifications have emerged since 2000. Wallerstein and Thorne (2004) and Dixon (2016) have proposed slightly more complex hydraulically based classifications for relatively small single-thread rivers. In contrast, Abbe et al. (1993) and Abbe and Montgomery (1996, 2003) have classified wood jam types that may form along morphologically complex mountain rivers from log steps in steep confined headwaters to rafts in lower gradient unconfined meandering and wandering reaches. These classifications contribute to summarizing wood jam numbers as a component of wood storage but also inferring the likely impacts of wood jams on fluvial processes and forms. Table 4 provides examples of assessments of wood storage and styles of wood accumulation on headwater and mountain streams (e.g., Gurnell et al., 2022; Kaczka, 2003; Wohl, 2022; Wyżga et al., 2015) and lower gradient, downstream reaches of varying geomorphological style (e.g., Boivin et al., 2017a; Lassettre et al., 2008; Pettit et al., 2005).

Wood mobility

A third important property of river wood is its mobility. Many research studies have monitored mobility by resurveying the locations of wood pieces and jams and any changes in jam types. This often involves resurveying specific reaches or transects and/or labelling wood pieces with numbered tags to track changes in the quantity of stored wood or the changing position of wood pieces (e.g., Boivin et al., 2017b; Chen et al., 2013; Gurnell et al., 2022; Pettit et al., 2005; Picco et al., 2021; Warren & Kraft, 2008). Recently, the use of GPS to relocate and record wood at specific sites (Curran, 2010; Ravazzolo et al., 2015; Tonon et al., 2017; Van der Nat et al., 2003); radio-tracking and monitoring of individual wood pieces or aerial units using repeat vertical or oblique images (Bertoldi et al., 2013; Kramer et al., 2017; Schenk et al., 2014; Smikrud & Prakash, 2006); video monitoring of moving wood (MacVicar & Piégay, 2012; Zhang et al., 2021); and frequent repeat measurements of wood trapped in reservoirs (Moulin & Piégay, 2004) have combined to allow more detailed appraisals (e.g., MacVicar et al., 2009). Wood mobility increases as the ratio of wood piece size to channel size decreases and as the frequency of retention structures (boulders, standing trees, roots, bed and bank irregularities) per unit channel area decreases. Indeed, wood accumulations are important irregularities that reduce wood mobility as wood pieces become snagged and incorporated into jams and then eventually break free from them. Lastly, as previously noted, floodplains can store wood for prolonged periods (e.g., Brooks & Brierley, 2002; Guiney & Lininger, 2022), significantly reducing overall wood mobility.

Wood budgets and budget components

Wood quantity and mobility are central to understanding the wood regime and budget of a river system (Wohl et al., 2019b). Evaluation of a wood budget for a river reach or entire catchment for any specific time period is challenging but crucial for understanding the key controls on wood inputs, storage and outputs through river reaches or entire catchments (Benda & Sias, 2003). Many researchers have attempted wood budget evaluations using a combination of direct measurements and indirect estimates of budget components (e.g., Boivin et al., 2017a; Hassan et al., 2016; Martin & Benda, 2001; Tonon et al., 2018). More frequent has been research on specific budget input and output components. Wood inputs to rivers have been observed or estimated for tree fall, bank erosion, debris flow and landslide processes (e.g., Dethier et al., 2016; Lancaster et al., 2003; Lucia et al., 2018; Picco et al., 2016; Ruiz-Villanueva et al., 2014c; Sobota et al., 2006; Stella et al., 2021). Observations of wood trapping within reservoirs have been used in combination with other information to very successfully undertake spatial and temporal analyses of the output component of catchment wood budgets and to estimate major controls (e.g., Senter et al., 2017; Seo et al., 2008, 2015). A final important influence on wood budgets is the wood properties. Wood density is important for wood mobility and varies with species and degree of decomposition (Brown, 1997; Ruiz-Villanueva et al., 2016a). Small differences in wood density may affect wood mobility and the stability of wood pieces and accumulations (Tabacchi & Planty-Tabacchi, 2003). Where wood is denser than water, wood behaviour is transformed. Wood decomposition reduces wood density, can completely remove wood pieces from the wood budget, and can cause wood to break into smaller pieces and thus become more mobile. Decomposition is affected by wood species and their interactions with decomposer communities (Díez et al., 2002; Freschet et al., 2012; Kahl et al., 2017) according to wood piece size and residence time (Iroumé et al., 2017).

5.2.2 | Interactions among wood and fluvial forms and processes

Flow patterns and sediment storage

Wood pieces and wood accumulations interrupt flow patterns and disrupt sediment movements. Wood can pond back water, attenuate river flows (Ader et al., 2021; Hinshaw et al., 2020) and induce complex local flow patterns (Daniels & Rhoads, 2003, 2004, 2007; Manners et al., 2007). These changes in flow drive changes in sediment erosion, mobilization and storage around the wood (e.g., Hassan & Woodsmith, 2004). In general, increasing quantities of in-channel or floodplain wood lead to increased sediment retention and attenuation of downstream sediment movements. Most field observations have been concerned with in-channel rather than floodplain wood, so the following comments largely refer to the former.

Headwater (and mountain) rivers

The size and frequency of in-channel wood pieces or accumulations are a crucial control of flow hydraulics and sediment dynamics in headwater streams (Ader et al., 2021; Welling et al., 2021). Short et al. (2015) attributed attenuation in the dispersal of a post-fire sediment pulse to the formation of in-channel wood jams. Instream wood was the most important driver of instream storage of fine sediment and particulate organic matter. Livers and Wohl (2021) found that channel-spanning wood jams stored more organic sediment than non-channel-spanning jams. Headwater streams receive wood from tree fall and hillslope processes and then redistribute the wood to form various wood features. Thus, a typical downstream sequence commences with randomly distributed, individual wood pieces (whole trees, branches, trunks, root wads) where the stream is not competent to move them. This is followed by cross-channel pieces and jams as wood pieces become mobile but are typically longer than the channel width. Lastly, increasing proportions of wood pieces and jams do not span the channel as wood piece sizes become shorter than the increasing channel width. As a consequence, Pfeiffer and Wohl (2018) found that the largest volumes of wood-associated coarse sediment are stored in intermediate-sized channels. These spatial patterns can be observed along all headwater channels but there are subtle differences in their geomorphological impact with changes in channel gradient and valley confinement (e.g., Abbe & Montgomery, 2003; Gurnell & Hill, 2022; Rot et al., 2000).

In steep mountain headwaters, sudden extreme inputs of wood and sediment from, for example, glacier meltwater outbursts (Oswald & Wohl, 2008) and debris flows (Benda et al., 2003; Hart, 2002; Lancaster et al., 2003; Lancaster & Grant, 2006; May & Gresswell, 2003) can result in major local disruptions in sediment and wood supply (Massong & Montgomery, 2000; Montgomery et al., 2003) and modifications to the valley bottom. These include the development of valley-spanning deposits of wood and boulders; elevated, overbank wood and boulder deposits; and vast in-channel and valley bottom wood accumulations. Furthermore, mobilized wood pieces in steep headwaters are often retained by boulders and rock outcrops enhancing step-pool development (Andreoli et al., 2007; Comiti et al., 2008; Curran & Wohl, 2003; Faustini & Jones, 2003; Mao et al., 2008; Scott et al., 2014; Seixas et al., 2020), inducing increases in step frequency (Gomi et al., 2003), and thus increases in the presence of step-step and step-pool channels.

In lower gradient headwater channels, bank erosion and tree fall are the main wood input mechanisms and trees become the main controls on the retention of mobile wood (i.e., by tree roots, standing trees, fallen trees, very large wood pieces, Gurnell, 2003; Hawley & MacMannis, 2019). All wood can induce geomorphological responses, but accumulations on river channel beds, especially when the wood spans the entire channel width, induce a wide range of responses including the creation of upstream (dammed), lateral (forced) and downstream (plunge) pools, riffles, mid-channel and side bars, and complex patterns of bank scour, bed sediment sorting and bed-margin aggradation (Cordova et al., 2007; Gurnell & Hill, 2022; Kail, 2003; Webb & Erskine, 2005). In lower gradient, less confined reaches of steep headwater streams and more generally along low-gradient, unconfined, headwater streams, in-channel wood accumulations can induce channel migration, overbank flows and the development of floodplain geomorphological features (Wohl, 2011) such as chutes and cutoffs (Webb & Erskine, 2003), networks of perennially and ephemerally flowing side channels (Sear et al., 2010), and complex sedimentation patterns (Jeffries et al., 2003).

Floodplain rivers

Research on the geomorphological impacts of predominantly dead wood in lower gradient, floodplain rivers illustrates how wood accumulations that do not span the channel can have highly variable geomorphological effects (Abbe & Montgomery, 2003; Gurnell et al., 2002). In large single-thread channels, wood tends to accumulate along the channel margins, often preferentially around bends. Linear wood accumulations may accumulate on point bars along inner banks, initiating scroll bar development, or within the riparian woodland on outer bank tops, deflecting overbank flows and inducing scour and ridge formation. More compact wood accumulations may form around individual floodplain trees inducing the formation of fine sediment lenses in the lee of affected trees, or at the entry to chute channels, inducing plunge pool formation and chute siltation. Along multi-thread braided and bedrock systems, wood accumulates around obstacles such as bars, bedrock irregularities or living trees growing on the river bed, inducing local deposition of fine sediment and, on braided systems, scour pool development (Gurnell et al., 2001; Parsons et al., 2006; Pettit et al., 2005; Pettit & Naiman, 2006). In more stable, anastomosing systems, log jams can span individual channels, inducing avulsions and channel switching (e.g., Phillips, 2012). However, as rivers become larger, it is the interaction between wood and trees that increasingly governs geomorphological effects, rather than the impact of dead wood alone. The newest directions in dead wood research since 2000 have focused on such wood-tree interactions.

5.2.3 | Linking wood and plants

At the scale of individual wood pieces or accumulations, wood can retain plant propagules to support vegetation regeneration (Pettit et al., 2005; Pettit & Naiman, 2006). Tree seedlings can survive and establish on decaying wood (Marx & Walters, 2008; Orman et al., 2016; Zielonka, 2006), eventually contributing to a range of fluvial geomorphological features if the wood is located in the river channel or on its margins. Fine sediment retained in and around wood jams often incorporates diverse propagule banks (Osei et al., 2015a), whose germination can lead to the development of in-channel plant cover (Francis et al., 2008); further sediment retention; the development of vegetated bars and benches; and eventually channel migration (Osei et al., 2015b). Furthermore, wood pieces from some tree species can sprout (e.g., Opperman et al., 2008), providing a very intimate link between wood and trees that influences wood behaviour and induces and accelerates landform development. These processes are explored in greater detail in Section 5.3.

