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MODELING THE INTERACTIONS BETWEEN RIVER MORPHODYNAMICS AND RIPARIAN VEGETATION

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[1] The study of river-riparian vegetation interactions is an important and intriguing research field in geophysics. Vegetation is an active element of the ecological dynamics of a floodplain which interacts with the fluvial processes and affects the flow field, sediment transport, and the morphology of the river. In turn, the river provides water, sediments, nutrients, and seeds to the nearby riparian vegetation, depending on the hydrological, hydraulic, and geomorphological characteristic of the stream. In the past, the study of this complex theme was approached in two different ways. On the one hand, the subject was faced from a mainly qualitative point of view by ecologists and biogeographers. Riparian vegetation dynamics and its spatial patterns have been described and demonstrated in detail, and the key role of several fluvial processes has been shown, but no mathematical models have been proposed. On the other hand, the quantitative approach to fluvial processes, which is typical of engineers, has led to the development of several morphodynamic models. However, the biological aspect has usually been neglected, and vegetation has only been considered as a static element. In recent years, different scientific communities (ranging from ecologists to biogeographers and from geomorphologists to hydrologists and fluvial engineers) have begun to collaborate and have proposed both semiquantitative and quantitative models of river-vegetation interconnections. These models demonstrate the importance of linking fluvial morphodynamics and riparian vegetation dynamics to understand the key processes that regulate a riparian environment in order to foresee the impact of anthropogenic actions and to carefully manage and rehabilitate riparian areas. In the first part of this work, we review the main interactions between rivers and riparian vegetation, and their possible modeling. In the second part, we discuss the semiquantitative and quantitative models which have been proposed to date, considering both multi- and single-thread rivers.

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1. INTRODUCTION

[2] Riparian systems are transitional environments between water bodies and surrounding elevated areas; they form an environment within which the aquatic and terrestrial components of the landscape interact [*Naiman et al.*, 2005]. Riparian zones have been variously defined as very complex ecotones with distinct vegetation and soil characteristics [*Malanson*, 1993] located on land adjacent to water bodies that is, at least periodically, influenced by flooding [*Mitsch and Gosselink*, 2000] and, thus, where vegetation may be influenced by elevated water tables and the ability of the soils to hold water [*Naiman and Decamps*, 1997]. From a physical or geomorphological perspective, the riparian zone has been described as "that part of the biosphere supported by, and including, recent fluvial landforms and is inundated or saturated by the bankfull discharge. This includes many flood plains, riparian wetlands, banks, and all fluvial landforms below the bankfull elevation" [*Hupp and Osterkamp*, 1996, p. 280]. Within riparian zones, hydrological, geomorphological, and ecological processes interact strongly, generating a highly dynamic landscape that is characterized by a heterogeneous mosaic of habitats (see Figure 1) and is subject to a strong flow energy gradient [e.g., *Hupp*, 2000; *Hughes et al.*, 2001], the flow energy being equal to the mechanical energy of the stream. Flows of water and associated mineral sediments and organic matter are the fundamental drivers of the morphodynamics of these zones and, through the associated transfer of organisms and nutrients, their ecology. These flows support the hydrological

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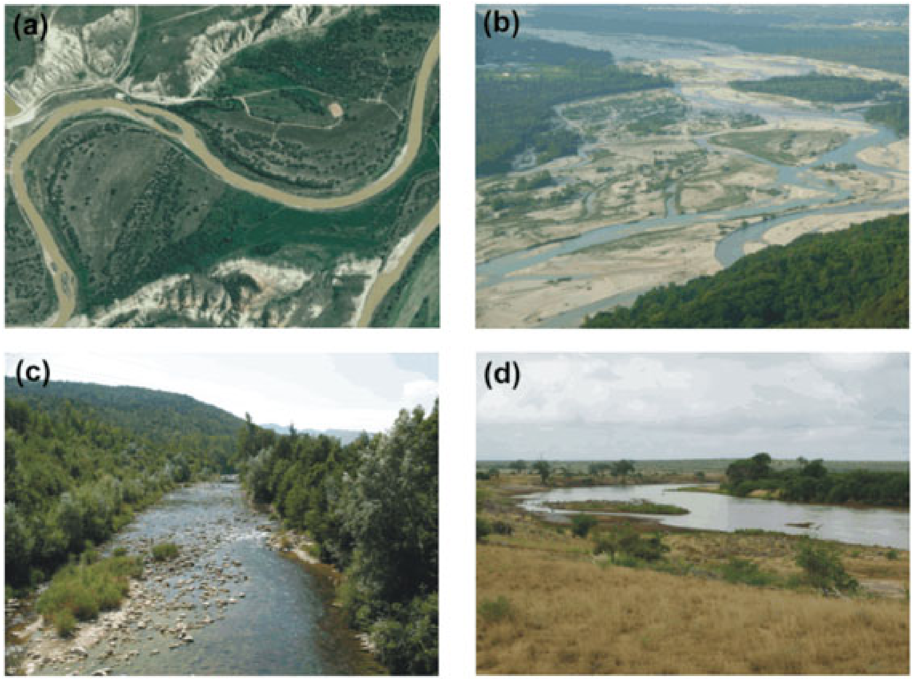

Figure 1. Examples of fluvial riparian zones. (a) The Little Missouri, USA; (b) the Tagliamento River, Italy; (c) the Tanaro River, Italy; and (d) the Galana River, Kenya.

connectivity (in the sense of *Amoros and Roux* [1988]) which refers to the water-driven exchange of matter and energy between different units of the riverine landscape [*Ward et al.*, 2002]: longitudinal connectivity between upstream and downstream aquatic and riparian systems; lateral connectivity between the river and its floodplain; and vertical connectivity between surface water bodies and groundwater in the alluvial aquifer and underlying bed rock [*Ward*, 1989; *Ward et al.*, 2002; *Gurnell et al.*, 2012]. At the same time, there are important feedbacks between the standing vegetation and fluvial processes, which have a fundamental effect on the character and dynamics of the riparian habitat mosaic [*Corenblit et al.*, 2007]. As a result of their complexity and dynamics, naturally functioning riparian systems show high biodiversity and production [*Naiman and Decamps*, 1997; *Ward et al.*, 1999; *Tockner and Stanford*, 2002]; act as important ecological corridors providing refugia and dispersal pathways for species [*Ward and Stanford*, 1995; *Naiman and Decamps*, 1997]; attenuate floods and moderate water balances by retaining runoff and increasing rates of both infiltration and evapotranspiration [e.g., *Nilsson et al.*, 1997; *Crockford and Richardson*, 2000; *Steiger et al.*, 2005; *Anderson et al.*, 2006]; and improve water quality by intercepting fine sediments and pollutants and promoting nutrient and organic matter processing [e.g., *Ettema et al.*, 1999; *Craig et al.*, 2008; *Osterkamp and Hupp*, 2012]. Riparian vegetation is fundamental to these regulating and supporting ecosystem services and is also crucial to the recreational and cultural services that riparian zones provide [e.g., *Brown and Daniel*, 1991; *Walker et al.*, 2002; *Buijse et al.*, 2002] as well as forming an important tool in the sustainable management and restoration of fluvial systems [e.g., *Lester and Boulton*, 2008; *Swab et al.*, 2008; *Wishart et al.*, 2008; *Pasquale et al.*, 2011].

[3] This review explores modeling approaches that focus on the links between riparian vegetation and river morphodynamics, something that is still lacking in the processes of river management and restoration decision-making. Vegetation affects several processes that influence river morphology [*Corenblit et al.*, 2007]. Riparian and aquatic vegetation affect the flow field [e.g., *Bennett et al.*, 2008] and thus the processes of sediment mobilization, transport, and deposition [e.g., *Prosser et al.*, 1995; *Ishikawa et al.*, 2003]. Plant roots and rhizomes affect mechanical and hydraulic soil properties [e.g., *Pollen-Bankhead and Simon*, 2010], and as a result, bank erosion resistance and soil moisture regime depend on vegetation. Large wood (living and dead trees, shrubs, logs, and branches) also plays an important role by protecting river banks, reinforcing floodplains and creating and stabilizing landforms on which new woody vegetation can establish [e.g., *Abbe and Montgomery*, 2003; *Gurnell et al.*, 2005, 2012; *Collins et al.*, 2012]. On the other hand, river processes are fundamental controls on riparian vegetation, including the provision of water and nutrients to support plant growth, the creation of new depositional sites for vegetation colonization, the removal of vegetated areas by erosion, and the provision of hydrological constraints on root development and architecture [*Pasquale et al.*, 2012]. Overall, the intensity and the spatial extent of river-driven disturbances (e.g., flooding, droughts, groundwater fluctuations, etc.) are the main factors that control riparian vegetation dynamics [*Camporeale and Ridolfi*, 2006; *Corenblit et al.*, 2007]. Modeling of riparian vegetation and morphological processes needs to incorporate

these complex interactions and feedbacks, building on multidisciplinary hydrological, hydraulic, geomorphological, and ecological knowledge [e.g., *Baird et al.*, 2005; *Corenblit et al.*, 2007; *Perucca et al.*, 2007; *Perona et al.*, 2009b; *Gurnell et al.*, 2012].

[4] Two different approaches to modeling have been adopted in the past. Drawing on detailed field investigations, ecologists, biogeographers, and geomorphologists have approached the topic through the analysis of information from different research areas from which they have often constructed conceptual models [e.g., *Osterkamp and Hupp*, 2010]. In this way, the spatial and temporal dynamics of riparian vegetation have been described and investigated, illustrating the crucial importance of a range of biotic and abiotic processes. However, although several processes have been qualitatively elucidated, no quantitative models have been proposed. In contrast, since the 1980s engineers and geophysicists have dedicated a great deal of effort to the development of increasingly more refined morphodynamic mathematical models. However, despite the fact that vegetation is fundamental for river hydraulics and morphology, ecological aspects have usually been neglected in these models, and vegetation has, at most, been considered only as a static element.

[5] Recently, knowledge from these different branches of river science has begun to be assimilated into new approaches within the rapidly developing interdisciplinary fields of fluvial biogeomorphology, hydroecology, and ecohydraulics [e.g., *Camporeale et al.*, 2005; *Corenblit et al.*, 2007]. These interdisciplinary approaches are proving very fruitful, and some semiquantitative and quantitative mathematical models of river-vegetation interactions have been proposed. We review these models, focusing particularly on the quantitative aspects of interactions between riparian vegetation and morphodynamics. Throughout, we refer mainly to temperate areas, where most of the data have been collected and most of the modeling studies have been developed. The review is divided into seven sections. In the next section (section 2), we outline a general framework of river-vegetation interactions that are developed in more detail in sections 3 and 4, including a description of some field evidence. Sections 5, 6, and 7 are devoted to reviewing semiquantitative and quantitative modeling approaches. In the final section, we draw some conclusions and discuss the main open questions, in the context of temperate areas. Unless specified differently, all formulas reported in the following are intended in SI units.

2. GENERAL FRAMEWORK OF THE RIVER-VEGETATION INTERACTIONS

[6] Figure 2 summarizes the main river-vegetation interactions within the riparian zone and some of their key characteristics. Rivers transfer water, mineral and organic sediments, chemicals, nutrients, plant propagules (seeds and vegetative fragments), and wood from upstream to downstream, delivering them into the riparian environment as well as transferring them into the river channel. These processes deliver water to the riparian aquifer as well as drain water back into the main channel, inducing fluxes through the hyporheic zone [e.g., *Jones and Mulholland*, 2000; *Hancock et al.*, 2005] and contributing to the control of water table levels within the riparian zone. In addition, the river is a source of water vapor and a thermal regulator of the riparian environment. The precise functioning of all of these processes depends on the hydrological, hydraulic, and geomorphological characteristics of the river [*Salo et al.*, 1986; *Bendix and Hupp*, 2000]. Many riparian vegetation processes depend mainly on river flows, including the dispersal of seeds and vegetative propagules into the riparian zone [e.g., *Mahoney and Rood*, 1998; *Merritt and Wohl*, 2002; *Gurnell et al.*, 2008; *Greet et al.*, 2011], the supply of soil moisture to support seed germination and plant growth and control plant water stress [e.g., *Lite et al.*, 2005; *Williams and Cooper*, 2005; *Pezeshki and Shields*, 2006; *Gonzalez et al.*, 2012], and the flood-induced death of riparian plants through uprooting, burial, or anoxia [e.g., *Friedman and Auble*, 1999; *Bendix and Hupp*, 2000]. These processes illustrate the importance of over-bank floods for riparian ecosystems, including the predictable annual flood regime that underpins the “flood pulse concept” [*Junk et al.*, 1989], but more frequent “flow pulses” [*Tockner et al.*, 2000] that occur within the bankfull channel can be also of major ecological importance in unmanaged river systems that support a complex part-vegetated transition between the water surface of typical low flows and the floodplain [*Bertoldi et al.*, 2009].

[7] Riparian vegetation affects the flow field, fluvial transport processes, and the morphology of the river through several mechanisms (Figure 2), including the influence of the vegetation canopy on flow turbulence structure [e.g., *Liu et al.*, 2010]; the increase in riparian sediment strength due to plant roots [e.g., *Docker and Hubble*, 2008; *Pollen-Bankhead and Simon*, 2010]; the effect of plant transpiration on riparian soil moisture content, hydraulic gradient, and water balance [e.g., *Tabacchi et al.*, 2000; *Cleverly et al.*, 2006]; and the effects of all of these processes on riparian erosion and sedimentation. Whichever mechanism is considered, both a passive and an active influence of vegetation can be detected on river morphodynamics [*Camporeale et al.*, 2005].