At a larger spatial scale, as illustrated by research on the Queets River, Washington, US, dead wood contributes to vegetation succession (Naiman et al., 2010) and can drive a complete cycle of landform development and forest dynamics. Very large wood pieces and accumulations within channels and channel margins influence channel patterns and landform development, including the development of elevated landforms across the valley bottom (Abbe & Montgomery, 2003; O'Connor et al., 2003; Van Pelt et al., 2006). In particular, major wood accumulations can become incorporated into the floodplain to form 'hard spots' (Montgomery & Abbe, 2006) that are extremely stable and so support the long-term development of forest patches. When these mature forest patches are eventually eroded, they contribute very large wood pieces to the river, sustaining a closely coupled 'large wood cycle' (Collins et al., 2012). Although this example refers to the dynamics of large dead wood, similar processes are observed in rivers whose wood may sprout. These processes are explored in Section 5.3.

5.3 | Riparian and aquatic plants

5.3.1 | Integrative concepts and frameworks

Recognition of the importance of sprouting wood for fluvial biogeomorphology has been a key theme since 2000 and has led to the development of several integrative concepts and frameworks.

Working on the gravel bed, braided Tagliamento River, Italy, Edwards et al. (1999) considered the ecological importance of islands as the product of the interaction between the fluvial regime and the dominant plants, the Salicaceae. Gurnell et al. (2001, 2002, 2005) then focused on the biogeomorphological role of the Salicaceae on the same river. They showed how the protection of riparian tree seedlings by wood was fundamental to initiating vegetation establishment on gravel bars. However, they showed that sprouting wood gave seedlings the greatest early protection and accelerated fine sediment retention. Indeed, sprouting wood was key to the aggradation and reinforcement of small (pioneer) islands supporting a diverse vegetation cover and complex mosaic of surrounding pool and bar habitats. This island model (Gurnell et al., 2001) has subsequently been refined in three ways. First, Gurnell and Petts (2006) identified areas where the aggregate physical conditions are most likely to promote pioneer island development, coalescence into established islands, and attachment to the floodplain. Second, Gurnell and Bertoldi (2020) expanded the original model to incorporate the dependence of the growth performance of pioneer woody vegetation on moisture availability and the dependence of vegetation survival and establishment upon 'Windows of Opportunity' (sensu Balke et al., 2011, 2014) between flow disturbances. Third, Bertoldi and Gurnell (2020) illustrated how different pioneer woody plant species can provide complementary roles in driving island development within spatio-temporal windows of establishment opportunities.

Corenblit et al. (2007b) proposed the integrative 'fluvial biogeomorphic succession' concept. This includes four temporal stages of reciprocal interactions among woody plants and fluvial processes: geomorphic, pioneer, biogeomorphic, and ecologic stages. These represent the changing balance between plants and fluvial processes as plants establish and become increasingly influential and physical processes less influential. Several subsequent papers illustrate and develop the concept in diverse biogeographical settings (e.g., Corenblit et al., 2009, 2011, 2015a). The fluvial biogeomorphic succession has also been incorporated into an 'evolutionary biogeomorphology' that considers the evolution of organisms, ecosystem structure and function, and landform organization at the Earth's surface over very long timescales (e.g., Corenblit et al., 2021, 2015b; Steiger & Corenblit, 2012).

Since 2000, research related to the above integrative concepts has highlighted many aspects of plant–fluvial process interactions in varied biogeographical settings. Research on contemporary and recent interactions includes an innovative model of neotropical carbon pumping (Salerno et al., 2023); regional investigations of different biogeomorphological interactions (e.g., Bätz et al., 2015, 2016; Belletti et al., 2015; Räpple et al., 2017, Stromberg et al., 2010a); and at-a-site considerations of the combined role of several plant species (e.g., Allen et al., 2018; Corenblit et al., 2018; Hortobágyi et al., 2018; Kim & Lee, 2022). Research concerned with extremely long time periods has also stressed the important role of plants in the development of river environments (e.g., Brooks et al., 2003; Davies et al., 2022; Davies & Gibling, 2010; Gibling & Davies, 2012; Tooth et al., 2008).

All of this integrative research considers the central role of certain plant species as physical ecosystem engineers (e.g., Gurnell, 2014) with a predominant focus on woody riparian plants. However, non-woody species are also being recognized as physical ecosystem engineers of river environments, including some aquatic macrophyte species (e.g., Clarke, 2002; Gurnell et al., 2013; Gurnell & Bertoldi, 2022b; James et al., 2002; Schoelynck et al., 2012). The combination of aquatic and riparian plants allows plant physical ecosystem engineering to be considered across a continuum of river geomorphological styles from anastomosing through stable to active meandering, wandering and braided river types (e.g., Gurnell et al., 2012, 2016b). Building on early research by Graf (1978, 1982) on the geomorphological transformation of rivers in the south-west of the United States as a result of invasion by Tamarix spp., physical ecosystem engineering by many non-native invasive species has also received increasing attention (e.g., Birken & Cooper, 2006; Caruso et al., 2013a, 2013b; Colleran et al., 2020; Moody & Schook, 2023). This research not only considers contemporary biogeomorphological adjustments along river systems but also prospects for future adjustments as climate changes (e.g., Corenblit et al., 2014b; Fei et al., 2014; McShane et al., 2015; Murray et al., 2012; O'Briain et al., 2023; Tickner et al., 2001). Table 5 refers to a wide body of research concerning interactions among plants and fluvial processes in a changing environment, emphasizing the impacts of climate change, flow regime change and invasions by non-native plant species.

5.3.2 | Plant traits and physical environmental controls

According to Laughlin (2014), 'plants are multifaceted organisms that have evolved numerous solutions to the problem of establishing, growing and reproducing with limited resources' (p. 187). Laughlin (2014) lists seven plant organs and whole-plant properties or groups of traits (and their functional relevance): height (competition for light); leaves (light interception, gas exchange, transport); stems (transport, support, defence, storage); roots (absorption, transport, support, storage); flowers (sexual reproduction); seeds (dispersal, dormancy, establishment); life history (vegetative reproduction, lifespan). In the context of fluvial biogeomorphogy, the focus needs to be on traits that enable plants to survive and complete their life cycles within highly disturbed river environments (e.g., Bywater-Reyes et al., 2022; Karrenberg et al., 2002; O'Hare et al., 2016; Tabacchi et al., 2019). Thus researchers have focused on differential responses to inundation (e.g., McCoy-Sulentic et al., 2017), flood disturbance (e.g., Kyle & Leishman, 2009), flood sequencing (Fernandez et al., 2021), and plant scour and burial (e.g., Catford & Jansson, 2014; Xiong et al., 2001). A recent review by Corenblit et al. (2024) presents a framework for future research developments in this area.

In this section we consider traits that enable plants to survive and engineer river environments (Table 5) under five broad themes: (a) reproductive strategies, propagule viability and dispersal; (b) propagule deposition-retention and seed banks; (c) propagule germination-sprouting and early establishment; and key traits of (d) the above-ground and (e) below-ground biomass of engineer plants.

Reproductive strategies, propagule viability and dispersal

Plants reproduce sexually through the production and germination of seeds, but many species can also reproduce asexually/vegetatively, whereby fragments of living plants can sprout to form new plants. Sexual reproduction introduces genetic diversity while asexual or clonal reproduction expands the population and can introduce diversity in its physical structure (Rood et al., 2003; Tinscert et al., 2020). Both of these reproductive strategies are important in river environments because they provide diversity in the timing of propagule release, the mechanisms and spatial pattern of dispersal, and the rapidity with which plants can establish when they are dispersed to suitable germination/sprouting sites. Building on the biogeomorphological assessment of dead wood (Section 5.2), the ability of many riparian tree species (e.g., the riparian Salicaceae (willows and poplars),

TABLE 5 Selected publications on the fluvial biogeomorphological role of living plants in the 21st Century.