[8] In relation to its passive role, vegetation affects roughness, hydraulic resistance, and bank erodibility in the same manner as any abiotic element with the same mechanical and morphological characteristics. As a consequence, the traditional modeling approach in hydraulic engineering has been to consider vegetation as an abiotic element. This type of approach is exemplified by many efforts to obtain theoretical and empirical estimates of hydraulic resistance in vegetated channels [e.g., *Kouwen and Unny*, 1973; *Kouwen and Fathi-Moghadam*, 2000; *Righetti and Romano*, 2004], of the structure of turbulence in streams flowing inside or surrounded by vegetation [e.g., *Nepf*, 1999; *Finnigan*, 2000; *Nepf*, 2012], and of the influence of riparian vegetation on the propagation of flood waves [e.g., *Li and Shen*, 1973; *Kouwen and Unny*, 1973; *Thorne*, 1990; *Masterman and Thorne*, 1992; *Abernethy and Rutherfurd*, 1998; *Millar*, 2000]. The active role of vegetation is expressed through

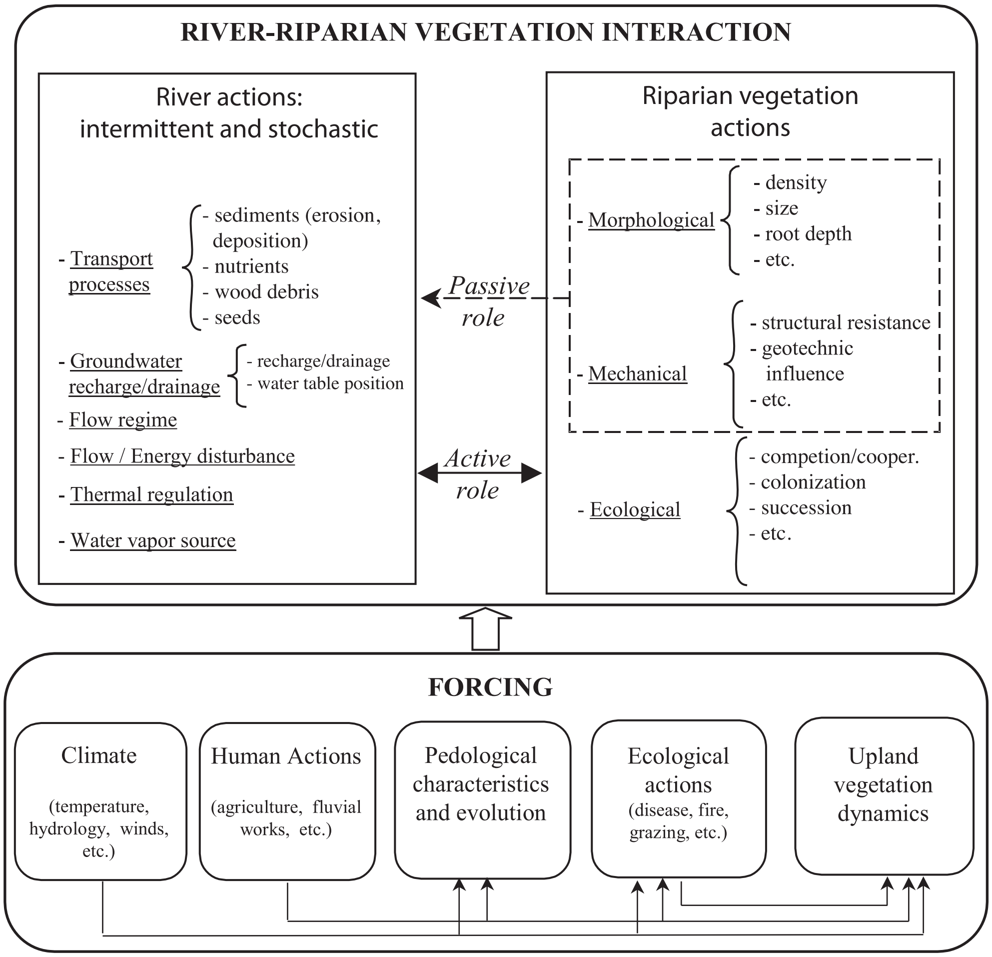

Figure 2. General scheme of the interactions between river and riparian vegetation.

biotic processes that influence the colonization, growth, and death of plants within the riparian zone. Biotic processes influence many hydraulic and morphodynamic processes and interact with them to affect vegetation dynamics. For example, seeds may be deposited on bare sediment surfaces created by fluvial processes. Once the seeds germinate and the plants begin to grow, the new vegetation starts to affect the local flow field, altering sedimentation/erosion processes and initiating vegetation-induced morphological changes. As a result, a close coupling is established between the river and riparian vegetation, which is regulated by linear and nonlinear feedback mechanisms and which magnifies as the plants grow. The very close relationship between fluvial morphodynamics and vegetation dynamics reflects the comparable temporal scales of river geometry evolution and vegetation development [e.g., *Phillips*, 1995], Table 1 and implies that the two dynamics cannot be modeled separately. Finally, river-induced actions have both a deterministic and a stochastic component (Figure 2). The latter plays an important role in inducing nontrivial behavior in the evolution of the river-vegetation system, but it is difficult to model [e.g., *Lytle and Merrit*, 2004; *Camporeale and Ridolfi*, 2007]. Furthermore, the whole process of river-vegetation interaction is prone to deterministic and stochastic external forcings

TABLE 1. Typical Order of Magnitude of the Rates, Relaxation Times, and Time Scales of Geomorphic and Ecological Phenomena[a]

Landscape Phenomenon	Rate (-)	Relaxation Time (years)	Time Scale (years)
Fluvial erosion-sedimentation	10^{-2}–10^{1}	10^{0}–10^{2}	10^{-1}–10^{2}
Establishment of complete vegetation cover	10^{-1}–10^{1}	10^{0}–10^{1}	10^{-1}–10^{1}
Secondary succession	10^{-2}–10^{0}	10^{1}–10^{2}	10^{0}–10^{1}
Primary succession	10^{-3}–10^{0}	10^{1}–10^{2}	10^{0}–10^{1}
Vegetation composition change	10^{-1}–10^{1}	10^{0}–10^{1}	10^{-1}–10^{1}

[a] After *Phillips* [1995]. The rate is given as percent per year of complete or maximum development. Relaxation time is the time the system takes to recover from vegetation disturbances.

related to climate conditions, the presence of animals, harvesting, fires, grazing, diseases, delivery of large wood, and human actions, which add further complexity to riparian morphodynamics [*Naiman and Decamps*, 1997; *Nilsson et al.*, 1997; *Timoney et al.*, 1997; *Seagle and Liang*, 2001; *Menard et al.*, 2002; *Zanoni et al.*, 2008].

3. INFLUENCE OF FLUVIAL PROCESSES ON THE RIPARIAN VEGETATION DYNAMICS

[9] In section 2, we stated that colonization and growth of riparian plants are affected greatly by river hydrology and morphology (see Table 2 for some relevant studies). In this section, we explore this topic in more detail by outlining the characteristics of riparian plants (section 3.1), describing the processes of colonization and succession (section 3.2 and 3.3), and then considering some simplified models of riparian plant growth (section 3.4)

3.1. Characteristics of Riparian Plants

[10] Riparian zones are highly heterogeneous and disturbed environments. They are composed of a wide variety of physical habitats in terms of their sediment caliber, moisture and nutrient conditions, inundation duration and frequency, and also susceptibility to drought. The characteristics of riparian habitats vary markedly in space and in time, providing a very challenging environment for plant colonization. As a result, plants that can successfully colonize riparian zones possess traits that allow them to cope with the harsh conditions [*Karrenberg et al.*, 2002]. Of the wide range of plants that grow in riparian zones, riparian shrub and tree species are particularly important for river morphodynamics because of their large size and ability to act as ecosystem engineers (in the sense of *Jones et al.* [1994]), driving the development of habitats that can be colonized by other species [*Gurnell et al.*, 2012].

[11] *Naiman et al.* [2005] identify four sets of functional adaptations that may be displayed by riparian plants: (i) *invaders* produce very large numbers of wind- and water-dispersed seeds; (ii) *endurers* resprout after breakage or burial; (iii) *resisters* tolerate extreme environmental conditions, including inundation, fires, or epidemics, whereas (iv) *avoiders* are unable to adapt to specific disturbance types. Successful riparian plants often possess all of the first three adaptations.

[12] For example, riparian willow and poplar (cottonwood) species are pioneer riparian tree species that reproduce freely both sexually and vegetatively. Enormous quantities of very small, light seeds are produced in the spring and early summer [*Braatne et al.*, 1996; *Imbert and Lefevre*, 2003; *Karrenberg et al.*, 2003] and are widely dispersed by wind (anemochory) and water (hydrochory). Seeds have a very short period of viability and germinate almost immediately once they are deposited on moist bare sediment surfaces. They, therefore, take advantage of exposed habitats produced by fluvial deposition and erosion. However, because of their short period of viability (up to a few weeks) and the high susceptibility of young seedlings to flood and drought stress, few survive [*van Splunder et al.*, 1995; *Johnson*, 2000], and these individuals tend to develop in very specific locations within the riparian zone (see section 3.2).

[13] Riparian willows and poplars also reproduce very freely asexually, with new plants sprouting from vegetative fragments or entire uprooted trees and shrubs. Flood-damaged trees that are not uprooted also sprout vigorously. Asexual reproduction can occur at any time during the growing season, and these species are able to regenerate from both roots and shoots. Their ability to produce adventitious roots is critical to their survival in aggrading riparian environments (i.e., environments where the land surface is rising as a result of sediment deposition), giving them enormous tolerance to burial and having important implications for the stabilization of fluvially deposited sediments.

[14] In suitable environmental (particularly soil moisture) conditions, growth rates of seedlings and sprouting rates from vegetative fragments can be extremely high. Up to 3 mm/day shoot growth in *Populus nigra*, *Salix alba*, and *Salix elaeagnos* seedlings, 10 mm/day in cuttings, and 15 mm/day shoot growth from uprooted deposited trees have been observed along the Tagliamento River, Italy [*Francis et al.*, 2006; *Moggridge and Gurnell*, 2009]. Root growth is also rapid. For example, a 30 mm/day water table decline in sand and gravel experimental substrates resulted in average daily increments in root depth of 27 and 20 mm, respectively, for *Salix elaeagnos*, and 15 and 10 mm, respectively, for *Populus nigra* [*Francis et al.*, 2005]. These rapid growth traits allow plants to establish and gain root anchorage quickly in alluvial sediments, so that they are soon able to resist uprooting by flood disturbances [*Karrenberg et al.*, 2003].

[15] However, the survival and growth performance of different riparian species is strongly affected by environmental conditions. For example, *Glenz et al.* [2006] in a review of the flooding tolerance of several central European tree and shrub species cite observations by *Spath* [1998, 2002], which indicate that while *Salix alba* was able to survive inundation by flood waters for almost the entire growing season at a site on the Upper Rhine, Germany, *Alnus* species and *Fraxinus excelsior* were only able to tolerate flooding for approximately 70% and 20% of the growing season, respectively. Furthermore, *Amlin and Rood* [2001] conducted inundation experiments on rooted cuttings of three willow species and three poplar species and showed that while all of the poplar species suffered a reduction in shoot and root elongation with inundation, the willow species were relatively unaffected and *Salix exigua* (sand bar willow) showed an increase in root and shoot elongation. Similar differences in sensitivity between species have been observed with respect to drought and the depression of the alluvial water table [e.g., *Amlin and Rood*, 2002, 2003; *Pasquale et al.*, 2012]. This sensitivity to hydrological processes has consequences for the colonization and distribution of tree species within the riparian zone [e.g., *Robertson and Augspurger*, 1999; *Dixon et al.*, 2002; *Cooper et al.*, 2003; *Turner et al.*, 2004; *Cooper et al.*, 2006; *Friedman et al.*, 2006; *Robertson*, 1999], a theme that is developed in section 3.2.

TABLE 2. Some Significant References to the Influence of Fluvial Processes on Vegetation Dynamics

Physical Process	Spatial / Temporal Scale	References
Seed dispersal		
Seed rain rate	3 river reaches / 4 years	*Cooper et al.* [1999]
Seed input	cross section / 2 years	*Tabacchi et al.* [2005]
Characteristics of riparian plants		
Development of species richness	river reach	*Nilsson et al.* [1997]
Influence of sedimentation and flooding	river reach / 2 years	*Friedman and Auble* [1999]
Influence of water levels on mortality and root depth	10 cross sections / 34 years	*Scott et al.* [2000]
Root volume ratio and diameter	25 cross section / 3 months	*Wynn et al.* [2004]
Root biomass spatial distribution	river reach / 2 years	*Kiley and Schneider* [2005]
Effect of flooding	5 cross sections / 1 year	*Vreugdenhil et al.* [2006]
Colonization of sites		
Influence of river flow	25–50 km / 80 years	*Bradley and Smith* [1986]
Seedlings density and influence of shade, position, competition	3 river reaches / 4 years	*Cooper et al.* [1999]
Influence of soil texture, elevation, light	river bend	*Robertson and Augspurger* [1999]
Influence of river discharge	river transect	*Bendix and Hupp* [2000]
Influence of river flow	rive reach	*Johnson* [2000]
Influence of river flow and stage	river transect / 1 year	*Rood and Mahoney* [2000]
Influence of flow and elevation on seedling distribution	river reach / 52 years	*Stella et al.* [2004]
Biomass selection by flood		*Perona et al.* [2012]
Growth of riparian plants		
Growth rate, maximum age, and diameter	-	*Botkin et al.* [1972]
Growth rate, shade tolerance, and diameter	-	*Phipps* [1979]
Growth rate, maximum age, diameter, etc.	-	*Pearlstine et al.* [1985]
Relationship between tree age and dbh	9 cross sections / 100 years	*Scott et al.* [1997]
Ecological succession and biogeography		
Tree density	river reach	*Johnson and Bell* [1976]
Tree density and species richness	cross section / centuries	*Nanson and Beach* [1977]
Tree distribution	17 cross sections	*Hupp and Osterkamp* [1985]
Tree density	25–50 km / 80 years	*Bradley and Smith* [1986]
Vegetation structure	River reach	*Kalliola and Puhakka* [1988]
Transition of tree species	cross section / centuries	*Shankman* [1993]
Maps of vegetation change	river reach	*Johnson et al.* [1995]
Vegetation patterns, species distribution, and tree density	cross section	*Carr* [1998]
Vegetation patterns	river bend	*Robertson and Augspurger* [1999]
Relationship between riparian species and unit stream power	river transect	*Bendix and Hupp* [2000]
Seedling density and height	river reach	*Rood and Mahoney* [2000]

3.2. Colonization of Riparian Sites

[16] Despite their ability to cope with the disturbances and stresses that characterize riparian environments, the distribution of riparian plants is heavily constrained by fluvial processes. Successful recruitment of riparian tree species following sexual reproduction is particularly strongly influenced by the river's flow regime. For riparian willow and poplar species, seeds are released through the spring and early summer, with different species flowering, setting, and releasing seed at different times. River flows during this period, coupled with the short viability of the seeds and the requirement for a bare, moist substratum for seed germination (section 3.1), limit the spatial distribution of potential germination sites. Moreover, once deposited, optimum growth of the young plants is related to moisture retention in the substratum and the rate of fall of the alluvial water table [*Barsoum and Hughes*, 1998; *Francis et al.*, 2005; *Guilloy et al.*, 2011]. This sensitivity underpins the recruitment box model (Figure 3) proposed by *Mahoney and Rood* [1998], which links seasonal river water level decline from spring high flows to the period of seed release; spatial location (elevation) of areas of moist, bare sediment; and the subsequent rate of river stage and alluvial water table decline. Where several riparian tree species grow along a river, species-specific dates of seed dispersal relate to different river levels and thus different areas of bare moist sediment, and also to different rates of water table decline following seed germination. As river stage declines, seeds deposited high within the river's active tract may not find sufficient moisture for germination and may be affected by too rapid a rate of water table decline, whereas seeds deposited at low elevations may experience a gentler rate of water table decline but a greater exposure to disturbance by water level fluctuations, particularly during the autumn and winter of their first year of growth. While flood disturbances may uproot or smother seedlings and erode and remove soil and organic matter, they also create areas of bare sediment for future seed germination. As a result of different times of seed dispersal, different riparian tree species may colonize different zones (elevations) of a river's active tract. Furthermore, different species may also grow most successfully within different elevation bands because of their sensitivity to soil moisture conditions and the rate of water level decline [e.g., *Amlin and Rood*, 2001, 2002; *Bhattacharjee et al.*, 2008] and susceptibility to removal or burial by floods. Thus, the river's flow regime appears to be crucial for riparian tree recruitment, maintenance of species diversity, and promotion of a wide age structure within riparian woodlands, as has been demonstrated through field observations, simulations, and literature syntheses [e.g., *Braatne et al.*, 2007; *Dixon and Turner*, 2006; *Greet et al.*, 2011]. Because of the strong dependence of recruitment on river level fluctuations, it is possible

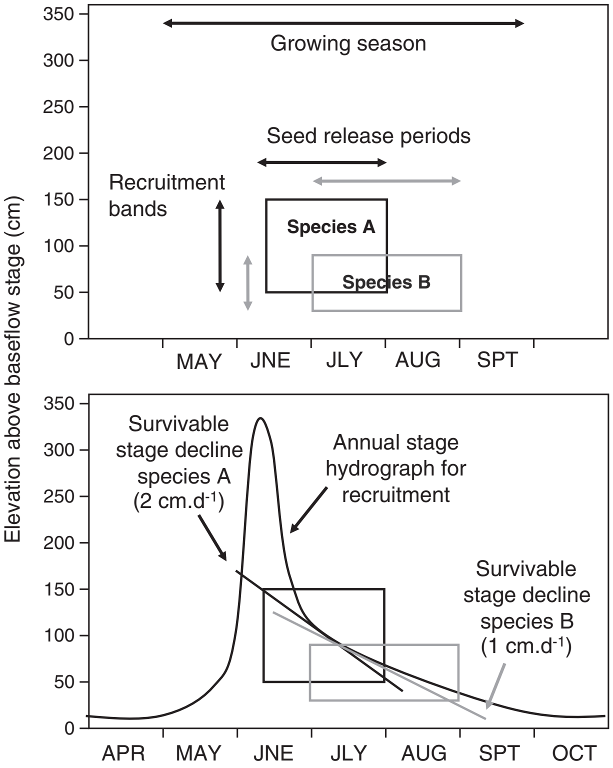

Figure 3. Example of the application of the recruitment box model of *Mahoney and Rood* [1998]. Seedling success is directly linked to the rates of water decline during and following seed release and germination by each of the species (A and B). Copyright (1998), with permission from Springer.

to develop models to interpret or predict recruitment from seeds under different flow regimes [e.g., *Lytle and Merrit*, 2004; *Ahn et al.*, 2007] and to prescribe flow regimes to support the restoration of riparian woodland along regulated rivers [*Rood et al.*, 2003, 2005].

[17] The flow regime is also crucial for the success of asexual reproduction, although sensitivity to the flow regime is not as strong as for sexual reproduction. Vegetative propagules can be dispersed throughout the year; the elevation at which they are deposited is controlled by river levels at the time of dispersal; and sprouting, establishment, and survival beyond the first year or two is dependent on moisture availability, particularly depth to water table, and flood disturbance frequency and intensity. Thus, *Francis* [2007] found that uprooted trees deposited in three different years along a reach of the Tagliamento River were most likely to regenerate the larger the deposited tree (internal resources) and the lower the deposition site within the active tract (closer to the alluvial water table). Nevertheless, there was a lower limit to the elevation range for deposited trees, whether or not they regenerated, which reflected the flooding history of the site; and successful regeneration of uprooted trees reached a maximum at around 1.1 m below floodplain level, within the 3 to 4 m elevation range of the active tract.

[18] River channel form, water level regime, and flow structure support characteristic, preferential sites for riparian tree seedling growth and the regeneration of vegetative fragments. For example, *Hupp and Osterkamp* [1985] describe a close correspondence between river channel cross-profile form, riparian vegetation, and water levels associated with particular durations and frequencies of inundation along Passage Creek, Virginia, USA. Similar structures were found in cross profiles of the Cecina River, Italy [*Hupp and Rinaldi*, 2007], where different riparian tree species were preferentially associated with bars, marginal benches, and floodplain edges. On meandering rivers, young plants tend to develop preferentially in horizontal bands on the inside of meander bends. These bands may reflect the optimum elevation for seed germination and growth [e.g., *Bradley and Smith*, 1986] (Figure 4), or they may be the result of sprouting of plant material (particularly wood pieces) that has been deposited with sediment during the creation of point or counterpoint bars, particularly scroll bars [e.g., *Hickin*, 1975; *Nanson and Beach*, 1977; *McKenney et al.*, 1995; *Gurnell and Petts*, 2006]. On braided rivers, young plants tend to appear across the surfaces of relatively high braid bars, often in the lee of patches of mature vegetation [*Moggridge and Gurnell*, 2009] or accumulations of large wood. However, in periods without significant floods, strips of seedlings can establish rapidly along the edge of low-flow channels regardless of the river cross profile or planform [*Gurnell et al.*, 2012].

[19] Because of the requirement for bare moist sediment to support the recruitment of riparian trees, strong recruitment may follow large damaging floods that remove areas of established riparian woodland [e.g., *Friedman and Lee*, 2002] (Figure 5). However, side channel abandonment, channel narrowing, or channel migration also expose bare sediment suitable for colonization [*Scott et al.*, 1996; *Johnson*, 2000; *Steiger et al.*, 2001a; *Friedman and Lee*, 2002; *Kondolf et al.*, 2007]. Riparian vegetation can also become established on bare sediment exposed or deposited by bank failure and fluvial erosion and deposition processes during river channel incision [e.g., *Hupp*, 1992, 1999; *Simon*, 1995]. A complex series of terraces and benches may form, on which riparian vegetation develops most easily during periods and at locations of high bank water tables. As bed incision proceeds, the bank water table falls, and so riparian plants remaining at higher elevations along the river margins usually succumb to water stress.

[20] In general, a site can only be considered to be developing some stability as a result of vegetation colonization if the plants survive the next stress condition, such as a destructive flood, drought, or a sudden falling of the water table. *Johnson* [2000] observed total tree seedling mortality in 90% of his study plots by the end of the first year following germination, and *Moggridge and Gurnell* [2009] lost 72% of seedlings across their study plots during a flood in the first winter following germination. Research on shoot and root development and uprooting resistance of riparian tree species (reviewed in section 3.1) indicates that young plants probably need to develop for at least 2 years for their roots and canopy to be able to resist moderate disturbance events.

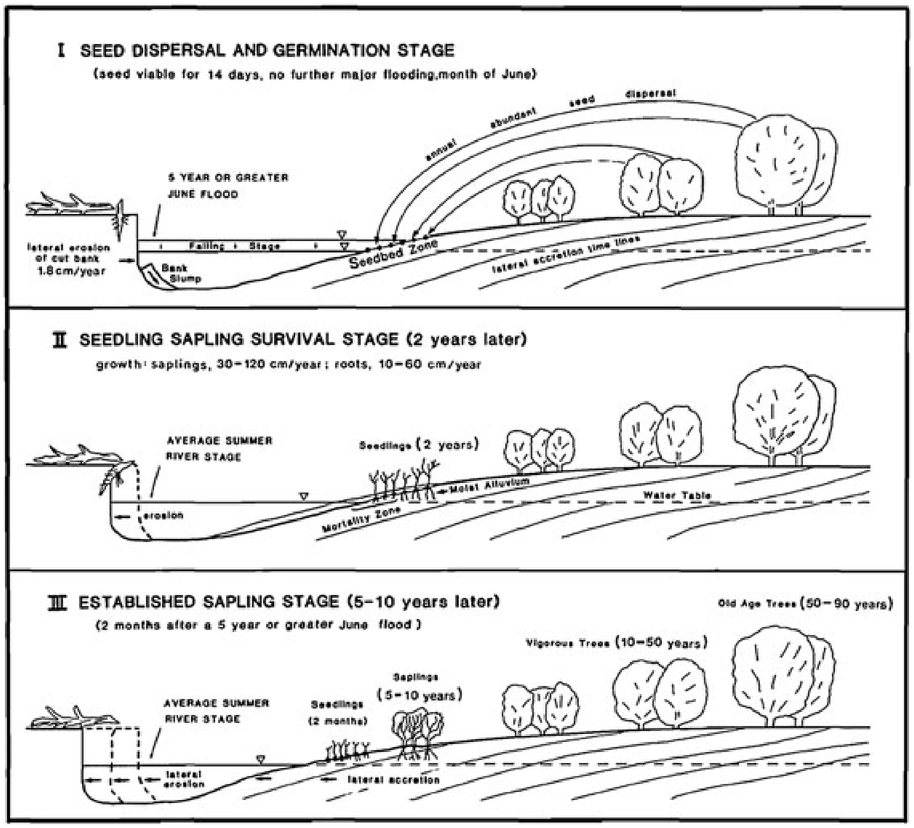

Figure 4. Scheme of seed dispersal, germination, growth, and establishment along the Milk River according to *Bradley and Smith* [1986]. Copyright (1986), with permission from NRC Research Press.