Perspective	Authors and dates
Integrating concepts and frameworks	
	Millar (2000), Tabacchi et al. (2000), Gurnell et al. (2001, 2005, 2012, 2013, 2016b), Tickner et al. (2001), Clarke (2002), Gurnell and Petts (2002, 2006), James et al. (2002), Brooks et al. (2003), Steiger et al. (2005), Corenblit et al. (2007a, 2007b, 2008, 2009, 2010, 2014a, 2014b, 2015a, 2015b, 2018, 2021), Gurnell (2007b, 2014), Huang and Nanson (2007), Bornette et al. (2008), Tooth et al. (2008), Corenblit & Steiger, 2009, Davies and Gibling (2009, 2010), Osterkamp and Hupp (2010), Stromberg et al. (2010b), Gibling and Davies (2012), Schoelynck et al. (2012), Steiger and Corenblit (2012), Stoffel and Wilford (2012), Curran and Hession (2013), Polvi and Wohl (2013), Fei et al. (2014), Moggridge and Higgitt (2014), Bätz et al. (2015), Belletti et al. (2015), Vesipa et al. (2015), Hupp et al. (2016), Kim and Kupfer (2016), Räpple et al. (2017), Allen et al. (2018), Hortobágyi et al. (2018), Politti et al. (2018), Polvi and Sarneel (2018), Castro and Thorne (2019), Jerin and Phillips (2020), Bendix and Stella (2022), Bertoldi & Gurnell (2020), Gurnell and Bertoldi (2020, 2022b), Davies et al. (2022), Kim and Lee (2022), Merritt (2022), O'Briain et al. (2023), Salerno et al. (2023).
Plant traits and physical environmental controls	
Reproductive strategies, propagule viability and dispersal	Andersson et al. (2000), Guilloy-Froget et al. (2002), Boedeltje et al. (2003, 2004), Karrenberg and Suter (2003), Rood et al. (2003), Combroux and Bornette (2004), Riis and Sand-Jensen (2006), Stella et al. (2006), Gurnell (2007b), Nilsson et al. (2010), Mouw et al. (2013), Sarneel (2013), Saumel and Kowarik (2013), Kehr et al. (2014), Sarneel et al. (2014a, 2019), González et al. (2016), Fraaije et al. (2017), Shumilova et al. (2019), Tinscert et al. (2020), Mazal et al. (2021), Fryirs and Carthey (2022).
Propagule deposition-retention and seed banks	Combroux et al. (2001), Goodson et al. (2001, 2002, 2003), Holzel and Otte (2001), Pettit and Froend (2001), Merritt and Wohl (2002), Nilsson et al. (2002), Tabacchi et al. (2005), Gurnell et al. (2006a, 2006b, 2007, 2008), Leyer (2006), Polzin and Rood (2006), Vogt et al. (2006, 2007), Engström et al. (2009), Chambert and James (2009), Moggridge et al. (2009), Stromberg et al. (2009), Moggridge and Gurnell (2010), Riis and Baattrup-Pedersen (2011), Baattrup-Pedersen et al. (2013), Yoshikawa et al. (2013), O'Donnell et al. (2014, 2015a, 2015b), Corenblit et al. (2016), Dawson et al. (2017), Pereira et al. (2021).
Propagule germination-sprouting and early establishment	Barrat-Segretain and Bornette (2000), Amlin and Rood (2001, 2002), Kalischuk et al. (2001), Barsoum (2002), Dixon et al. (2002), Dixon (2003), Francis et al. (2005, 2006), Woods and Cooper (2005), Francis and Gurnell (2006), Leyer (2006), Stenvall et al. (2006), Capon (2007), Francis (2007), Moggridge and Gurnell (2009), Nakai et al. (2009), Predick et al. (2009), González et al. (2010), Lowe et al. (2010), Sarneel et al. (2014b), Riis et al. (2014), Wintenberger et al. (2017), Bigelow et al. (2020).
Above-ground biomass	James et al. (2002), Järvelä (2002), Stephan and Gutknecht (2002), Riis and Biggs (2003), Sand-Jensen (2003, 2008), Bouma et al. (2005), Green (2005), O'Hare et al. (2007), Wilson (2007), Franklin et al. (2008), Riis et al. (2008), Sand-Jensen and Pedersen (2008), Bociag et al. (2009), Folkard (2009), Janauer et al. (2010), Bal et al. (2011), Puijalon et al. (2011), Stone et al. (2011), Albayrak et al. (2012), Miler et al. (2012), Neary et al. (2012), Nepf (2012), Zhu et al. (2012), Västilä and Järvelä (2014), Manners et al. (2015), Diehl et al. (2017b), Hortobágyi et al. (2017a), Nadal-Sala et al. (2017), Cornacchia et al. (2018), Butterfield et al. (2020), Zhu and Tsubaki (2022).
Below-ground biomass	Abernethy and Rutherfurd (2000, 2001), Toledo and Kauffman (2001), Schenk and Jackson (2002), Simon and Collison (2002), Karrenberg et al. (2003), Wynn et al. (2004), Gyssels et al. (2005), Kiley & Schneider (2005), Schutten et al. (2005), De Baets et al. (2007), Dupuy et al. (2007), Snyder and Williams (2007), Danjon and Reubens (2008), Docker and Hubble (2008), Piotrowski et al. (2008), Pregitzer (2008), Brassard et al. (2009), Burylo et al. (2009, 2012), McNickle et al. (2009), Tanaka and Yagisawa (2009), Wang et al. (2009), Wiehle et al. (2009), Guswa (2010), Pollen-Bankhead and Simon (2010), Liffen et al. (2011, 2013a, 2013b), Pollen-Bankhead et al. (2011), Rood et al. (2011a), Zapater et al., 2013, Bardgett et al. (2014), Edmaier et al. (2014), Mardhiah et al. (2014), Polvi et al. (2014), Brunner et al. (2015), Bywater-Reyes et al. (2015), Tron et al. (2015), Vennetier et al. (2015), Zanetti et al. (2015), Pawlik et al. (2016), Shouse and Phillips (2016), Vannoppen et al. (2016), Bankhead et al. (2017), Hales and Miniat (2017), Holloway et al. (2017a, 2017b, 2017c), Jablkowski et al. (2017), Gurnell et al. (2018), Andreoli et al. (2020), Yu et al. (2020), Balcombe et al. (2021), Stamer et al. (2024).
Interactions among plants and fluvial processes and forms within different environmental settings	
	Dykaar and Wigington (2000), Millar (2000), Tooth (2000), Tooth and Nanson (2000), Rosales et al. (2001), Friedman and Lee (2002), Gradzinski et al. (2003), Anderson et al. (2004), Griffin and Smith (2004), Micheli et al. (2004), Rutherfurd and Grove (2004), Sweeney et al. (2004), Tooth and McCarthy (2004a, 2004b), Allmendinger et al. (2005), Cooperman and Brewer (2005), Beechie et al. (2006), Gurnell et al. (2006c), Pettit and Naiman (2006), Pettit et al. (2006), Robertson (2006), Rodrigues et al. (2007), Dunkerley (2008), McBride et al. (2008), Rosales et al. (2008), Zanoni et al. (2008), Atger et al. (2009), Erskine et al. (2009), Jansen and Nanson (2010), Bertoldi et al. (2011b), Charron et al. (2011), Parker et al. (2011), Pietsch and Nanson (2011), Rood et al. (2011b), Horn et al. (2012), Marchetti et al. (2013),

(Continues)

TABLE 5 (Continued)

Perspective	Authors and dates
	Mikuś et al. (2013, 2019), Montero and Latrubesse (2013), Perona et al. (2014), Slocombe and Davis (2014), Wintenberger et al. (2015), Zen et al. (2017), Gregory et al. (2019), Gurnell et al. (2019), Hawley and MacMannis (2019), Jerin (2019, 2021), Milan et al. (2020).
Interactions among plants and fluvial processes and forms in a changing environment	
	Merritt and Cooper (2000), Piégay et al. (2000), Pearce and Smith (2001), Pettit et al. (2001), Steiger et al. (2001), Stromberg (2001a, 2001b), Liébault and Piégay (2002), Nilsson and Svedmark (2002), Amlin and Rood (2003), Beschta (2003), Samuelson and Rood (2004), Auble et al. (2005), Lite and Stromberg (2005), Pataki et al. (2005), Stromberg et al. (2005, 2007, 2010a), Beschta and Ripple (2006), Birken and Cooper (2006), Cooper et al. (2006), Webb and Leake (2006), Ahna et al. (2007), Alvarez-Uria and Korner (2007), Braatne et al. (2007), DeWine and Cooper (2007), Rood et al. (2007a, 2007b, 2008), Engström et al. (2009), Stallins et al. (2010), Cunningham et al. (2011), Dean and Schmidt (2011), Greet et al. (2011, 2012, 2013), Guilloy et al. (2011), Hall et al. (2011), Cooper and Andersen (2012), González et al. (2012), Murray et al. (2012), Rivaes et al. (2013), Kominoski et al. (2013), Meier et al. (2013), Stella et al. (2013), Wilcox and Shafroth (2013), Garssen et al. (2014, 2015), Manners et al. (2014), Reynolds et al. (2014), Hough-Snee et al. (2015), Lawson et al. (2015), Lind and Nilsson (2015), McShane et al. (2015), Duquette et al. (2016), Foard et al. (2016), Gurnell and Grabowski (2016), Perkins et al. (2016), Stromberg and Merritt (2016), Thapa et al. (2016), Čuda et al. (2017), Van Looy and Piffady (2017), Martínez-Fernández et al. (2018), Colleran et al. (2020), Dong (2022), Matte et al. (2022), Viles and Coombes (2022), Butterfield et al. (2023), Moody and Schook (2023), O'Briain et al. (2023), Wieting et al. (2023).

Note: Publications are listed in chronological order with respect to each perspective.

Karrenberg et al., 2003) to sprout when uprooted and dispersed is fundamental to their survival and ability to act as physical engineers of river systems (Gurnell, 2014; Gurnell et al., 2001, 2005).

The biogeomorphological relevance of sexual reproduction along river corridors is well illustrated by the riparian Salicaceae. These pioneer woody species require moist, unvegetated riverine sediments for successful germination/sprouting (Guilloy-Froget et al., 2002; Karrenberg et al., 2003) and so their seed release period is attuned to the annual flow regime, particularly periods of flow recession during late spring to early summer that gradually expose moist, bare riverine sediments. While this broad pattern is encapsulated in Mahoney and Rood's (1998) 'Recruitment Box' model, research since 2000 has revealed increasing species-specific information. All riparian Salicaceae species produce enormous quantities of small light seeds that can be dispersed by wind or water, but different species flower and release seeds at different times and their seed release extends over different time periods. These species exhibit trade-offs between seed mass, the number of seeds produced, the length of the seed release period, and the length of the period over which the seeds remain viable (e.g., González et al., 2016; Karrenberg & Suter, 2003). These traits minimize the chances of hybridization while maximizing the opportunity for some viable seeds to reach suitable sites (i.e., 'seedling safe sites', Polzin & Rood, 2006) to successfully germinate, survive disturbances and reach maturity. Asexual reproduction complements sexual reproduction, since it can occur in any season, take advantage of any flow pulses for dispersal, and, if the propagules are dispersed to suitable sites and remain viable, can lead to sprouting and the establishment of new plants. Asexual reproduction is an important strategy for aquatic (e.g., Boedeltje et al., 2003; Combroux & Bornette, 2004; Riis & Sand-Jensen, 2006) as well as riparian engineer species.

Although there are numerous mechanisms that can disperse sexual and asexual propagules from the parent plant, the two key mechanisms within river corridors are wind (anemochory) and water (hydrochory). While anemochory can disperse small light seeds over long distances, hydrochory is more likely to transfer propagules of engineer species to suitable germination/sprouting sites. Hydrochory often follows anemochory as a secondary dispersal mechanism. For either of these mechanisms, analogies can be drawn with the transport of sediment particles (Gurnell, 2007b; Yoshikawa et al., 2013) whereby propagules from different species can adopt different dispersal pathways according to their size, shape and density (e.g., Boedeltje et al., 2003; Carthey et al., 2016; Nilsson et al., 2002; Sarneel et al., 2014a; Saumel & Kowarik, 2013).

Propagule deposition-retention and seed banks

Following dispersal, propagules are deposited. If they have only a short period of viability, their fate depends on the suitability of the depositional site for germination/sprouting or on rapid re-mobilization and transfer to a more suitable site. However, many riparian and aquatic plant species produce propagules that remain viable for several months to a year or more (Fenner & Thompson, 2005), allowing them to accumulate and form seed/propagule banks at depositional sites (Goodson et al., 2001; Riis & Baattrup-Pedersen, 2011). There is increasing evidence that the hydrodynamic properties of the propagules influence the composition of propagule banks located at different elevations within the river channel and riparian zone (e.g., Goodson et al., 2002; Gurnell et al., 2006a, 2008) and in association with different depositional-morphological environments (Combroux et al., 2001; Corenblit et al., 2016; Pereira et al., 2021). In a further parallel with sediment dynamics, propagule banks incorporating numerous riparian species accumulate in sheltered sites on the river bed (Gurnell et al., 2007), providing temporary storage for long-lived propagules until flows mobilize and transfer them to more suitable germination sites. Sediment dynamics and calibre appear to combine with propagule longevity to produce different subsurface, vertical, viable propagule profiles (e.g., O'Donnell et al., 2014, 2015b).

Propagule germination-sprouting and early establishment

Successful germination or sprouting and early growth performance depend on species responses to environmental conditions. In addition to field observations (e.g., Kalischuk et al., 2001; Leyer, 2006), field and laboratory experiments have illustrated varying survival and growth responses of seedlings and cuttings of different species to site elevation (depth to groundwater), inundation regime (e.g., Amlin & Rood, 2001), rate of water table decline (e.g., Francis et al., 2005; González et al., 2010), substrate calibre (e.g., Francis & Gurnell, 2006; Woods & Cooper, 2005) and site exposure/shelter (Moggridge & Gurnell, 2009). Overall, asexual propagules tend to grow more quickly, allowing them to better resist disturbance and survive (Barsoum, 2002) and their survival and growth performance is affected by the size (internal resources) of the propagule (e.g., Francis, 2007). Experiments with aquatic plant fragments also suggest that the type of fragment and season of dispersal affect their development (Barrat-Segretain & Bornette, 2000). Such experiments not only illustrate the range of conditions within which a species can germinate/sprout and survive, but also the ways in which the young plants adapt their above- and below-ground growth performance and architecture within this range. Furthermore, the changing above- and below-ground biomass of different plant species as they grow also display adaptations that support the survival of plants in disturbed riverine environments and their ability to act as physical engineers.

Above-ground biomass

The above-ground biomass of riparian and aquatic engineer species varies in height, architecture and flexibility according to species, plant age and history. The flexibility of the above-ground biomass of woody riparian plants tends to decrease with plant age, whereas for aquatic plants there are small seasonal variations in flexibility, but the main variations occur among species. Puijalon et al. (2011) recognized a trade-off among aquatic plant species according to whether they are flexible and adjust their form to minimize the forces they encounter or they are relatively rigid with a high resistance to breakage. During inundation, any flow-induced re-configuration of flexible vegetation changes its flow resistance, altering the likelihood of plant uprooting, but also altering the shear stresses imposed on the river bed below and around the plants and thus the likelihood of sediment deposition or scour. As a result of differences in their flexibility and re-configuration potential, aquatic plant species typically occupying particular areas of a river channel according to local hydraulic conditions (e.g., Janauer et al., 2010; Riis & Biggs, 2003). Beyond the scale of an individual plant or plant patch, groups of plant patches typically display spatial patterns that optimize flow velocity, turbulence and drag on individual patches (Cornacchia et al., 2018). Flume experiments have investigated the hydraulic and sedimentation effects of these plant traits in the context of riparian (e.g., Manners et al., 2015; Stone et al., 2011; Västilä & Järvelä, 2014; Zhu & Tsubaki, 2022) and aquatic species (e.g., Miler et al., 2012; Nepf, 2012; Zhu et al., 2012). Flow-plant interactions vary from leaf and plant, through patch to reach scales (e.g., Folkard, 2009; Green, 2005) driving different scales and distributions of sediment deposition and scour.

Below-ground biomass

The above-ground biomass of a plant can only interact with flows of water and sediment if the plant resists uprooting and survives sediment deposition and erosion events. Plant survival depends heavily on the growth performance, architecture, strength and overall resistance to uprooting of its below-ground biomass. From a broad biogeomorphological perspective, riparian root biomass varies with vegetation composition, season and hydrological regime (Kiley & Schneider, 2005); the structural type of riparian vegetation (Wynn et al., 2004); and channel geometry, particularly depth (Toledo & Kauffman, 2001). The root architecture and strength of woody riparian plants have the most profound effect on biogeomorphological sediment retention and landform development along river margins and exposed areas of the river bed (e.g., bars, islands). Tree root architecture is enormously variable (see reviews by Danjon & Reubens, 2008; Pregitzer, 2008; Schenk & Jackson, 2002) with root systems incorporating a mix of coarser, perennial roots that anchor trees (Burylo et al., 2009) and finer, more ephemeral roots that forage for resources (Comas et al., 2013; McNickle et al., 2009). The resulting root architecture varies according to tree species and environmental conditions (Brassard et al., 2009). The relative influence of species and environmental conditions changes with increasing environmental disturbances. Tree root systems become particularly complex within dynamic river corridors, where they provide anchorage and forage for resources in continuously changing environmental conditions. Riparian tree roots display species-specific traits but also strong responses to moisture conditions (Guswa, 2010; Rood, Bigelow, & Hall, 2011a), soil and sediment type (Zanetti et al., 2015) and disturbance pressures (e.g., Hortobágyi et al., 2017a; Stamer et al., 2024). For example, Holloway et al. (2017a) found statistically significant changes in coarse and fine root density and root-area ratio for a single species (*Populus nigra*) according to sediment calibre, moisture content and depth. Because many riparian tree species, including the Salicaceae, reproduce vegetatively from fragments, these species can also produce networks of adventitious roots and new stems by suckering. These processes give rise to highly complex underground structures that evolve as the plants experience flood stresses and sediment deposition. Furthermore, entire stands of genetically identical individuals (clones) often develop as a result of vegetative reproduction, and their roots are susceptible to grafting and thus developing even more complex root structures (Holloway et al., 2017a, 2017b). Additional below-ground structures that influence the stability and erosion resistance of sediments around root systems are mycorrhizae, which encourage soil aggregation (Mardhiah et al., 2014; Piotrowski et al., 2008). Overall, root strength and architecture combine to reinforce aggrading landforms and protect landforms against fluvial erosion (e.g., Abernethy & Rutherfurd, 2000, 2001; Docker & Hubble, 2008; Simon & Collison, 2002; Vannoppen et al., 2016; Yu et al., 2020).

The below-ground biomass of aquatic plants is also very important from a biogeomorphological perspective. Aquatic plants display strong seasonal changes in above-ground biomass, in many cases losing all foliage in winter but then showing a seasonal pattern of growth in spring and summer followed by senescence in autumn. This seasonal pattern is accompanied by changes in below-ground biomass such that the below-ground organs penetrate and stabilize any sediments that accumulate around the plants. A comprehensive study of the emergent species, *Sparganium erectum* (branched bur-reed; Liffen et al., 2011, 2013a, 2013b) revealed seasonal patterns in above-ground biomass (quantity, height, stem diameter, stem density) and below-ground biomass (quantity, depth profile, mix of roots and rhizomes). These seasonal patterns were reflected in changes in plant uprooting resistance, and leaf and rhizome strength. In particular, during the winter when no foliage was present to protect any summer-deposited sediments, living roots also disappeared but rhizomes remained, penetrating and binding together the exposed upper layers (20 to 50 cm depth) of the bed sediments. It is likely that other aquatic plants, especially emergents, show a similar pattern and drive reach-scale flow velocity and fine sediment retention patterns (Gurnell et al., 2006c), eventually leading to reach-scale landform development and terrestrialization (Gurnell & Bertoldi, 2022b).

5.3.3 | Interactions among plants and fluvial processes and forms within different environmental settings

Interactions among plants and fluvial processes are widely recognized at the landform scale. There are general associations between roots (e.g., Pollen-Bankhead & Simon, 2010) and above-ground biomass (e.g., Malkinson & Wittenberg, 2007) and bank stability. Trees, in particular, have noticeable effects on bank form including the presence of undercutting and buttressing (e.g., Pizzuto et al., 2010; Rutherfurd & Grove, 2004) and on channel dimensions (e.g., McBride et al., 2008). In headwater streams, tree roots can span the channel bed, affecting the longitudinal channel profile by acting as grade control structures that retain sediments, create steps, and induce in-channel habitats such as pools (e.g., Hawley & MacMannis, 2019). In larger river channels, following Gurnell et al. (2001, 2005), trees have been shown to play a key role in the development and maintenance of vegetated bars and islands in diverse river environments (e.g., Mikuś et al., 2019; Rodrigues et al., 2007; Rood, Goater, et al., 2011b; Wintenberger et al., 2015).

At reach and landscape scales, vegetation interacts with fluvial processes in many different ways.

In ephemerally flowing streams, Friedman and Lee (2002) observed cycles of sudden channel widening during flash floods and then gradual narrowing between floods in streams located in Colorado, US. The inter-flood narrowing phase is accelerated by vegetation colonization, especially by Salicaceae spp.. Research in Australia has revealed engineering of anabranching systems by woody shrubs (Tooth & Nanson, 2000). The shrubs drive ridge development in the channel bed through lee-side sediment accretion. Complex anabranching patterns evolve as these ridges lengthen, interact, coalesce and funnel flows and transported sediments.

Bed rock rivers can also show characteristic plant-related landforms. In a large bedrock channel of the Sabie River, South Africa, Pettit et al. (2006) and Pettit and Naiman (2006) observed numerous wood piles following a major flood. Most were retained by living, standing or root-secured, toppled trees. The piles retained flood-transported sediment and seeds, forming pioneer landforms around which vegetated alluvial mounds evolved and contributed to an increasingly multi-thread bedrock macrochannel. In an anabranching mixed bedrock-alluvial reach of the Orange River, South Africa, Tooth and McCarthy (2004a) observed the development of stable alluvial islands between flowing channels whose positions reflected the pattern of joints, fractures and foliations in the bedrock. Thus, the position of the islands was controlled by physical factors but riparian vegetation played an important role in island survival and growth. Milan et al. (2020) investigated a bedrock-influenced, anastomosing reach of the Sabie River, South Africa, and demonstrated how topographic lows in the bedrock can become topographic highs as sediments retained by vegetation produce bedrock-cored islands in the later stages of sediment accumulation. Jerin and Phillips (2020) described 'biogeomorphic keystone' species in a small incised bedrock system in Kentucky, US. They noted three species-specific biogeomorphological impacts: biogeomorphological pool formation; root-bank-associated bioprotection; and avulsion island development, also linked to bioprotection. The pools develop within areas of root-induced channel bed weathering by American sycamore. American sycamore and chinquapin pine developed root banks that prevented bank erosion. The same tree species created bioprotected stable patches that formed the core of avulsion-cut islands.