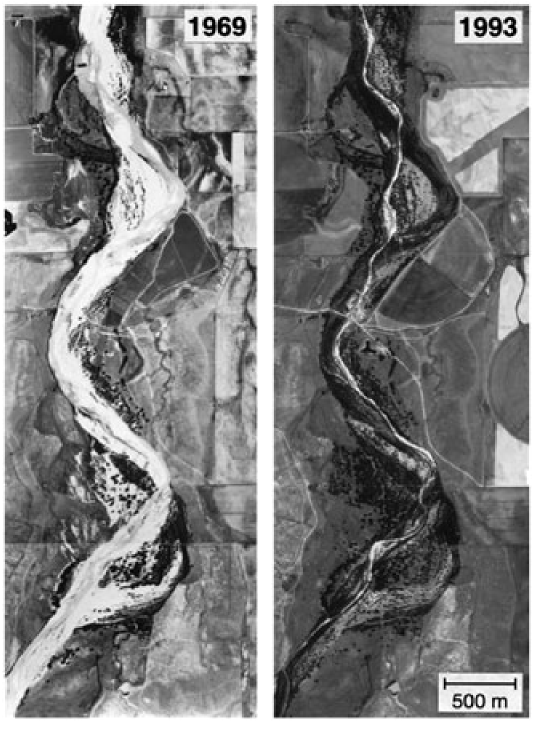

Figure 5. Change in bottomland vegetation and morphology along the West Bijou Creek, Colorado, USA [*Friedman and Lee*, 2002]. Copyright (2002), with permission from Ecological Society of America.

3.3. Ecological Succession Within Riparian Zones

[21] "Ecological succession is a directional sequence of changes through time in species composition and other plant community characteristics (productivity, biomass, diversity, etc.)" [*Odum*, 1969]. However, due to the strong stochastic behavior of river flows, succession in riparian environments is interrupted and reset by disturbances such as floods and droughts, leading to complex and dynamic spatial distributions of riparian patches at different successional stages as both disturbance magnitude and intervening recovery time vary [*Décamps and Tabacchi*, 1994].

[22] Ecological succession in riparian environments progresses as pioneer species colonize bare alluvial sediments and then are gradually replaced by postpioneer species. Pioneer riparian trees and shrubs develop from seeds or vegetative fragments and grow and trap fluvial sediments and plant propagules, leading to the creation of sediment patches within which propagules of other species can germinate or sprout. These patches aggrade, enlarge, coalesce, and support increasing vegetation cover and species richness. On the Tagliamento River. this process leads to over 60% ground vegetation cover on the aggrading patches within 3 years [*Kollmann and Schneider*, 1999; *Francis et al.*, 2008], which further encourages sediment trapping and surface aggradation. Therefore, the process of island (and floodplain) development results from a close interaction between plants and physical processes. Colonization and growth of pioneer species on open (unvegetated) river bar surfaces lead

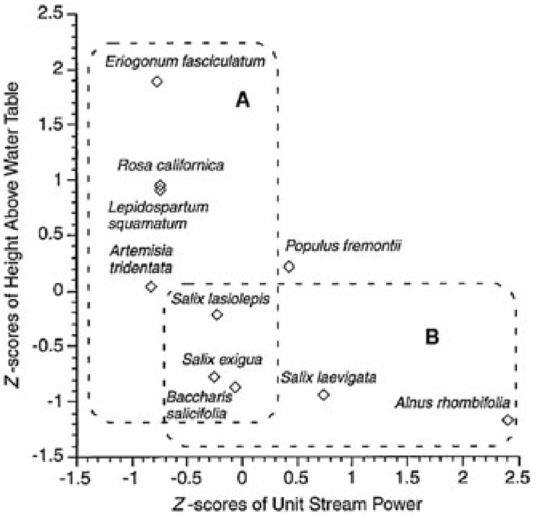

Figure 6. Plant species distribution as a function of unit stream power and height above the water table [after *Bendix and Hupp*, 2000].

to sediment retention and the lateral and vertical development of an island landform on the bar surface. As the island develops, the physical conditions at its surface change. The increasing elevation of the island surface leads to a reduction in frequency and duration of flood inundation and an increase in the vertical distance between the island surface and the underlying water table. The soil water regime is also affected by a change in surface sediment composition, which is usually finer and has a higher organic content on an island than on the bar surface on which the island is constructed. These changes in physical conditions alone lead to a gradual change in the species composition of the vegetation. However, in addition, as the process of plant colonization, growth, and aggradation continues, areas of bare, moist sediment suitable for colonization by pioneer riparian species become increasingly rare, and so pioneer species are gradually replaced by postpioneer species that are more suited to the elevated, less disturbed, more competitive, and dryer island surface environment. For example, *Kollmann et al.* [1999] found that the oldest islands on the Tagliamento River were distinguished from younger islands by the presence of a range of terrestrial tree species (*Acer pseudoplatanus*, *Pinus nigra*, *Pinus sylvetris*, *Prunus spinosa*, *Sorbus aria*, *Tilia cordata*).

[23] However, in riparian environments, this process of succession is inevitably interrupted by fluvial disturbances, leading to the development of a mosaic of patches at different successional stages. This has been termed the "shifting habitat mosaic" [*Pringle et al.*, 1988; *Stanford et al.*, 2005] and is characteristic of natural floodplain ecosystems. The nature, geometry, and relative elevation of the riparian-floodplain patches varies with river flow energy and style [*Nanson and Croke*, 1992], and thus the mode of construction, topographic and sedimentological characteristics, and rate of turnover of the patches or landforms. Since the patches are inundated and impacted by flows of different frequency, they are inevitably associated with species that are tolerant of different soil moisture, inundation, and shear stress conditions [e.g., *Bendix and Hupp*, 2000] (Figure 6) and possess other traits that suit them to the environmental conditions that characterize particular patch types [e.g., *Richter and Richter*, 2000] (Figure 7). As a result, fluvial landforms of different type, relative elevation, and

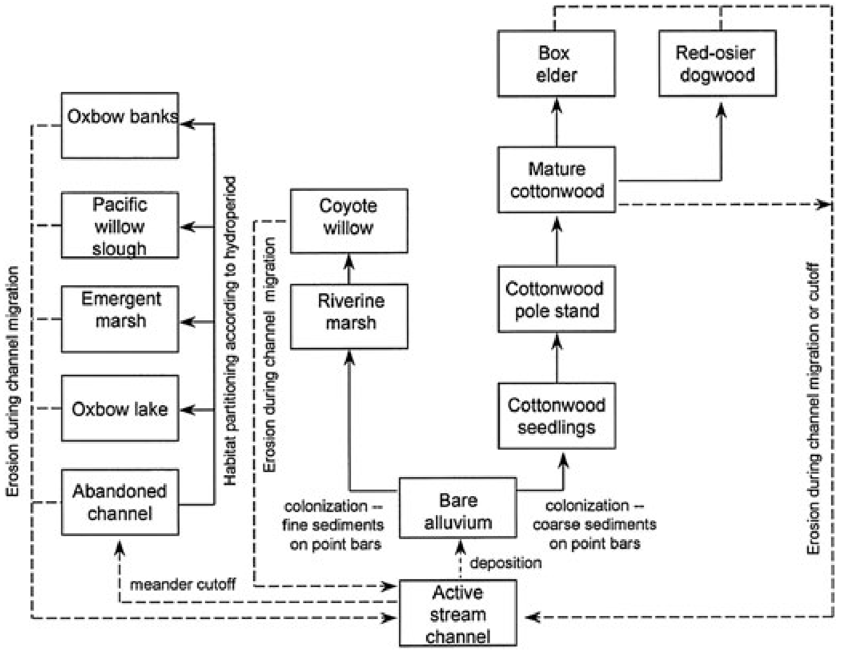

Figure 7. Example of vegetation succession along the Yampa river. The boxes represent the various habitat types that compose the riparian mosaic. The dashed lines represent changes driven by fluvial geomorphic processes. The solid lines describe changes related to biotic succession [*Richter and Richter*, 2000].

susceptibility to disturbance frequently support different plant species and assemblages. Of course, the particular plant species and communities found on these fluvial landforms vary with the broad environmental setting in which a river is located, but numerous research investigations have demonstrated close associations between vegetation composition and fluvial landforms within many different river systems across the world [e.g., *Hupp and Osterkamp*, 1985, 1996, *Hupp and Rinaldi*, 2007; *Salo et al.*, 1986; *Scott et al.*, 1996; *Van Coller et al.*, 1997; *Dykaar and Wigington*, 2000; *Pettit et al.*, 2001; *Cooper et al.*, 2003; *Turner et al.*, 2004; *Shin and Nakamura*, 2005; *Stella et al.*, 2011; *Cline and McAllister*, 2012].

3.4. Simplified Models for the Growth of Pioneer Plants

[24] A modeling strategy should allow a good compromise between the need to fit the complex dynamics of plant ecology and the need to provide a simple mathematical tool. As described in the previous sections, the growth and vigor of established riparian tree species depends on many of the same parameters as recruitment, and among these, the hydrological ones play a decisive role.

[25] *Botkin et al.* [1972] was one of the first researchers to develop a model for tree growth, although it did not take into account the direct influence of the river. Later, *Pearlstine et al.* [1985] revised a previous ecological model, proposed by *Odum* [1983] called FORFLO (Forest Floodplain Succession Model), and mathematically modeled the key processes that affect the growth of plants in the riparian zone as (see also *Shugart and West* [1977] and *Phipps* [1979]

$$\frac{\mathrm{d}D}{\mathrm{d}t} = \frac{1 - DH/D_{\max}H_{\max}}{274 + 3b_2D - 4b_3D^2} \cdot p, \tag{1}$$

where D is the diameter at breast height, H is the height of the tree, $D_{\max}$ and $H_{\max}$ are the maximum recorded diameter and height (in centimeters), t is time (in years) and G, b_2, and b_3 are the species-specific growth rate parameters. Equation (1) gives a logistic-shaped growth curve (see *Camporeale and Ridolfi* [2006]) and assumes that a tree in optimal conditions will grow to two thirds of its maximum height at one half of its maximum age (in this case, the term p is set to unity.) The definition of optimality is debated in the literature, but in the present context, we define as optimal the conditions that maximize the growth. This optimal growth rate is reduced by computing the term p in equation (1) as the product of some dimensionless factors, $p = \mathcal{S}\cdot\mathcal{T}\cdot\mathcal{R}\cdot\mathcal{H}$, which account for the stand density, $\mathcal{S}$, the influence of temperature, $\mathcal{T}$, shading tolerance, $\mathcal{R}$, and the position of the water table in the soil, $\mathcal{H}$. Thus, function $\mathcal{S}$ simulates the effect of competition for nutrients and water, whereas $\mathcal{T}$ accounts for the dependence of photosynthesis on temperature. *Botkin et al.* [1972] recognized three shade tolerance classes and described $\mathcal{R}$ as a function of the available light A—scaled between 0 and 1—through the following relations:

$$\mathcal{R} = \begin{cases} 1 - e^{-4.64(A-0.005)} & \text{(shade-tolerant)} \\ \frac{1.87(A-0.064)}{A+0.436} & \text{(intermediate shade-tolerant)} \\ 2.24(1 - e^{-1.136(A-0.008)} & \text{(shade-intolerant),} \end{cases} \tag{2}$$

[26] The last important factor which affects tree growth is the vertical distance from the phreatic water table. This dependence has been modeled by *Phipps* [1979] as $\mathcal{H} = 1 - 1.3(T - W)^2$ where T and W are, respectively, the actual and the optimal depth of the water table (i.e., the depth which maximizes the growth).

[27] An interesting attempt to account for the stochastic nature of the problem of plant growth was proposed by *Lytle and Merrit* [2004]. Their model describes the growth of *Populus deltoides* (cottonwood) from germination to the adult stage, taking into account the main hydrological processes of drought and flooding and including the effects of random fluctuations. This environmental stochasticity is modeled by transition matrices that describe the transition probability during the different life stages of cottonwood. Therefore, the model has the stochastic form $N(t + 1) = A(t) \cdot N(t)$, where $N(t)$ is a vector that contains the abundances of the vegetated plots, and $A(t)$ is a set of transition matrices that fluctuate according to the variations in river discharge. Thus, a fraction of each stand may be lost each year due to flooding or drought mortality, and this space becomes available for colonization by new seedlings the following year.

4. INFLUENCE OF RIPARIAN VEGETATION ON RIVER MORPHODYNAMICS

[28] River morphodynamics can be defined as the sum of the complex interactions between the flow field and sediment which occur in the river environment [*Seminara*, 1998]. Such interactions involve the spatial and temporal dynamics of bed forms at different length scales (e.g., ripples, dunes, bars, meanders). Although the fundamental role of vegetation for river morphodynamics (arrow pointing toward the left in Figure 2) has often been recognized, the underlying mechanisms are not fully understood yet.

[29] Vegetation affects each basic element of the morphodynamic system [*Gibling and Davies*, 2012]. It modifies the flow field and its turbulent structure [*Lopez and Garcia*, 1998; *Defina and Bixio*, 2005] and therefore influences sediment transport and bedform formation [*Thorne*, 1997]. It also affects bank strength and can therefore modify the conditions that can induce bank collapse. All these effects concur to influence local morphodynamics and thus the overall river morphology [e.g., *Millar*, 2000; *Murray and Paola*, 2003; *Allmendinger et al.*, 2005]. Table 3 summarizes some field and laboratory evidence concerning the influence of vegetation on morphodynamics processes. Although the processes are interrelated [e.g., *Tsujimoto*, 1999], for the sake of clarity, they will be analyzed separately in this section but they will be considered jointly in the presentation of the morphodynamic models in sections 5 to 7.