Braided river systems can exhibit a variety of vegetated patches but only those supported by erosion-resistant species, particularly riparian tree species, develop into significant island landforms in these highly disturbed systems. A key characteristic of these vegetated landforms is that they are far from permanent, but because they can form quite rapidly, they are a characteristic feature of the habitat mosaic of many braided systems. For example, Zanoni et al. (2008) observed two scales of change on a braided reach of the Tagliamento River, Italy over two centuries. The first was the changing width of the braid channel and the second was the continual appearance and disappearance of islands. While the ratio of channel area to island area remained the same, dissection and building islands appeared in different proportions through sediment retention by trees and the incorporation of parts of the forested floodplain by avulsions. Islands typically survived for a maximum of ca. 20 to 25 years, and avulsions and attachment of islands to the floodplain drove channel width adjustments. Changes in flow energy can affect the extent and nature of vegetated landforms within braided systems. For example, periods of several years without major floods on the Tagliamento River, Italy have seen the establishment of strips of tree seedlings along the margins of low flow channels, which progressively trap and retain fine sediments to initiate ridged landforms similar to levées (Bertoldi & Gurnell, 2020). This ridge-forming process plus the coalescence of ridges and islands is likely to be important as vegetation contributes to channel planform transitions from braided to wandering or meandering patterns. On the Platte River, Nebraska, US, where flow regulation has progressively reduced the energy and frequency of physical disturbances, accelerated vegetation colonization of bars has driven the development of islands and the transformation of the river's planform from a dynamic braided system to a stable anabranching system (Horn et al., 2012; Johnson, 1997). Griffin and Smith (2004) describe even stronger and opposite dynamics during the transformation of a single-thread river, located in Colorado, US, into a braided system by an extreme flood. The flood destabilized the floodplain by removing its shrub cover, causing 'floodplain unravelling' and the establishment of a braided channel.

Meandering systems also illustrate the biogeomorphological impacts of riparian vegetation. Vegetation frequently controls rates of both outer (cut) bank retreat and inner bank deposition (Allmendinger et al., 2005; Parker et al., 2011) but it also affects bank forms. The cut bank can display vertical and undercut profiles depending on rooting depth to bank height ratios. The inner bank can display scroll bars formed by sediment deposition around ridges of deposited, often sprouting, trees (Zen et al., 2017), or benches stabilized by trees (Erskine et al., 2009).

Heavily vegetated anabranching (anastomosing) systems are an extremely low-energy river type that develops on poorly drained floodplains. For example, Gradzinski et al. (2003) comment that the impact of vegetation on the anastomosing upper Narew River in Poland is overwhelming. Here in the long term, vegetation has built an erosion-resistant peat layer that stabilizes channel banks, while in the shorter term, aquatic plants trap bed material, aggrading the channel bed to produce channel blockages and induce avulsions that create new channels. Tooth and McCarthy (2004b) describe the changing role of marginal sedges and grasses rooted in peat underlain by unconsolidated sediment in the wetlands of the Okavango Delta, Botswana. As water leaks into the margins from the river channels, discharge decreases downstream and splits into numerous distributary channels. The upstream channels actively meander and migrate by scouring the basal sediments and undermining the marginal vegetation. Downstream, the distributaries form an anastomosing system of straight stable channels where the vegetated banks resist erosion by the decreasing flows and so prevent bank scour and thalweg meandering.

The above brief descriptions of the biogeomorphological role of vegetation along a gradient of river types of decreasing flow energy have been integrated into conceptual diagrams and illustrative graphs by several researchers. These attempt to link engineer plants to landforms within river environments of different energy and planform. Examples include Millar (2000), Beechie et al. (2006), Gurnell et al. (2012, 2016b).

Finally, in all of the above cases where plants actively interact with fluvial processes, it is important to recognize temporal hysteresis in those interactions. Plants create landforms that can only be removed by greater disturbances than those that contribute to their formation. The longer the landforms persist and evolve, the greater the disturbance required for landform removal. Therefore, landform construction and destruction are both driven by vegetation interactions with fluvial disturbances and they follow hysteretic sequences regardless of landform type, river type setting or any transitions between river types.

5.4 | Advancing techniques

In Section 5.3, reference was made to new techniques where they were relevant to the discussion. This section considers new techniques that have emerged since 2000 in a more integrated way and, as in previous sections, we support the text overview with tables citing a more extensive body of research. We focus on physical experiments (supported by Table 6), mathematical models (supported by Table 7), and remote sensing.

5.4.1 | Physical experiments

Plants and plant analogues have been used in physical experiments for many decades. In hydraulic experiments, vegetation has often been reproduced by artificial elements, ranging from rigid cylinders to flexible plastic strips (see Vargas-Luna et al., 2016 for a review). The use of artificial elements often matches the idealized conditions of laboratory experiments, and better ensures their reproducibility and detailed control of all relevant parameters. Artificial surrogates can also overcome scaling issues by allowing the selection of specific dimensions and biomechanical properties that represent drag, elastic, and buoyant forces (Sukhodolov et al., 2022).

In the late 1990s and early 2000s, researchers started to use real plants to better reproduce the effect of vegetation on the flow field (e.g., Järvelä, 2002), but also to study other effects related to sediment transport dynamics and the additional cohesion provided by roots (Gran & Paola, 2001). Increased recognition of vegetation as one of the three relevant components of a fluvial system, together with the growth of the field of ecohydraulics (Rice et al., 2010), stimulated the development of new experiments with real or surrogate vegetation that combined river hydraulics, fluvial geomorphology and stream ecology. This promoted specific studies aimed at exploring how to use vegetation in laboratory experiments, along with scaling issues and infrastructural needs (see Thomas et al., 2014). Growing conditions of different plant species, as a function of temperature, light and substrate, were also explored to support an informed choice of species depending on the objectives of the experiments and the

TABLE 6 Selected publications on physical experiments that reproduce fluvial biogeomorphological interactions in the 21st Century.

Topic	Authors and dates
Use of vegetation in laboratory experiments	
	Jiang et al. (2009), Rice et al. (2010), Clarke (2014), Thomas et al. (2014), Vargas-Luna et al. (2016), Łoboda et al. (2018), Lokhorst et al. (2019), Vettori and Nikora (2020), Vettori and Rice (2020), Sukhodolov et al. (2022).
Living vegetation	
Vegetation effect on the flow field	Fathi-Maghadam and Kouwen (1997), Nepf (1999), Kouwen and Fathi-Moghadam (2000), Nepf and Vivoni (2000), Ghisalberti and Nepf (2002, 2006), Järvelä (2002), Armanini et al. (2005), Baptist et al. (2007), McBride et al. (2007), Nepf and Ghisalberti (2008), Wilson et al. (2008), Albayrak et al. (2012), Siniscalchi et al. (2012), Sukhodolov and Sukhodolova (2012), Sukhodolova and Sukhodolov (2012), Aberle and Järvelä (2013), Cameron et al. (2013), Luhar and Nepf (2013), Neary et al. (2012), Nikora et al. (2013), Västilä et al. (2013), Västilä and Järvelä (2014), Tinoco et al. (2015), Vargas-Luna et al. (2015), Kitsikoudis et al. (2016), Chembolu et al. (2019), Shi et al. (2023).
Vegetation effect on sediment flux	López and Garcia (1998), Jordanova and James (2003), Baptist et al. (2007), Nepf and Ghisalberti (2008), Kothyari et al. (2009), Zong and Nepf (2010, 2011), Neary et al. (2012), Yager and Schmeeckle (2013), Tinoco and Coco (2014, 2016), Le Bouteiller and Venditti (2015), Vargas-Luna et al. (2015), Armanini and Cavedon (2019), Licci et al. (2019), Bonilla-Porras et al. (2021), Liu et al. (2021), Zhao and Nepf (2021), Xu et al. (2022).
Vegetation re-configuration	Statzner et al. (2006), O'Hare et al. (2007), Luhar and Nepf (2011), Albayrak et al. (2012), Miler et al. (2012), Siniscalchi and Nikora (2012, 2013), Cameron et al. (2013), Albayrak et al. (2014), Vettori and Nikora (2018).
Vegetation growing conditions	Francis et al. (2005), Francis and Gurnell (2006), González et al. (2010), Perona et al. (2012), Crouzy et al. (2013), Kui et al. (2014), Pasquale et al. (2014), Gorla et al. (2015), Manners et al. (2015), Kui and Stella (2016), Wang et al. (2016), Diehl et al. (2017b), Fraaije et al. (2017), Kui et al. (2019), Javernick and Bertoldi (2019), Díaz-Alba et al. (2023).
Vegetation resistance to uprooting	Karrenberg et al. (2003), Edmaier et al. (2011, 2015), Burylo et al. (2012), Pasquale et al. (2012), Crouzy et al. (2014), Bywater-Reyes et al. (2015), Bankhead et al. (2017), Khanal and Fox (2017), Bau' et al. (2019), Calvani et al. (2019), Andreoli et al. (2020), Bau' and Perona (2020), Piqué et al. (2020).
Vegetation effects on river morphology	Gran and Paola (2001), Jang and Shimizu (2007), Tal and Paola (2007, 2010), Braudrick et al. (2009), Van Dijk et al. (2013), Le Bouteiller and Venditti (2014), Bertoldi et al. (2015), Lightbody et al. (2019), Vargas-Luna et al. (2019), Mao et al. (2020), Weisscher et al. (2020), Fernandez et al. (2021), Kyuka et al. (2021), Bywater-Reyes et al. (2022), Calvani et al. (2023), Li et al. (2023), Song et al. (2023).
Large wood	
Large wood entrainment and transport mechanisms	Braudrick and Grant (2000), Bocchiola et al. (2006, 2008), Crosato et al. (2013), Davidson et al. (2015), Spreitzer et al. (2019a, 2019b, 2020a, 2020b), Friedrich et al. (2022).
Large wood and local river habitat	Mutz et al. (2007), Bocchiola (2011), Gallisdorfer et al. (2014), Davidson & Eaton (2013), Schalko et al. (2021).
Large wood and river morphology	Braudrick and Grant (2001), Welber et al. (2013), Bertoldi et al. (2014b, 2015), Mao et al. (2020), Ravazzolo et al. (2022).

Note: Publications are listed in chronological order with respect to each topic.

prototype landscape (Clarke, 2014; Jiang et al., 2009; Lokhorst et al., 2019; Vettori & Rice, 2020).

Although more complex, the use of real plants and, where possible, field experiments are crucial. This is because experimental simplifications, especially the use of artificial elements with exactly the same shape and characteristics and regular patterns, can bias outcomes by altering the natural physical processes involved in interactions between vegetation and the flow field (Statzner et al., 2006; Tinoco et al., 2020).

Interactions between flow and vegetation

The introduction of new concepts in fluvial biogeomorphology in the 1990s and early 2000s promoted numerous physical experiments investigating vegetation-flow-morphology interactions in a controlled environment. Several experiments focused on the direct effect of vegetation on the flow field and sediment flux (Table 6). Although static (rigid), often cylindrical dowels were still frequently used (Vargas-Luna et al., 2016), researchers started to reproduce vegetation with more complex shapes or to use living plants to better understand the role of stem flexibility and the different effects of leaves and branches (e.g., Aberle & Järvelä, 2013). In the last decade, laboratory experiments have also been used to investigate the effect of the flow field on vegetation by inducing re-configuration of leaves and branches (e.g., Albayrak et al., 2012). In addition to roughness, flume experiments have also investigated how vegetation can alter sediment transport flux by decreasing the shear stress acting on the bed, intercepting transported particles, and therefore affecting both bedload and suspended load (e.g., Baptist et al., 2007 and Vargas-Luna et al., 2015 for review).

Experiments have demonstrated that vegetation not only strongly affects the mean velocity but also the vertical velocity profile and turbulence characteristics. For example, Nepf (2012) reviewed several experimental studies aimed at accurately describing mean and

TABLE 7 Selected publications on mathematical modelling of fluvial biogeomorphological interactions in the 21st Century.

Topic	Authors and dates
Vegetation colonization	
Recruitment models	Mahoney and Rood (1998), Douhovnikoff et al. (2005), Dixon and Turner (2006), Burke et al. (2009), Balke et al. (2011, 2014), Benjankar et al. (2014, 2020), Asaeda et al. (2015), Morrison and Stone (2015), Caponi et al. (2019), Gilbert & Wilcox (2021), Tranmer et al. (2023), Serlet et al. (2024).
Succession models	Benjankar et al. (2011, 2012, 2016), Egger et al. (2012, 2015, 2017), García-Arias et al. (2013, 2014), Rivaes et al. (2013, 2014, 2015, 2017), Politti et al. (2014), García-Arias and Francés (2016), Diehl et al. (2017a, 2018), Muñoz-Mas et al. (2017), Sanjaya and Asaeda (2017), Ochs et al. (2019).
Regime models	
	Millar (2000, 2005), Eaton (2006), Eaton and Giles (2009), Eaton et al. (2010), Miyamoto and Kimura (2016), Davidson and Eaton (2018), Zen and Perona (2020).
Stochastic analytical models	
Vegetation distribution	Camporeale and Ridolfi (2006, 2007), Perona et al. (2009a, 2009b), Tealdi et al. (2011, 2013), Crouzy and Perona (2012), Crouzy et al. (2013), Vesipa et al. (2015, 2016), Perona and Crouzy (2018), Latella et al. (2020).
Ecomorphodynamic equations	Perona et al. (2014), Bärenbold et al. (2016), Crouzy et al. (2016), Bertagni et al. (2018), Calvani et al. (2022a, 2022b), Carbonari et al. (2022).
Root profile	Laio et al. (2006), Schwarz and Cohen (2012), Tron et al. (2014, 2015), Perona and Crouzy (2018), Bau' et al. (2021), Perona et al. (2022).
Bank related processes	
Bank reinforcement	Pollen and Simon (2005), Rinaldi et al. (2008), Luppi et al. (2009), Pollen-Bankhead and Simon (2009, 2010), Thomas and Pollen-Bankhead (2010), Pollen-Bankhead et al. (2011), Simon et al. (2011), Polvi et al. (2014).
Meander evolution	Perucca et al. (2006, 2007), Camporeale and Ridolfi (2010), Motta et al. (2012), Eke et al. (2014), Schuurman et al. (2016), Zen et al. (2016).
Numerical models	
	Murray and Paola (2003), Hooke et al. (2005), Wu et al. (2005), Coulthard et al. (2007), Crosato and Saleh (2011), Li and Millar (2011), Nicholas (2013), Nicholas et al. (2013), Bertoldi et al. (2014a), Gran et al. (2015), van Oorschot et al. (2016, 2017, 2022), Guan and Liang (2017), Bywater-Reyes et al. (2018, 2022), Caponi and Siviglia (2018), Lokhorst et al. (2018), Martínez-Fernández et al. (2018), Caponi et al. (2020, 2023), Jourdain et al. (2020), Toda et al. (2020), Li et al. (2022), Scamardo et al. (2022), Stecca et al. (2022), Zhu and Tsubaki (2022).
Large wood	
Large wood recruitment	Downs and Simon (2001), Welty et al. (2002), Benda and Sias (2003), Mazzorana et al. (2009, 2011), Eaton et al. (2012), Kasprak et al. (2012), Rigon et al. (2012), Ruiz-Villanueva et al. (2014b), Steeb et al. (2017, 2023), Cislaghi et al. (2018), Zischg et al. (2018), Gasser et al. (2019), Stella et al. (2021).
Large wood transport	Ruiz-Villanueva et al. (2014a, 2014b, 2016c, 2016e, 2020), Hassan et al. (2016), Kang and Kimura (2018), Persi et al. (2018, 2020, 2021), Kang et al. (2020)

Note: Publications are listed in chronological order with respect to each topic.

turbulent flow, and mass transport, in the presence of both submerged (i.e., with most of the biomass close to the bed) or emergent aquatic vegetation, mainly reproduced using rigid cylindrical elements. The formation of canopy-scale vortices strongly affects the flow within and downstream of a vegetated patch, inducing oscillations and re-configuration of the vegetation and specific patterns of sediment deposition (e.g., Zong & Nepf, 2011).

Vegetation growth and resistance to uprooting

Understanding interactions between vegetation and river morphology also requires investigation of the ability of plants to colonize, grow and develop sufficient resistance to withstand the action of flow and sediment transport during flood events. Field experiments (e.g., Francis & Gurnell, 2006; Pasquale et al., 2014) and greenhouse experiments (e.g., Francis et al., 2005; González et al., 2010; Gorla et al., 2015) employing cuttings have explored the growth performance and resistance to hydric stress of different riparian tree species growing on substrates of different calibre (for a review for Salix spp., see Díaz-Alba et al., 2023). Mortality is mainly caused by flood disturbance and associated impacts on the bed, including scour (Pasquale et al., 2014) and burial (Kui & Stella, 2016). Flood disturbance acts as a selective mechanism that eliminates weaker plants while allowing the more resistant individuals or species to continue to grow, with a positive feedback that can lead to a bimodal spatial vegetation distribution (Perona et al., 2012; Wang et al., 2016).

Several experiments have compared the effects and responses of native (e.g., Salix spp.) and invasive species (e.g., Tamarix spp.) as a function of flow and sediment supply variations (e.g., Kui et al., 2014). Understanding these interactions can be used to design environmental flows that can help control plant invasions (Kui et al., 2019).

The mechanism of uprooting, as the main cause of vegetation damage, has also attracted research that has quantified root anchoring forces as a function of species, root length, root architecture and sediment properties (e.g., Edmaier et al., 2011; Karrenberg et al., 2003). Recent observations indicate that, in most cases, vegetation can be uprooted only in association with local scour (e.g., Bankhead et al., 2017; Bywater-Reyes et al., 2015).

Vegetation effects on river morphology

Living plants have been used in laboratory experiments to reproduce the stabilizing effect of roots on deposited sediments and evaluate the role of plants as ecosystem engineers capable of changing the equilibrium morphology of a river reach. In a pioneering experiment, Gran and Paola (2001) used alfalfa in a physical model of a braided network to show that vegetation strongly reduces bank erosion and lateral migration, forcing flow into a smaller number of anabranches. Further experiments (e.g., Braudrick et al., 2009; Tal & Paola, 2007, 2010) confirmed that the added cohesion conferred by vegetation is an important ingredient in the development and maintenance of single-thread, meandering rivers. In addition, the reduction of sediment flux induced by the presence of vegetation determines a morphological adaptation of the system, with an increased bed slope inside the vegetated patch (Le Bouteiller & Venditti, 2014).

In these early experiments, vegetation was generally seeded uniformly across the channel area. Further experiments investigated the effect of different dispersal mechanisms (water vs. wind) and different vegetation colonization locations (bars vs. floodplain) (e.g., Van Dijk et al., 2013; Vargas-Luna et al., 2019). Recently, more attention has been devoted to the interaction between the flow and a developing vegetation cover that can increase its resistance and modify its effects on morphological processes (Fernandez et al., 2021; Kyuka et al., 2021).

Large wood

In addition to living plants or plant analogues, wood has also been the focus of much experimental work. This follows the pioneering work of Braudrick et al. (1997), who reproduced wood transport in a laboratory flume and defined three possible transport regimes (uncongested, semi-congested, and congested) as a function of the probability of interactions between logs. Since 2000, researchers have developed physical experiments to better understand the mechanisms of wood transport and interactions with river hydraulics and geomorphology. We identify three main lines of research relevant to fluvial biogeomorphology: large wood entrainment and transport mechanisms; large wood and local river habitat; large wood and river morphodynamics. We do not address interactions between large wood and hydraulic structures. For details on this topic, we refer the reader to the recent review by Friedrich et al. (2022).

Large wood entrainment and transport mechanisms

Threshold flow conditions for log entrainment have highlighted the primary roles of log density and diameter, but also the relevance of the presence of a root wad, the orientation of the log relative to the flow, and the local acceleration of the flow field (Bocchiola et al., 2006; Braudrick & Grant, 2000; Crosato et al., 2013; Davidson et al., 2015). Recently, Spreitzer et al. (2019a) used smart sensors installed in wood dowels to accurately survey entrainment, movement and impacts of wood in their laboratory experiments. Their methods open new opportunities to reconstruct rolling and flow alignment processes as well as interactions with channel boundaries and other logs.

Large wood and local river habitat

A contribution to understanding the relationship between large wood and the broader fluvial environment has come from experiments that investigate the effect of deposited wood on river habitat. Scaled experiments have evaluated and improved the design of restoration actions involving the introduction of wood (Gallisdorfer et al., 2014; Mutz et al., 2007; Schalko et al., 2021). Experiments have also investigated reach-scale changes in river morphology under moving bed conditions, mostly induced by decreased sediment transport and increased sediment storage (Davidson & Eaton, 2013). Decreased flow velocity induced by large wood accumulations is likely to determine fine sediment deposition, which may also incorporate a seed bank and subsequently habitat for seed germination as observed in the field by Osei et al. (2015a, 2015b).

Large wood and river morphology

In rivers large enough to allow large wood to be transported downstream by the flow, log travel distance has been quantified as a function of the ratio of log length and diameter to channel width and depth (Braudrick & Grant, 2001; Welber et al., 2013). Experiments on dynamic braided rivers have shown that there is a strong link between large wood dynamics and morphological changes, determining a high dispersion of logs on the bar surfaces. However, when living vegetation is added to the experiments, bar stabilization induced by the additional cohesion provided by roots, limits the temporal variability of the flow and promotes wood deposition in specific locations (Bertoldi et al., 2015; Mao et al., 2020). In narrower rivers, large wood is more likely to form large jams that can have a significant impact on local scour and geomorphic change, with the presence of root wads enhancing the magnitude and stability of the accumulations (Ravazzolo et al., 2022).