4.1. The Flow Field

[30] Thorough understanding of river fluid mechanics requires knowledge of advanced mathematical and physical tools that are beyond the scope of the present review and are available in standard textbooks such as *Henderson* [1966])

TABLE 3. Some Field and Laboratory Evidence Concerning the Influence of Vegetation on River Morphodynamics (the asterisk indicates: Flume Sizes in Meters: Length × Width)

Physical Process	Spatial / Temporal Scale	References
Flow field		
Depth-averaged velocity along a vegetated floodplain	cross section	*Pasche and Rouve* [1985]
Streamwise velocity and water surface elevation	river reach	*Thorne and Furbish* [1995]
Canopy drag coefficient and momentum budget	flume tests (24 × 0.38)*	*Nepf* [1999]
Friction factors for flexible coniferous trees	flume tests and in air tests	*Kouwen and Fathi-Moghadam* [2000]
First four moments and momentum budget	flume tests (19.5 × 0.91)*	*Lopez and Garcia* [2001]
Velocity vectors	flume tests (9 × 2)*	*Gran and Paola* [2001]
Local flow over flexible bottom vegetation	flume tests (14 × 0.60)*	*Carollo et al.* [2002]
Mean velocity, correlations and spectra	flume tests (24 × 0.38)*	*Ghisalberti and Nepf* [2002]
Friction factors	flume tests (50 × 1.1)*	*Jarvela* [2002]
Effect of vegetation morphology on drag and friction factor	flume tests (10 × 0.3)*	*Wilson and Horritt* [2002]
Shear layers generated by submerged vegetation	flume tests (24 × 0.38)*	*Ghisalberti and Nepf* [2004]
Effect of flow depth, stem density, and channel slope	flume tests (3.0 × 0.10)*	*James et al.* [2004]
First four moments, spectra and quadrant analysis	flume tests (18 × 0.90*	*Poggi et al.* [2004]
Mixed moments and momentum balance	flume tests (18 × 0.90)*	*Poggi et al.* [2004]
Resistance and drag coefficient for flexible vegetation	flume tests (150 × 2.0)*	*Armanini et al.* [2005]
Manning coefficient for flexible submerged vegetation	flume tests (14.4 × 0.60)*	*Carollo et al.* [2005]
Flow resistance of channels with macrophytes	field data collection	*Green* [2006]
Friction factors and drag coefficient with emergent vegetation	flume tests (3.3 × 1.22)*	*Musleh and Cruise* [2006]
Effect of nonflat bed conditions	flume tests (18 × 0.90)*	*Poggi and Katul* [2007]
Effect of density on the dispersive stresses	flume tests (18 × 0.90)*	*Poggi and Katul* [2008]
Bank stability		
Erosion potential and bank height	river reach	*Abernethy and Rutherfurd* [1998]
Root reinforcement and safety factors	river reach	*Abernethy and Rutherfurd* [2000]
Root reinforcement, apparent cohesion due to roots	river reach	*Abernethy and Rutherfurd* [2001]
Shear strength as a function of biomass, or root density	river reach	*Micheli and Kirchner* [2002b]
Cohesion distribution due to roots of different species	cross section	*Simon and Collison* [2002]
Tensile strength for different root diameters	field and laboratory tests	*Pollen and Simon* [2005]
River migration		
Erosion rate in function of vegetation roots in sediment	6–7 km	*Smith* [1976]
Erosion rates in presence of heavy vegetation	river reach / 37 years	*Odgaard* [1987]
Erosion rate in function of areal density of vegetation	one river bend / 2 years	*Pizzuto and Meckelnburg* [1989]
Erosion occurrences in different vegetated reaches	20–30 km	*Beeson and Doyle* [1995]
Migration rate in function of different vegetation types	17 cross sections	*Brooks and Brierley* [2002]
Migration rates	river reach / 40 years	*Micheli and Kirchner* [2002a]
Migration rates and bank erodibility	river reach / 40 years	*Micheli et al.* [2004]
Migration rates between different vegetated sites	10 km/ 26 years	*Allmendinger et al.* [2005]
Morphological change		
Channel planform change	6 km	*Mackin* [1956]
Bank erosion and channel form following afforestation	500 m reach / 2 years	*Murgatroyd and Ternan* [1983]
Effect on cottonwood density	25–50km / 80 years	*Bradley and Smith* [1986]
Channel narrowing, changes in width, sinuosity, bed elevation	7 km / 30 years	*Friedman et al.* [1996]
Channel width, depth and velocity	cross section	*Huang and Nanson* [1997]
Species richness change	20/70 years	*Nilsson et al.* [1997]
Channel form ratio and straightening	17 river reaches /∼100 years	*Rowntree and Dollar* [1999]
Channel evolution, avulsion and channel expansions	10 km / 40 years	*Gilvear et al.* [2000]
Channel widening and narrowing	60 years	*Merritt and Cooper* [2000]
Channel change from meandering to braided	1 km / 53 years	*Millar* [2000]
Formation of anabranching channels	30 km	*Tooth and Nanson* [2000]
Mean channel width and depth	river reach	*Gran and Paola* [2001]
Fluvial island formation, LWD variations	22 sites / 10 years	*Gurnell et al.* [2001]
Channel narrowing following basin afforestation	20years	*Liebault and Piegay* [2002]
Bankfull width with different vegetation densities	26 river reaches / 3 years	*Hession et al.* [2003]
Stream width	10 km / 26 years	*Allmendinger et al.* [2005]
Species composition change	182 plots of floodplain / 2 years	*Leyer* [2005]
Channel change from wandering to meandering	40km / 55 years	*Piegay et al.* [2005]
Channel change from braiding to straightening	20km / 65 years	*Coulthard et al.* [2007]
Field and laboratory evidence of channel change	20 km / 17 years	*Jang and Shimizu* [2007]
Channel width / depth temporal change	6.5 km	*Tooth et al.* [2008]
Sedimentation		
Over-bank sedimentation rate	river reach / centuries	*Nanson and Beach* [1977]
Sediment sorting index	river reach / 20 years	*Osterkamp and Wood* [1987]
Accretion rate	10 km / 26 years	*Allmendinger et al.* [2005]

and *Nezu and Nakagawa* [1993]. It is sufficient to note that the major difficulty in analyzing the effect of in-stream and bank vegetation on the flow field arises from the complicated features of (i) the vegetation geometry and (ii) the turbulent flow field. The first source of complexity can be tackled through the introduction of spatial averaging of the flow field over quite large horizontal slabs containing the vegetation [*Nikora et al.*, 2007]. In this way, individual elements of vegetation are identified as dispersed obstacles that provide a spatially averaged drag force, so eliminating the plant-to-plant variations of vegetation, although the vertical structure of the flow field remains preserved. Spatial averaging gives rise to extra dispersive terms in the stress tensor (the Leonard stresses) which are associated, in the energy budget, with the wakes of individual plant elements, and *wake production* or the turbulence produced by the mean flow work against the pressure drag of vegetation [*Raupach and Shaw*, 1982]. The second source of complexity, which is the structure of the turbulence, is tackled through the use of temporal averaging. This operation leads to the well-known Reynolds stress in the stress tensor. Both Leonards and Reynolds stresses require some closure relationships.

[31] Through the cascade of energy, turbulence is active at different length scales, from the smallest (the Kolmogorov scale) to the largest (the length scale of the energy-containing turbulence). As a result, the problem of the closure of turbulence requires a rigorous analysis of all the scales, for example, through the investigation of frequency spectra [*Poggi et al.*, 2004]. Such an approach has been widely developed for forest and crop canopies in the atmospheric field, where it has led to important results, such as the fact that the expectation of isotropy is violated within the canopy [e.g., *Finnigan*, 2000]. However, it is too complicated to investigate and to model the main features of river flow in the presence of vegetation, because of the large range of relevant scales. Conversely, instead of considering all the length scales, it is common practice to consider depth as the threshold which separates the processes related to fine turbulence, with typical eddies smaller than the depth separated from the macroscopic eddies related to the secondary circulation, which scale with river width [*Tsujimoto*, 1999].

[32] At the depth scale, turbulent flow with vegetation is dominated by large coherent structures, and the interaction of the flow field with vegetation produces large amounts of fine-scale turbulence in the wakes of stems, additional drag forces, interference with the turbulent length scales, and anisotropy of the mean flow [*Naot et al.*, 1996; *Finnigan*, 2000]. When the vegetation is completely submerged, the mean vegetation profile is also inflected, with the inflection point located at the top of the vegetated layer [*Raupach et al.*, 1996]. This evidence, as well as the observation that both turbulence intensity and shear stress peak at the inflection point, suggest the mixing layer analogy as a possible means of interpreting high turbulence intensities in the roughness sublayer [*Raupach et al.*, 1996].

[33] At the width scale, the existence of a vegetated zone along banks causes different fluvial processes, mostly related to erosion and sedimentation [*Tsujimoto*, 1999]. The flow near the vegetation is retarded and the bed sediment transport is weak. Suspended sediment transport, which is subjected to turbulent mixing and to cellular secondary currents [*Nezu and Nakagawa*, 1993], leads to a lateral net flux, deposition near the vegetated zone, and accretion of the bank line. *Tsujimoto* [1996] identified the presence of organized fluctuations of the flow field in the vegetation zone, which induce the alternation of the bed load direction. Such an alternation has been proposed as the cause of the formation of longitudinal sand stripes near the vegetated zone.

[34] Depending on which kind of averaging (temporal or spatial) one wishes to adopt, different modeling approaches can be distinguished [*Nikora et al.*, 2007]: direct numerical simulation (DNS) completely avoids the necessity of averaging; large eddy simulation (LES) adopts a spatially filtered Navier-Stokes equation (equivalent to a weak spatial averaging); time averaging leads to the Reynolds averaged Navier-Stokes equations (RANS); and the extension of spatial averaging to the RANS provides the double-averaged Navier -Stokes equation (DANS). This latter approach reduces the computation effort involved in DANS and LES simulations and thus is particularly common in the context of vegetated channel flows. Again, the degree of sophistication of the models depends on the choice of the closure relations and on the length scale of interest. First-order closure models are able to easily reproduce the mean flow, but they do not consider the budget of second-order statistics, such as the Reynolds stresses, while second-order closure models (e.g., Reynolds stress models) are too computationally expensive [*Katul et al.*, 2004]. A good compromise is the adoption of 1.5-closure models, known as k-ϵ models, where the closure of the eddy viscosity requires the conservation equation to be solved for turbulent kinetic energy, k, and turbulent kinetic dissipation rate, ϵ [*Lopez and Garcia*, 1998; *Defina and Bixio*, 2005; *Lopez and Garcia*, 2001]. At the order of depth scale, *Katul et al.* [2004] pointed out that for 2-D uniform flows, there is no clear advantage in using the ϵ-equation when the mixing length, l_m, can be a priori specified. They assumed a value of l_m which is locally independent of the vertical coordinate, z, within the vegetated layer and the classical rough-wall boundary layer formulation above the vegetation (i.e., a linear function of z). Slightly more advanced schemes have been adopted for the case of 3-D formulations, where the standard k-ϵ model is corrected using a dissipation term, wall damping functions, and algebraic relationships for turbulence anisotropy [*Shimizu and Tsujimoto*, 1994; *Naot et al.*, 1996]. For more details, see the review by *Simon* [2004].

[35] When the length scale of interest is the river width, a common choice is to adopt shallow water equations, namely, depth-averaged two-dimensional models in straight and meandering tree-lined channels under steady flow conditions [*Van De Wiel and Darby*, 2004; *Wu and Wang*, 2004; *Wu et al.*, 2005]. Some authors have also proposed models for the transverse profile with physically based expressions for the depth-averaged velocity in partially vegetated channel flows [*Pasche and Rouve*, 1985; *Ikeda et al.*, 1991; *Darby*, 1999], and *Rameshwaran and Shiono* [2007]. These models apply lateral distribution methods (LDMs) which consider the depth-integrated form of the streamwise Reynolds equations. Very recently, *White and Nepf* [2008, 2007] have proposed an alternative vortex-based method which sheds light on the lateral momentum fluxes between the vegetated zone and the main channel, supporting their proposal with detailed experimental investigations. Furthermore, *Wu et al.* [2005], *Temmerman et al.* [2005], and *Lopez-Bermudez et al.* [2002] have developed morphodynamic models for unsteady conditions.

[36] When these models [e.g., *Wu et al.*, 2005] are considered, only the main features of the extremely complex interactions between vegetation and river dynamics are identified and retained, and some simple closure relations for wake production, drag force, and bed resistance are usually employed. In this context, *Kean and Smith* [2004], following the approach by *Nepf* [1999], proposed a model where the wake production of turbulence, due to shrub stems or trees, can be expressed as

$$P_t = \frac{1}{2} C_d \frac{D_s}{\lambda^2} u^3, \tag{3}$$

where D_s is the stem diameter and λ is the stem spacing. Assuming vertical stems, the production of turbulent kinetic energy, due to vegetation, can be expressed as

$$P_t = K_t \left(\frac{\partial u_t}{\partial y} \right)^2, \tag{4}$$

where K_t is the eddy viscosity within the stems and u_t is the local velocity within the stems. The drag force has the classical formulation

$$F_D = \frac{1}{2} C_d \rho A |U_v| U_v, \tag{5}$$

where C_d is the drag coefficient, A is the area occupied by vegetation in the downstream direction, and U_v is the mean velocity in the stem layer. If the vegetation is emergent, U_v is set equal to the mean stream velocity, whereas, if the vegetation is submerged,

$$U_v = \eta_v U \left(\frac{h_v}{h} \right)^2, \tag{6}$$

and η_v is a coefficient that is approximately equal to 1 [*Stone and Shen*, 2002]. The usual drag coefficient can be replaced by a coefficient C_{dm} that takes into account the section of effective flow. The relationship between C_d and C_{dm} is

$$C_d = C_{dm} \frac{U_{vm}^2}{U_v^2}, \tag{7}$$

where U_{vm} is the velocity between the stems.

[37] The interaction between the flow field and the vegetation has the overall effect of increasing the resistance and so reducing the flow conveyance. The effect on river dispersion has been investigated in *Perucca et al.* [2009]. This aspect is sometimes accounted for by neglecting the drag resistance and absorbing the entire vegetation influence in an overall equivalent bed resistance. The empirical measure of bed resistance and the calibration of equivalent bed roughness in the presence of vegetation is a classical topic in hydraulics research [e.g., *Wilson*, 2007; *Vionnet et al.*, 2004; *Armanini et al.*, 2005; *James et al.*, 2004; *Wilson and Horritt*, 2002]. In this context, the effect of the vegetation friction factor is evaluated by a variant of the Colebrook-White equation

$$\frac{1}{\sqrt{f}} = a + 0.4 \log \frac{R}{k}, \tag{8}$$

where R is the hydraulic radius, k is the roughness height of the vegetation, and a is a dimensionless coefficient that is a function of the transverse shape of the channel.

[38] Hydraulic resistance also depends on the age and structure of the plants. The impact of vegetation density on the Manning coefficient, n_v, was considered by *McKenney et al.* [1995] through

$$n_v = R^{\frac{2}{3}} \sqrt{\frac{C_f \sum A_i}{2gAL}} \tag{9}$$

where R is the hydraulic radius, C_f is the friction factor, A_i is the section of the plants normal to the streamlines, i.e., the product of diameter and submerged height, A is the flow section, and L is the reach length. *McKenney et al.* [1995] pointed out that, because of structure and plant density changes, vegetation becomes less effective in causing flow resistance after about 5 years of growth. The reasons for this are (i) the thinning of the trees, due to competition, and (ii) degradation of the lower branches with growth. Both mechanisms reduce the term $\sum A_i$ in equation (9).

[39] Vegetation flexibility is another factor that is taken into account when vegetation resistance is estimated. In order to consider vegetation flexibility, an index, MEI, is usually evaluated. This is an acronym for the product of stem density M and flexural rigidity in bending EI, where E is the stem modulus of elasticity and I is the cross-sectional second moment of inertia of the stem. *Kouwen et al.* [1973] noted that the roughness k depends on this flexibility index and also on flow parameters, such as the local boundary shear stress. They also proposed a methodology to evaluate the MEI coefficient and reported some computed values of the index for different types of grass. The MEI coefficient can be also evaluated by means of experimentally based formulae, such as the ones proposed by *Temple* [1987].

4.2. Bank Erosion

[40] Since vegetation affects geotechnical and hydrologic processes, it also follows that it influences bank stability. In general, three main mechanisms of bank erosion can be highlighted. The first one is *mass failure*, which occurs when the weight of the bank is greater than the shear strength of the soil. Different mass wasting mechanisms can occur, such as sliding, toppling, or fall of material from the bank [e.g., *Abernethy and Rutherfurd*, 1998]. Low, steep banks (generally steeper than 60°) are prone to slab failure when a block of soil topples forward into the channel. Rotational failure tends to occur in high, less steep banks. The second mechanism is *fluvial scour*, which occurs when the forces exerted by the flow are greater than the structural bank resistance of the river.

[41] The third mechanism is *subaerial scour*. This mechanism involves several climate-related factors that are external to the river system and which reduce soil strength, including soil desiccation, tree fall, wind throw of trees, etc. Subaerial scour is usually much less important than the other erosion processes, and it becomes apparent only when the other processes are limited, or where the climate is extremely cold or wet, or frequent abrupt changes in temperature occur, as in desert areas [e.g., *Thorne*, 1982; *Wynn*, 2005].

[42] A key effect of vegetation is the ability of roots to modify bank material strength [e.g., *Hey and Thorne*, 1986a;

Thorne, 1990; *Abernethy and Rutherfurd*, 1998]. The positive effects of vegetation on shear resistance are attributable to the fact that the vegetation roots can withstand tensile stresses. The tensile strengths of root have been measured by a number of different investigators. Some values have been reported in the literature by *Gray and Barker* [2004] and *Pollen et al.* [2004], and they appear to lie in the range of 10 to 40 MPa for most species. The presence of root strengthening near the bank surface may cause displacement of the failure surface and thus produce a larger pulse of sediment input to the channel. An important feature is that vegetation roots usually have the greatest effect close to the soil surface, where their density is highest and the soil is weakest.

[43] Some models have been developed to evaluate the increase in shear strength attributable to roots. For example, the model proposed by *Gray and Barker* [2004] models roots as fibers whose mobilized tensile strength depends on fiber elongation. Several authors have tried to quantitatively evaluate the increase in soil cohesion, due to the presence of roots, by means of laboratory or field observations [e.g., *Abernethy and Rutherfurd*, 2001]. A commonly used formula for soil cohesion in the presence of vegetation is the one proposed by *Wu* [1979]. *Abernethy and Rutherfurd* [2001] proposed the equation $C_r = n_i a_i t_i / A_w$ to compute cohesion for 10 cm increments of soil depth, where i is the root size class, A_w is the cross-sectional area of a 10 cm depth profile where the number of roots and their size classes are measured, a_i is the average cross-sectional area of the roots measured within size class i, and t_i is the tensile strength of roots within size class i. A more recent analysis based on field data collection, laboratory testing, and computer simulations has been proposed by *Pollen-Bankhead and Simon* [2010].

[44] Another important effect of vegetation is its influence on scour rates. Since boundary shear stress is proportional to the square of near-bank velocity, a reduction in flow velocity produces a much greater reduction in erosion.

[45] The rigidity of vegetation also influences scour. Trees are not as effective as grasses or shrubs at retarding near-bank velocities when the flow is slow [e.g., *Trimble*, 1997]. As velocity increases, local flow accretion around the trees may generate scour, although a dense root mat, such as that found on willows, directly protects banks from scour. Fine roots are particularly effective in holding bank material together.

[46] As a consequence of the impact of vegetation on bank stability processes, river migration rates can be greatly affected [*Smith*, 1976; *Pizzuto and Meckelnburg*, 1989; *Thorne and Furbish*, *Thorne and Furbish*, 1995; *Mamo and Bubenzer*, 2001]. *Micheli and Kirchner* [2002b] also investigated the stabilization effect of vegetation; producing the experimental relationship between shear strength and the biomass density shown in Figure 8.

[47] Reductions in the bank erodibility coefficient, E, by a factor of 2 or 3 as a result of the impact of vegetation have been observed along some American rivers [*Odgaard*, 1987; *Allmendinger et al.*, 2005]. *Beeson and Doyle* [1995] found a fivefold difference by comparing a bare site with a highly vegetated one, while *Micheli and Kirchner* [2002a] found a tenfold difference when they compared humid Californian meadows with dry meadows. However, in spite of such important field evaluations, no systematic data are available that link the bank erodibility coefficient, E, with vegetation biomass.

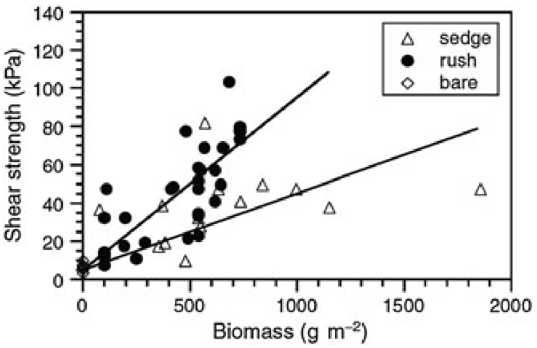

Figure 8. Shear strength versus biomass density along the Sacramento River, USA [after *Micheli and Kirchner*, 2002b]. The increase in shear strength is roughly 0.04 kPa per g m^{-2} biomass.

[48] The ability of vegetation to stabilize river banks is partially dependent on scale: Not only is the size of vegetation relative to the watercourse important but also the absolute size of the vegetation. Vegetation stabilization tends to be more effective along relatively small water courses [e.g., *Nanson and Hickin*, 1986]. Large uprooted trees can serve to stabilize banks along large rivers, but on smaller streams, the same trees can cause acceleration of the water flow that results in local bank erosion [*Thorne*, 1982].

[49] Riparian vegetation can also have a destabilizing effect on stream banks by adding surcharge or increasing infiltration through root macropores [e.g., *Abernethy and Rutherfurd*, 1998; *Simon and Collison*, 2002]. The effects of large wood in a channel can also alter the flow field, thus influencing bank erosion rates, channel width, and depth [e.g., *Zimmerman et al.*, 1967; *Gurnell*, 1997; *Brooks and Brierley*, 2002].

4.3. Erosion and Sedimentation Processes in the Floodplain

[50] Although it is recognized that over-bank flow affects depositional and erosional patterns on a floodplain, little is known about the precise influence of vegetational factors on sediment dynamics [*Steiger et al.*, *Steiger et al.*, 2001a; *McKenney et al.*, 1995; *Lopez and Garcia*, 1998; *Nicholas and Walling*, 1998; *Nicholas and Mitchell*, 2003]. In general, sedimentation rates have been observed to increase when vegetation is present [e.g., *Nanson and Beach*, 1977; *Hickin*, 1974] and particle retention on leaves and on the bed have been measured in simulated submerged plant stands [*Pluntke and Kozerski*, 2003]. Sedimentation rates also depend on the distance from the river, flood duration, and tree diameter [e.g., *Steiger et al.*, 2001b, 2001a]. Field evidence also indicates differences in sedimentation rates between natural riparian woodland and plantations [*Steiger et al.*, 2001a].

[51] The rate (discharge) of sediment deposition, Q_d, can be modeled in a simplified way as the sum of three terms: the gravitational term, the sediment trapped by vegetation, and the organic deposition [*D'Alpaos and Lanzoni*, 2006]. The last two terms have been modeled experimentally, and specifically, Q_{dt}, the sediment trapped by vegetation, has been modeled following an experimental approach by *Palmer et al.* [2004] as $Q_{dt}=C_0 u \eta d n_v h_v$, where η is a rate of sediment entrapment, d is stem diameter, n_v is the number of stems per unit area, and h_v is the mean stem height.

[52] The erosion process is generally modeled to occur when shear stresses are greater than a critical shear stress, even if this approach is debated. Eroded sediment discharge Q_e can be expressed according to *Collins et al.* [2004] and *D'Alpaos and Lanzoni* [2006]

$$\begin{aligned} Q_e &= Q_{e0}\tfrac{\tau_b-\tau_c}{\tau_c} && \text{if } \tau_b > \tau_c \\ Q_e &= 0 && \text{if } \tau_b \leq \tau_c, \end{aligned} \tag{10}$$

where τ_b is the tangential shear stress at the bed, τ_c is the critical shear stress, and Q_{e0} is an empirical rate of erosion. The tangential shear stresses, τ_b, is usually evaluated by multiplying the total shear stress by an empirical factor which depends on vegetation [*Samani and Kouwen*, 2002; *Smith*, 2004; *Baptist*, 2005].

[53] Reference must be made to the work by *Wu et al.* [2005], who proposed some formulations both for emergent and submerged vegetation. According to *Wu et al.* [2005], if the vegetation is emergent

$$\tau_b = \frac{\rho g n^2}{R_s^{1/3}}|\overline{U}|U, \qquad R_s = \frac{h \cdot b_v}{2h + b_v}, \tag{11a,b}$$

where b_v is the spacing between plants, and n is the Manning coefficient (thus assuming uniform flow). If the vegetation is submerged

$$\tau_b = \rho C_{fu} U_v^2 + \rho C_{fs}(U - U_v)^2 \tag{12}$$

$$R_s = \frac{h_v}{h}\frac{h_v b_v}{2h_v + b_v} + \frac{h - h_v}{h}(h - h_v), \tag{13}$$

where C_{fu} and C_{fs} are the friction coefficients on the channel bed and at the top of the vegetation elements, U is the average velocity in the water column above the vegetation, and U_v is the apparent velocity between the vegetation, as defined by *Stone and Shen* [2002].

[54] Once the tangential shear stress at the bed is computed, an estimation of the critical shear stress, τ_c is needed. Estimated values of critical shear stress τ_c are between 20 and 200 Pa [*Collins et al.*, 2004]. The models by *Collins et al.* [2004] and *Pollen and Simon* [2005] incorporate the increment of shear stress provided by roots.

[55] From a theoretical viewpoint, suspended sediment transport is usually modeled as a convection-diffusion process [e.g., *James*, 1986]. The general formulation, in unsteady conditions, is

$$\frac{\partial C}{\partial t} + \boldsymbol{u} \cdot \nabla C - w_s \frac{\partial C}{\partial z} = \nabla(\boldsymbol{\epsilon} \nabla C) \tag{14}$$

where C is the depth-averaged concentration of suspended sediment, $\{x, y, z\}$ are the longitudinal, transversal, and vertical coordinates, $\boldsymbol{u} \equiv \{u, v, w\}$ is the corresponding velocity vector, $\boldsymbol{\epsilon} \equiv \{\epsilon_x, \epsilon_y, \epsilon_z\}$ is the local diffusivity vector, w_s is the fall velocity of suspended sediment, and ∇ is the gradient operator.