5.4.2 | Mathematical modelling

Progress in understanding the physical processes and the mutual interactions and feedbacks between flow, sediment and vegetation has motivated the development of an increasing number of mathematical models, which are then used to predict the future evolution of a river system or to assess the main controls of external parameters (Table 7). Most models consider one specific process. However, it is becoming more common to integrate multiple mechanisms and feedbacks among the physical and biological components of the modelled system. These models show that many processes and patterns arise from interactions but are not present when only individual components are considered (Kleinhans, 2023). Extended reviews of riparian vegetation modelling have been conducted by Camporeale et al. (2013), Solari et al. (2016), and Vesipa et al. (2017), particularly emphasizing flow variability.

Recruitment models

The first and still most widely used model for predicting vegetation recruitment is the Recruitment Box model (Mahoney & Rood, 1998). This considers seed dispersal and moisture availability as the primary controls on vegetation recruitment in a system with a well-defined hydrological regime and the occurrence of a late spring (snowmelt) flood during which seeds of most of the Salicaceae family are released. The model has been further developed and improved to account for different plant species, reproductive mechanisms, and flow conditions (e.g., Benjankar et al., 2014; Dixon & Turner, 2006; Douhovnikoff et al., 2005). Recent applications have coupled the model with an hydraulic model to estimate bed shear stress, to evaluate and guide the restoration of native vegetation (Benjankar et al., 2020).

A different approach was developed for tidal environments by Balke et al. (2011, 2014), who considered the timescale required for seeds to germinate, develop sufficient resistance (i.e., a sufficiently long root system) to withstand inundation and uprooting by flood drag, and develop greater resistance to withstand sediment transport and erosion. The time available between major disturbances is referred to as a Window of Opportunity. The model has been successfully applied to riparian systems in a temperate climate where rain-driven floods occur at different times during the growing season, and where bar surfaces are rarely too far from groundwater to prevent seedling recruitment (Caponi et al., 2019; Serlet et al., 2024).

Colonization and succession models

Recruitment models have been extended to include vegetation establishment and potential ecological succession in order to predict the long-term evolution of the fluvial landscape. Benjankar et al. (2011) developed the spatially detailed CASiMiR-vegetation model, that simulates vegetation dynamics with an annual time step. Vegetation cover is classified in successional stages (from bare soil to mature vegetation) and different types of vegetation are considered (riparian trees, reeds, wetland communities). Succession or retrogression of vegetation depends on local values of disturbance-related parameters (especially shear stress and inundation duration) and on crossing of specific thresholds. The model has been extensively applied to different bioclimatic environments and hydrological alterations and has been improved by adding further processes, such as groundwater availability and evapotranspiration (García-Arias & Francés, 2016). Although these models include potential vegetation removal by flooding, they do not account for morphological adaptation of the reach and thus feedbacks between vegetation establishment and sediment flux.

Reach-scale vegetation effects on channel width and pattern (regime models)

Since 2000, riparian vegetation has been considered as one of the main parameters in regime models, predicting reach-scale channel width and morphological pattern based on an estimate of formative discharge, longitudinal slope and grain size. Millar (2000) introduced a parameter (bank friction angle) to account for additional bank cohesion from vegetation. The model resulted in a better discrimination between braiding, meandering and wandering planform styles. Similarly, Millar (2005) proposed a model to compute regime channel dimensions and planform style using a relative bank strength coefficient to parameterize the effect of riparian vegetation. The bank stability model and width estimator were improved by Eaton (2006) by dividing the bank into an upper vertical part and a lower slope of cohesionless material, leading to a novel channel pattern estimator (Eaton et al., 2010), which demonstrated that vegetation is a necessary ingredient, along with flow strength and sediment size, in a three-variable problem. Recently, Davidson and Eaton (2018) extended the previous models by adding a stochastic module and considering a distribution of floods instead of a single "formative" discharge.

Stochastic analytical models of vegetation distribution

In the last 20 years, analytical models have often been used as an efficient tool to account for the stochasticity of flow and to explore changes in the solution in the parameter space. Riparian vegetation is strongly dependent on the hydrologic regime, both in terms of water availability and flood disturbance, and the non-linear and threshold-driven interactions suggest that the sequence and timing of floods play a crucial role. Camporeale and Ridolfi (2006) proposed the first model including the probabilistic structure of the river flow time series to investigate the distribution of vegetation biomass along a generic river cross section. Water stage fluctuations affect vegetation depending on the vegetation's elevation, and thus its distance from the groundwater table and its exposure to flooding. Different vegetation types (i.e., different values of growth rate and resistance) as well as different hydrologic regimes can be easily compared and can produce different statistically stable states or a bimodal distribution with alternating phases of unvegetated bed and high biomass (Camporeale & Ridolfi, 2007). A similar approach has been used to explore several aspects of the interactions between vegetation and flow, such as hydrologic alterations, competition between species, vegetation recovery time after large floods, vegetation removal by floods and the process of uprooting (e.g., Tealdi et al., 2011, 2013; Vesipa et al., 2016). A direct feedback of vegetation on bed morphology was introduced by Vesipa et al. (2015) where the presence of vegetation induces sediment deposition and thus increases bed elevation and flood protection. The positive feedback leads to an increase in vegetation biomass, especially when flood disturbance is high.

Over the last decade, analytical models have been developed based on the theoretical framework proposed by Perona et al. (2014), where 'ecomorphodynamic equations' for mass (water and sediment) and momentum conservation are coupled with a vegetation biomass equation that accounts for both vegetation growth and erosion. This framework has been used to determine the existence of stable solutions and the formation of spatial patterns. Bertagni et al. (2018) coupled the ecomorphodynamic equations with a stochastic description of flood occurrence in one of the first models to couple sediment and vegetation dynamics with unsteady flow conditions. Model results showed that flow variability reduces vegetation growth and promotes bare bed conditions.

Increasing attention on plant roots as one of the main controls on biogeomorphological feedbacks is reflected in recent models that address the vertical distribution of roots of phreatophytic plants as a function of (random) fluctuations in groundwater level (Tron et al., 2014, 2015). Quantifying root architecture is a crucial step towards better modelling the interaction between vegetation and river morphology, as root length is the main control on vegetation uprooting. Recently, Perona et al. (2022) developed the root distribution model, linking the vertical root distribution model of Tron et al. (2014) with a model of the lateral and fine root distribution (Schwarz & Cohen, 2012) and a model of the vertical distribution driven by rainfall infiltration (Laio et al., 2006). In this way, the new model provides 3D root architecture and fine root biomass as a function of both groundwater level fluctuations and rainfall infiltration.

Modelling bank erosion and meander evolution

Pollen and Simon (2005) and Pollen-Bankhead and Simon (2010) modelled the effect of roots on sediment cohesion and bank erosion by considering progressive root failure within a fibre bundle approach. Bank erosion is a particularly crucial component in modelling the evolution of meandering rivers. In most long-term theoretical analyses, the bank migration rate is simply computed as a linear function of the near-bank excess velocity. However, in the last decade, further processes have been included, such as the presence of horizontal soil layers with different properties, and also different vegetation-related processes controlling outer bank erosion and inner bank deposition (e.g., Eke et al., 2014). 1D and 2D numerical models have been used by Schuurman et al. (2016) to explore the role of bar-floodplain conversion as a control on meander dynamics. By coupling a dynamic vegetation model such as that of Camporeale and Ridolfi (2006) with a meander evolution model, Perucca et al. (2006, 2007) investigated their mutual feedbacks and showed how riparian vegetation significantly alters meander shape and its temporal evolution.

Modelling morphological evolution

Since 2000, vegetation has been incorporated into hydraulic and morphological models with increasing numbers of processes and feedbacks, witnessing expanding understanding of the importance of vegetation. Plants have been reproduced from a simple addition to roughness to a full coupling of vegetation recruitment and growth as a function of environmental conditions. The first model to add the effect of vegetation on sediment cohesion, and thus on overall sediment transport flux and bank erosion, was the cellular model of Murray and Paola (2003), which showed how the addition of this simple feedback was sufficient to change river morphology from multi-thread to single-thread. Other cellular models included the effect of vegetation coupled with soil moisture and water availability (Hooke et al., 2005) and in terms of root reinforcement (Coulthard et al., 2007).

In numerical models that solve the shallow water and sediment balance equations, vegetation was initially included as a fixed element that locally increased roughness and modified turbulence patterns, thus affecting bedload and suspended sediment transport (e.g., Li & Millar, 2011). In the 2010s, models started to include vegetation dynamics, initially as a simple colonization of exposed surfaces (e.g., Crosato & Saleh, 2011; Nicholas, 2013). This (over) simplified approach was useful to highlight the impact of vegetation on the long-term river planform style.

More recently, models have incorporated more dynamic vegetation processes, allowing vegetation to grow as a function of environmental conditions such as water availability and flood damage (Bertoldi et al., 2014a). Such models can also incorporate a more detailed representation of root growth and vertical distribution (as proposed by Tron et al., 2014), reproducing in a physically sound way the process of uprooting associated with local scour (Caponi & Siviglia, 2018). In other cases, a dynamic vegetation module has been coupled to a morphodynamic code (Delft3D) to include several ecological processes and feedbacks describing vegetation colonization, growth and removal by floods or adverse environmental conditions (van Oorschot et al., 2016). Several models have been developed in the last 10 years (see Table 7) and have proved to be valid tools to explore the relevance of different processes and conditions, with the potential to guide future field and laboratory scale research.

Today, these models are not only developed and used by scientists, but are also increasingly available to river managers (e.g., Caponi et al., 2023), providing further evidence of the widespread recognition of the relevance of biogeomorphological feedbacks.

Modelling large wood

Recognition that large wood was a relevant component of a fluvial system led to the development of mathematical tools to predict (i) the potential wood supply from hill slopes and river banks, and (ii) the fate of transported wood.

Quantitative estimation of wood supply to the river network and assessment of potential sources of recruitment remain challenging tasks (see Steeb et al., 2023 for a recent review). Initial models mainly considered recruitment processes from riparian areas along the river network (tree mortality, windthrow and bank erosion) and provided a potential supply through empirical equations. Advances in GIS software allowed the implementation of spatially distributed models with mapping of recruitment areas from digital elevation models and forest cover, including landslides and debris flows (Benda & Sias, 2003) and the connectivity of source areas to the river network (Ruiz-Villanueva et al., 2014c). The most commonly used models in practical applications are GIS-based models that predict potential source areas and associated wood volumes based on empirical relationships derived from field observations (Steeb et al., 2017).