[56] The numerical solution of equation (14) is onerous, and three-dimensional models are very complex [e.g., *Temmerman et al.*, 2005]. However, when a straight channel with a steady, longitudinally uniform flow is considered, two-dimensional models can be used [e.g., *James*, 1986; *Ikeda et al.*, 1991; *Nicholas and Walling*, 1998; *Tsujimoto*, 1999; *Wu et al.*, 2005]. In these models, only the depth-averaged vertical diffusivity $\bar{\epsilon}_z$ and the depth-averaged transverse diffusivity $\bar{\epsilon}_y$ are taken into account [*James*, 1986; *Ikeda et al.*, 1991]. These diffusivities can be modeled as indicated below.

[57] Vertical depth-averaged diffusivity for sediments without vegetation, $\bar{\epsilon}_z$, can be estimated by means of the relationship $\bar{\epsilon}_z = \beta \bar{\epsilon}_w$, where $\bar{\epsilon}_w$ is the water diffusivity [*James*, 1986] and $\beta \leq 1$. In the presence of emergent vegetation, vertical diffusivity has been estimated by *Elliott* [2000] from laboratory experiments and varies with velocity, slope, and flow depth.

[58] *Nepf* [1999] experimentally investigated transversal depth-averaged diffusivity in flows through arrays of cylindrical rods. She found that transversal diffusivity, $\bar{\epsilon}_y$, varies with the stem characteristics and flow velocity according to

$$\frac{\bar{\epsilon}_y}{Ud} = \alpha (C_d A d)^{(1/3)} + \left(\frac{\beta^2}{2}\right) A d, \tag{15}$$

where U is the mean flow velocity, d is the cylinder diameter, β and α are scale factors, C_d is the drag coefficient, and A is the projected plant area per unit volume. Other experimental results have instead shown that transversal diffusivity within stems of emergent vegetation is independent of stem density and flow depth [*Sharpe and James*, 2006].

[59] Some formulae derived from empirical data, such as the ones proposed by *James* [1986] and by *Ikeda et al.* [1991], model the transversal depth-averaged diffusivity, $\bar{\epsilon}_y$. Finally, *Nicholas and Walling* [1998] used a transport model where $\bar{\epsilon}_y = \bar{\epsilon}_z$. The diffusivity coefficient, in this case, is modeled using the standard relationship [*Pizzuto*, 1987] $\bar{\epsilon} = Chu_*$, with $C = 0.13$ after *Fisher et al.* [1979], and where h is the water depth and u_* the shear velocity.

4.4. River Morphology

[60] The influence of bank and bed vegetation on channel shape (width and depth) has been investigated in several studies [e.g., *Andrews*, 1984; *Hey and Thorne*, 1986b; *Huang and Nanson*, 1997; *Williams and Wolman*, 1984], and distinct differences in channel dimensions have been observed. One way of synthesizing these important empirical findings is to refer to the classical hydraulic geometry relations proposed by *Leopold and Wolman* [1957], which relate channel width (W) and depth (D) to the dominant discharge (Q) as

$$W = aQ^b, \qquad D = cQ^f, \tag{16a,b}$$

where the average value of the exponents falls frequently in the ranges b = 0.4–0.5 and f = 0.3–0.4. Some authors (see Table 4) have shown that the coefficients of the power laws (16) depend significantly on bank vegetation. For instance,

TABLE 4. Hydraulic Geometry Coefficients and Exponents in the Presence of Different Types of Riparian Vegetation[a]

Reference	Vegetation Type	Coefficients	Notes
Andrews [1984]	dense grass cover	$a = 3.6$, $b = 0.5$ $c = 0.491$, $f = 0.370$	The coefficients refer to nondimensional variables.
	sparse grass cover	$a = 4.1$, $b = 0.5$ $c = 0.485$, $f = 0.377$	The coefficients refer to nondimensional variables.
Hey and Thorne [1986b]	grass with no trees	$a = 4.33$, $b = 0.5$ $c = 0.33$, $f = 0.35$	
	1–5% tree/shrub cover	$a = 3.33$, $b = 0.5$ $c = 0.33$, $f = 0.35$	
	5–50% tree/shrub cover	$a = 2.73$, $b = 0.5$ $c = 0.33$, $f = 0.35$	
	> 50% tree/shrub cover	$a = 2.34$, $b = 0.5$ $c = 0.33$, $f = 0.35$	
Huang and Nanson [1997]	gravel channels, dense trees	$a = 1.8$, $b = 0.5$ $c = 0.64$, $f = 0.3$	Banks are lined by trees, and no vegetation is on the channel bed.
	gravel channels, sparse trees	$a = 2.9$, $b = 0.5$ $c = 0.34$, $f = 0.3$	
	sand channels	$a = 25.252 \cdot n^{0.709}$, $b = 0.5$ $c = 0.059 \cdot n^{-0.804}$, $f = 0.2$	Banks are lined by trees, and beds are covered with willows and shrubs.

[a]Modified from *Huang and Nanson* [1997].

Huang and Nanson [1997] observed that the coefficients a and c were equal to 2.9 and 0.34, respectively, for sparsely vegetated and non-tree-lined banks, and equal to 1.9 and 0.64 when densely tree-lined banks were considered. They also observed that the exponents b and f seemed less sensitive to the presence of riparian vegetation.

[61] A mathematical model on the effects of vegetation on channel width and depth in a gravel river was proposed by *Ikeda and Izumi* [1990]. The model predicts the depth at the center of the channel, D_c, as

$$D_c = \frac{0.0306}{\Phi_j^2} R_s m^{0.0933} d_{50} S^{-1}, \qquad (17)$$

where Φ_j is the dimensionless depth-averaged fluid velocity which depends on the vegetation density, R_s is the submerged specific gravity of the sediment, m is a parameter (usually equal to 2 for natural gravel rivers), and S is the channel slope. *Ikeda and Izumi* [1990] also offered an analytical expression to compute the width of a channel with bank vegetation. Their model indicates that vegetation density can increase channel depth and decrease channel width. For example, the dependence of channel width on vegetation density is illustrated in Figure 9.

[62] Vegetation has also been shown to impact on channel width along meandering rivers, where it reduces erosion and induces bank accretion [*Beeson and Doyle*, 1995; *Eschner et al.*, 1983]. However, vegetation does not always induce channel narrowing. For example, when bed vegetation is also present, an increase in bed roughness can induce channel widening, due to the deflection of the flow onto the banks [*Hey and Thorne*, 1986b].

[63] Field investigations have not only identified the significance of vegetation for channel morphology, but they have also revealed wide variations in the magnitude and nature of that response [e.g., *Trimble*, 1997]. For example, *Mackin* [1956] observed that the channel pattern of the Wood River changed with bank vegetation: The river braided where the valley floor was a prairie but began to meander where it entered forest vegetation. *Bertoldi et al.* [2011a] showed that the entire morphology of the braided Tagliamento River changed as the riparian vegetation cover on the braid bars increased so that there was a systematic shift in the skewness and kurtosis of the elevation frequency distribution.

[64] There are many examples of channel change in braided rivers associated with the influence of vegetation. Some examples include research by *Tal et al.* [2004] along the Waitaki River, New Zealand [*Tal et al.*, 2004], in the Rogativa catchment, Spain [*Boix-Fayos et al.*, 2007], on Slesse Creek, USA [*Millar*, 2000], and the Sutsunai River, Japan [*Jang and Shimizu*, 2007]. Laboratory experiments have also provided perspectives on the impact of vegetation on channel morphology, including the research by *Gran and Paola* [2001] and, more recently, by *Coulthard* [2005], *Jang and Shimizu* [2007], *Tal and Paola* [2007], and *Perona et al.* [2012]. *Gran and Paola* [2001], working at the St. Anthony Falls Laboratory, USA, used a fixed dis-

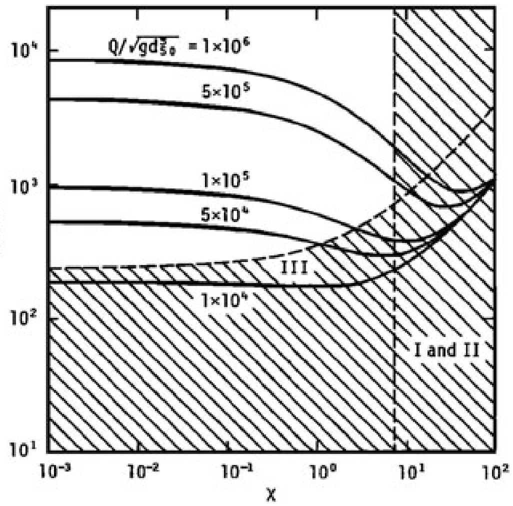

Figure 9. Width, B, of the channel as a function of vegetation density, χ, and discharge, Q, in dimensionless form. The hatched area indicates the region where the analysis is not applicable [from *Ikeda and Izumi*, 1990].

charge, sediment supply rate and grain size to develop a braided channel morphology and then applied alfalfa seeds to the morphology. Following germination and growth of the seedlings, they reintroduced the preseeding discharge of water and sediment. They showed over a number of experimental runs that increasing densities of vegetation combined with the same water and sediment discharge increased bank stability resulting in fewer, narrower, deeper, and less mobile channels. *Tal et al.* [2004] extended this work by allowing the flow to vary and investigating how the impact of vegetation on braid morphology varied with different flood inter-arrival times. They also showed that the braiding index (BI) decreased with increasing vegetation density. Evaluation of the influence of flooding on braided channels has recently been revisited by *Perona et al.* [2012] working at the Total Environment Simulator, Hull, UK. For the first time, they evaluated vegetation growth under periodic flood disturbances of constant magnitude. *Perona et al.* [2012] forced the biological and hydrological processes to interact and studied the related time scales in order to shed light on the role of flood disturbances in selecting the component of the biomass that has a higher chance of survival in relation to its growth stage.

[65] The above studies all used experimental conditions that were relevant to temperate river systems. The dynamics of vegetation along ephemeral streams has been investigated by *Coulthard* [2005], who obtained opposing results to those obtained in the experiments by *Gran and Paola* [2001] and *Tal and Paola* [2007]. He observed that the braiding index increased with vegetation density. Vegetation in ephemeral rivers is less dense and often deeply rooted due to lower water availability, and so it tends to increase the BI and encourage bar development.

5. CONCEPTUAL AND SEMIQUANTITATIVE MODELS

[66] In section 3, we referred to the way in which fluvial processes interact with vegetation to create landforms or patches at different elevations (inundation frequencies) within the riparian zone. We described how the character and turnover of this natural riparian patch mosaic varies along rivers of different planform style located in different environmental settings.

[67] In this section, we explore concepts that link vegetation and river morphodynamics. First, we review broad associations that have been recognized between riparian vegetation and the planform style of river systems (section 5.1). We then focus on the river margin zone of close interaction between vegetation and physical processes (section 5.2), and the vegetated landforms that characterize this zone along rivers of different planform style (section 5.3).

5.1. Vegetation and Channel Planform Style

[68] In their analysis of rivers of different style within the Pacific Coastal Forest of the northwest U.S., *Beechie et al.* [2006] found that the turnover of vegetated patches increased from single-thread straight, through meandering and island-braided to bar-braided planforms. They also found that channels less than 15–20 m in width showed negligible bank movement. They attributed this to the relatively low bank height of narrow channels in comparison with tree rooting depth and thus the potential for bank erosion below rooting depth in larger channels.

[69] The effect of vegetation on river bank strength and floodplain stability is not only a crucial ingredient in controlling bank erosion but also in establishing and maintaining single-thread channel patterns in the field and laboratory [*Gran and Paola*, 2001; *Brooks and Brierley*, 2002; *Braudrick et al.*, 2009; *Crosato and Saleh*, 2011] and in moderating rates of meander migration. Various theoretical and empirical analyses support the importance of bank reinforcement by vegetation for defining threshold conditions between single-thread and braided channel styles. For example, *Millar* [2000] devised a theoretical meandering-braiding transition for gravel bed rivers, which incorporated bank reinforcement by vegetation, and *Eaton et al.* [2010] showed that bank strength has a distinct impact on thresholds between braided, anabranching, and single-thread channel styles when these are explored in relation to gradients of dimensionless discharge and slope. Field evidence supports the critical role of vegetation in channel narrowing, floodplain aggradation and reinforcement, and thus facilitation of a transition from braided or wandering to single-thread channel forms. This has been particularly evident where river corridors have been invaded by *Tamarix* species (salt cedar) in southwest U.S. [*Birken and Cooper*, 2006; *Cadol et al.*, 2011; *Dean and Schmidt*, 2011]. Conversely, overgrazing or clearance of riparian/floodplain shrub vegetation has resulted in channel incision and widening [*Stromsoe and Callow*, 2012], and floodplain unraveling and conversion from single-thread to braided planforms [*Smith*, 2004]. Rates of meander migration also have been found to be notably higher across agricultural floodplains in comparison with forested floodplains [*Micheli et al.*, 2004]. In contrast, in ephemeral streams in semiarid environments, colonization of the river bed by shrubs and trees can lead to channel widening and the creation of anabranching systems as the trees displace flood flows laterally [*Wende and Nanson*, 1998; *Tooth and Nanson*, 2000; *Pietsch and Nanson*, 2011].