Transport and deposition of recruited wood along the river network have been modelled in combination with 1D or 2D computational fluid dynamics models. The first coupled model simulating log entrainment and transport was proposed by Ruiz-Villanueva et al. (2014a, 2014b). The model couples an Eulerian approach to solve the shallow water equations with a Lagrangian approach to reproduce the trajectory of each log. The model has been used to investigate different controls on wood transport, such as different river morphologies (Ruiz-Villanueva et al., 2016c) and the effect of unsteady flow conditions

(Ruiz-Villanueva et al., 2020). Similar models have recently been proposed by Persi et al. (2018) and Kang and Kimura (2018), which also consider the presence of root wads and include bedload transport and morphological changes (Kang et al., 2020).

5.4.3 | Remote sensing

There have been huge advances in remote sensing techniques over the last two decades. New sources of high-resolution, multi-dimensional data have emerged across a wide range of spatial scales and multiple timescales (for recent reviews see Piégay et al., 2020; Tomsett & Leyland, 2019). These new monitoring techniques, together with the computational ability to process large datasets, are transforming river science (Marcus & Fonstad, 2010) and are increasingly being employed operationally by river managers (Huylenbroeck et al., 2020). They are turning fluvial geomorphology from a data-poor discipline to a data-rich predictive science (Reichstein et al., 2019) and are also revolutionizing the monitoring of riparian vegetation and large wood by exploiting the many advantages of remote sensing in terms of spatial coverage, survey frequency, and reduced cost and effort in the field (e.g., Rusnák et al., 2022). Thus, remote sensing is adding new dimensions to research in fluvial biogeomorphology by not only allowing analyses across large areas and extended time scales but by supporting the testing and development of conceptual models with data that would be unattainable from fieldwork alone. As a result, remote sensing is being used to monitor and analyse biogeomorphological features at a range of spatial scales, from individual plants to entire regions.

Remote sensing at the individual plant scale

Detailed measurements of individual plants have been made possible by the development of terrestrial laser scanners (TLS) that provide dense point clouds from which to characterize the complex vertical structure of riparian vegetation and its effects on roughness (Antonarakis et al., 2009, 2010), sediment deposition induced by coherent flow structures (Bywater-Reyes et al., 2017), and also plant movements recorded by video imagery (Boothroyd et al., 2017). Very high spatial resolution imagery (with a ground resolution <0.1 m) acquired from unmanned aerial vehicles (UAVs) have been successfully used to map floodplain vegetation (Dunford et al., 2009) and to classify riparian species and their health (Michez et al., 2016). Large wood jams in gravel bed rivers have been mapped by TLS (Tonon et al., 2014) and recently UAVs and Structure-from-Motion photogrammetry (SfM) have been used to map and quantify the volume and porosity of individual large wood jams (Spreitzer et al., 2019b, 2022).

Remote sensing at the reach scale

Reach-scale survey has benefited most from advances in UAVs and digital photogrammetry, which have allowed fast, accurate and relatively inexpensive monitoring, including reconstruction of 3D topography and vegetation canopy structure (Westoby et al., 2012). Several studies have used aerial imagery, with images dating back nearly 100 years, but the costs associated with undertaking these surveys mean that they are rarely acquired for a specific research application and the temporal frequency of images is usually limited. However, technological advances and the ease of use of UAVs have led to their application for data gathering specifically for research purposes. Dunford et al. (2009) reported one of the first applications of UAV for riparian vegetation mapping. More recently, Hervouet et al. (2011) used annual high-resolution surveys to investigate vegetation recruitment processes along braided river reaches in the French Alps and then to extend the results to the regional scale using satellite imagery. Annual images acquired by UAVs were also used by Räpple et al. (2017) to investigate the drivers of vegetation establishment and growth along the Drôme River (France).

Flynn and Chapra (2014) and Husson et al. (2014) demonstrated the potential of UAV monitoring and RGB imagery for mapping submerged aquatic vegetation. Photographic surveys can also include infrared cameras, which improve vegetation detection and provide accurate classification of river landscape cover and temporal change (Milani et al., 2018).

UAV surveys and photogrammetric reconstruction of surface topography by SfM have been used to quantify the reach-scale volume of deposited large wood, including individual logs and jams (MacVicar et al., 2009; Pavlowsky et al., 2023; Sanhueza et al., 2019). The ability to obtain accurate 3D models of the riverbed and riparian trees was exploited by Hortobágyi et al. (2017b) to investigate biogeomorphological feedbacks. They combined aerial, UAV and ground-based imagery to perform cross-scale studies from a single plant to reach scale.

Lidar is a further source of 3D data that can support many biogeomorphological investigations. Lidar can support monitoring of riparian vegetation, providing spatially accurate data on both tree height and vegetation density (Hutton & Brazier, 2012). For example, Forzieri et al. (2011) used a combination of airborne Lidar and multispectral satellite data to produce maps of riverbed roughness estimated from the reconstruction of individual plant characteristics. Abalharth et al. (2015) and Atha and Dietrich (2016) assessed the potential of Lidar data to map the presence and volume of large wood deposits. Bertoldi et al. (2013) integrated Lidar, aerial imagery and field data to study large wood deposits and their relationship to nearby bank erosion. The combination of digital elevation models and canopy height models derived from Lidar surveys with aerial imagery has supported several biogeomorphological investigations. For example, Bertoldi et al. (2011b), Picco et al. (2015) and Lallias-Tacon et al. (2017) have investigated the dynamics of vegetated islands and floodplains along multi-thread rivers, and Michez et al. (2017) mapped over 12,000 km of rivers by merging canopy height models obtained by digital photogrammetry and Lidar, proving the benefits of this technique for regional analysis.

Fast moving processes, such as the transport of large wood during flood events, require a different type of monitoring, and video recordings have become quite widely used in the last decade. MacVicar and Piégay (2012) proposed a video monitoring system that proved efficient in quantifying the number and volume of logs transported during floods and showed that the amount of transported wood is significantly larger during the rising limb of floods (see also Ghaffarian et al., 2020). The occurrence of wood-laden flows and characterization of the amount of wood, from clear wood to hyper-congested flows, have also been monitored using video (Ruiz-Villanueva et al., 2018), showing the relevance of data sources that were not intended for scientific application but are readily available as a result of the widespread use of smartphones.

Remote sensing at extended reach to landscape scales

Remote sensing offers dramatic advantages in surveying large areas by providing spatially continuous and consistent data.

Over extended reaches, data from different sources have been used to map river macro-units, ranging from the simple separation of water, bare sediment and vegetation to the identification of different physical habitats and vegetation successional stages. Lidar surveys have been combined with multispectral (CASI) data (Geerling et al., 2007; Straatsma & Baptist, 2008) or RGB and near-infrared imagery (Demarchi et al., 2016; Kutz et al., 2022) to obtain high-resolution and accurate mesohabitat mapping of the river environment and floodplain vegetation. Recently, deep learning methods have been used to calibrate an automatic classifier of RGB images (Carbonneau et al., 2020b), demonstrating the potential to develop a generalized, open source classifier for high-resolution RGB imagery, acquired from aerial or UAV surveys, that can produce accurate results and greatly reduce operator effort.

Larger (e.g., landscape scale) areas can be easily monitored using satellite data. In the last two decades, technological advances have yielded data sets down to metre or sub-metre spatial resolution with up to daily revisit times. Data from satellite sensors with different characteristics are available to match research objectives. The long temporal coverage, now reaching 40 years, and free availability of Landsat data have been exploited for long-term catchment scale analysis (Henshaw et al., 2013; Peixoto et al., 2009; Salerno et al., 2022), and were combined with UAV imagery by Morgan et al. (2021). Landsat data have been recently used to investigate carbon export driven by morphological dynamics of tropical rivers (Salerno et al., 2023). Detailed analysis of extended reaches can exploit higher spatial resolution data sets from commercial satellites such as ASTER (Bertoldi et al., 2011a), QuickBird, and SPOT-5 (Johansen et al., 2007, 2010), which have been used to map vegetation dynamics and successional stages. Recent advances in computational power and data management tools have provided the opportunity to automatically classify freely available datasets, such as the 10 m resolution multispectral data from the ESA Sentinel-2 satellite. For example, Carbonneau et al. (2020a) developed a convolutional neural network classifier, trained using UAV imagery, that mapped water, sediment and vegetation classes with an accuracy greater than 95%. Cloud-based computing platforms such as Google Earth Engine are a further tool to help researchers deal with big geospatial data sets (Boothroyd et al., 2021).

6 | THE FUTURE?

This 'annotated bibliographic review' has illustrated the gradual evolution of fluvial biogeomorphology from its early beginnings in the mid-20th century to its enormous expansion during the first two decades of the 21st century. Based on recent developments, we end with some suggestions for likely areas of major future research expansion.

i. Above all, we see recent developments as a firm foundation for team research involving geomorphologists, ecologists and hydrologists in integrated projects that combine observations from the field, laboratory and remotely sensed sources. In particular, carefully designed field and laboratory experiments paralleled and informed by mathematical modelling techniques are likely to form a sound foundation for future multidisciplinary or interdisciplinary developments.

ii. As remote sensing and proximate monitoring techniques (including smart sensors) yield increasingly large and diverse data sets with unprecedented spatial and temporal resolution, more sophisticated data handling and analysis methods will be needed to process such 'big data'

iii. The context of environmental change is already a rapidly expanding area (as illustrated by the citations in Table 5) but so far most of this research has considered changing flow regimes (especially as a consequence of direct water abstractions and flow regulation by dams) and the biogeomorphological effects of alien plant invasions. While both of these may reflect environmental changes, this topic needs fuller, deeper and more integrated examination, especially focusing on likely fluvial biogeomorphological responses to projected changes in climate.

iv. Despite its considerable breadth, this review has not considered river management to any significant degree because our focus has been on the development of the scientific subdiscipline—fluvial (plant) biogeomorphology. However, it is important to stress that over the last 40 years the emphasis and priorities of river managers have progressively shifted from controlling river channel forms and processes to restoring and supporting natural forms and processes. This reflects a desire to develop nature-based solutions to managing risks such as flooding while at the same time supporting healthy, naturally functioning, biodiverse river systems. If this shift is to be truly successful, managers need guidelines and tools that go beyond a consideration of flow, sediment transport and channel morphodynamics to include the critical role of vegetation. The science reviewed here is central to developing guidelines and tools to support sustainable river management approaches and practices.

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DATA AVAILABILITY STATEMENT

Data sharing not applicable—no new data generated.

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