[70] In summary, the biomechanical properties of riparian vegetation that underpin bank development, stabilization, and reinforcement play an important role in maintaining particular planform styles, controlling channel margin dynamics of rivers of a particular style, and defining threshold conditions at style transitions. Therefore, field measurements of these biomechanical properties [e.g., *Docker and Hubble*, 2008; *Hopkinson and Wynn*, 2009; *Pollen-Bankhead and Simon*, 2010; *Pollen-Bankhead et al.*, 2011] provide an important contribution to the quantitative models described in section 6.

5.2. Force and Resistance at the Interface Between Riparian Vegetation and Fluvial Disturbance

[71] The strength of interactions between plants and fluvial processes along humid temperate rivers shifts with the

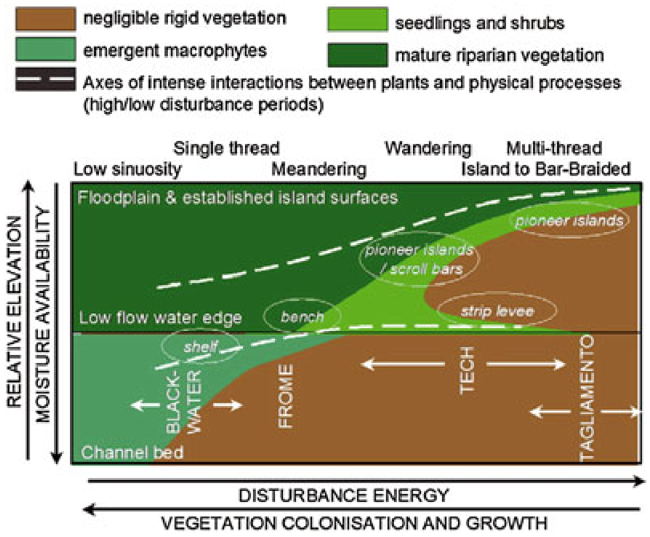

Figure 10. Vegetated landforms (white ellipses) located in zones of intense interaction between plants and physical processes (white dashed lines) found on four rivers of different size, energy, and planform [from *Gurnell et al.*, 2012].

time-varying intensity of fluvial processes and also with the time- and space-varying colonization and growth performance of the vegetation [*Corenblit et al.*, 2007, 2011; *Gurnell et al.*, 2012]. As a result, a temporally and spatially shifting zone of intense interaction is located along the margin between the vegetation-dominated floodplain and the physical process dominated low-flow river channel. The size and character of this interaction zone varies among rivers of different energy and style.

[72] *Gurnell et al.* [2012] suggested that within this zone of intense interaction, particular aquatic and riparian plant species and large wood pieces drive the construction of vegetated landforms and also protect established landforms from destruction. In this context, the plant species and large wood pieces act as ecosystem engineers, providing the construction and reinforcement capabilities necessary to create particular landforms associated with different river planform styles, and thus facilitate colonization of these landforms by other plant species. Based on field observations of two single-thread (Blackwater, Frome), one wandering (Tech), and one braided river (Tagliamento), *Gurnell et al.* [2012] identified some examples of pioneer landforms created by engineering plants (Figure 10). Section 5.3 introduces landforms that have been associated with plants and wood in the literature and considers how these operate within the intense interaction zone between vegetation and physical processes in different styles of river system.

5.3. Vegetated Landforms

[73] There are numerous fluvial landforms that are constructed in association with dead or living vegetation. As illustrated by the examples described by *Gurnell et al.* [2012], particular vegetated landforms may characterize rivers of particular size, energy, and style. In this section, we review the landforms associated with (i) bankside trees, (ii) dead wood, (iii) living/sprouting wood, and (iv) aquatic plants and peat.

[74] Riparian trees interact with fluvial processes to form distinctive landforms such as tree buttresses and root-reinforced slumped blocks along river margins. These landforms can persist, maintaining the bank edge position for long periods and inducing scour and pool formation on the adjacent river bed [*Davis and Gregory*, 1994; *Rutherfurd and Grove*, 2004; *Pizzuto et al.*, 2010]. Slumped blocks reinforced by the roots of herbaceous vegetation can protect banks in a similar manner [*Parker et al.*, 2010]. All of these features act to slow bank retreat and thus affect channel migration rates as well as channel cross profiles.

[75] In rivers bordered by tree species that do not regenerate vegetatively, large wood is central to the creation of vegetated landforms. Numerous geomorphological studies have described the quantities of large wood found in different river systems and the wood structures that are created, but research on the Queets River, Oregon, USA, has resulted in the most integrated overview of the geomorphological functioning of wood within river systems. On this river system, the riparian tree species produce wood that decays slowly and so wood landforms are long-lived. *Latterell et al.* [2006] demonstrated the very close relationship between elements of the river and floodplain habitat mosaic and large wood, whereas *Abbe and Montgomery* [2003] described and classified wood accumulations according to their position and geomorphological function in the Queets River channel network (Figure 11). *Abbe and Montgomery* [2003] observed that in small streams, wood features resulted directly from tree fall and deposition of wood pieces into the river channel, including the formation of log steps or jams extending across the channel width. Such features trap organic and mineral sediment and so have a significant effect on local scour and fill of the channel profile as well as marginal vegetation development. In circumstances where the wood pieces are sufficiently small relative to channel width, significant movement of wood can occur, allowing bench jams to form with key pieces oblique or parallel to the flow. Sediment and smaller wood pieces accumulate behind large key pieces, forming distinct benches along the channel margin that gradually aggrade, creating local floodplain pockets.

[76] Further downstream, wood piece length is predominantly smaller relative to channel width, and large-wood jams, called valley jams, may accumulate across the entire channel and onto the floodplain. These can trap sediment and lead to a variety of geomorphological changes. They can evolve into large island-like structures; induce bank erosion through flow deflection; induce avulsions (i.e., the cutting of new river channels by diverted water), dissecting islands from the preexisting floodplain; and become attached to and incorporated into the floodplain, forming erosion-resistant floodplain hardspots. Smaller flow deflection jams may also accumulate at the channel margins around in situ toppled trees. These may develop into sizeable structures that protect the local channel bank from erosion, trap wood delivered from upstream, and deflect flow toward the opposite bank inducing erosion and channel widening.

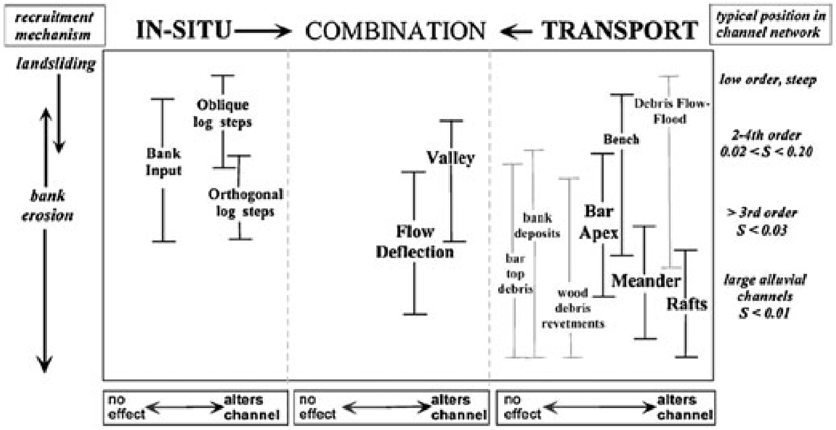

Figure 11. Wood accumulation types observed within the drainage network of the Queets River [from *Abbe and Montgomery*, 2003]. Copyright (2003), with permission from Elsevier.

[77] Where the channel planform supports the development of midchannel bars, bar-apex jams often develop. These are jams of large wood that snag on the upstream face of midchannel bars, causing flow divergence and downstream accumulation of plumes of finer sediment that can aggrade and support vegetation colonization and the development of vegetated patches and larger island features. Similarly, meander jams may form on point- and side-bars, modifying channel curvature, wood and sediment accumulation, and vegetation development. In some cases, wood is incorporated within sedimentary structures forming wood-cored scroll bars [e.g., *Nanson*, 1983] and wood-covered counterpoint bars [e.g., *Hickin*, 1984], which may also result in collapse features when the buried wood eventually decays.

[78] In addition to these major wood jam features, *Abbe and Montgomery* [2003] also noted the importance of relatively small pieces and accumulations of wood, which can cause blockages within complex multi-thread river sections, contributing to smaller scale avulsions and revegetation of blocked channels within islands and floodplains and across complex, anastomosing channel sections. They also refer to the development of enormous downstream rafts of wood. While no examples of these were found during field investigation of the Queets River, such rafts are known to have occurred historically on large forested river systems. The rafts were the result of the buildup of vast quantities of wood pieces that eventually blocked large river channels and floodplains.

[79] Thus, large wood appears to feed a hierarchy of landforms in rivers of different size and morphology. All of these landforms are associated with deposition and erosion of sediment and wood around wood key pieces, leading to the initiation of stable patches that can become vegetated to form benches, islands, and floodplains. As the river planform evolves, large accumulations of wood can become buried within the floodplain [e.g., *Arseneault et al.*, 2007]. Within the Queets system, these wood structures, formed by past fluvial activity, persist as erosion-resistant hard points in the floodplain [*Montgomery and Abbe*, 2006; *Collins et al.*, 2012]. Because of their long-term erosion resistance, they support the oldest patches of floodplain forest and thus provide the source of the largest key pieces for new wood accumulations, driving a "floodplain large-wood cycle" [see *Collins et al.*, 2012] (Figure 12).

[80] On rivers that support riparian tree species capable of resprouting from wood pieces and entire uprooted trees, landforms associated with both dead and living wood are observed. However, many of the tree species that regenerate freely in this way also produce wood that decays rapidly, conveying a greater relative importance and longevity to landforms associated with regenerating wood pieces.

[81] Benches are landforms that are widely observed in association with vegetation along rivers of varying size and planform. Bench development has been observed along low-flow channel margins following sediment accumulation around sprouting wood, tree roots extending into the

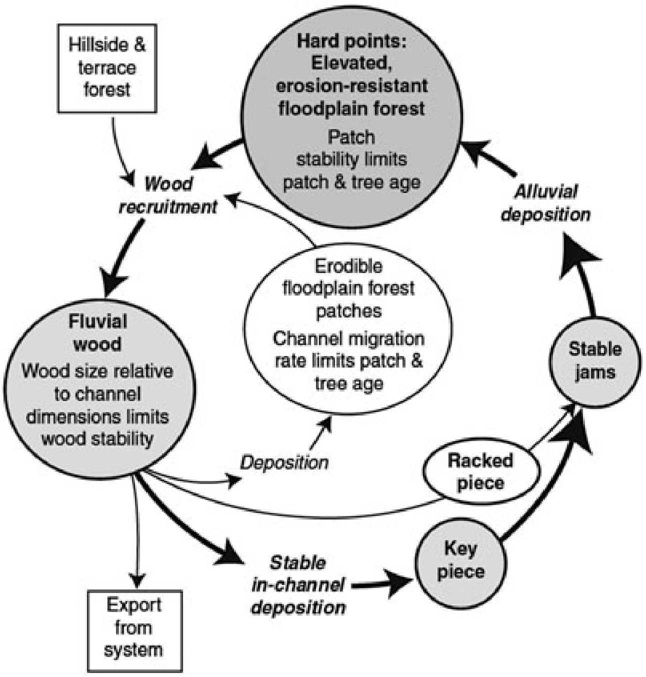

Figure 12. The floodplain large-wood cycle [from *Collins et al.*, 2012]. Copyright (2012), with permission from Elsevier.

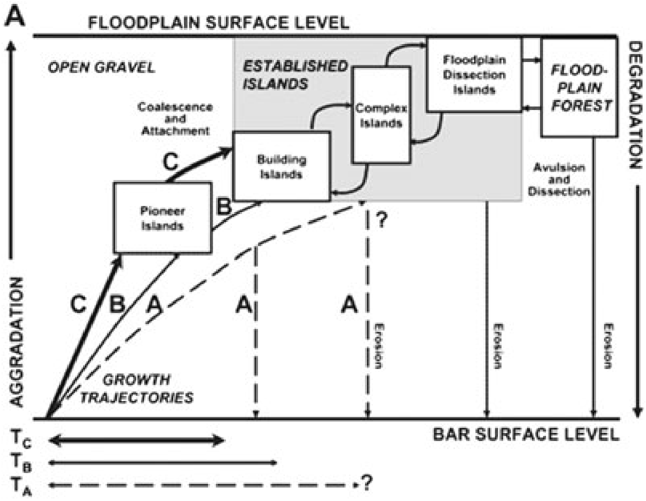

Figure 13. Conceptual model of island development, illustrating the differing impacts of vegetation dominated by three growth trajectories on open bar surfaces (A, dispersed seedlings growing from bar gravels; B, seedlings germinating in fine sediments trapped behind large wood accumulations; C, regeneration from living wood pieces and whole uprooted trees) that, under the same environmental conditions, are associated with three different initial growth rates (TA, TB, TC) [from *Gurnell and Petts*, 2006].

channel, and in association with rapid tree colonization [e.g., *Rowntree and Dollar*, 1999; *Erskine et al.*, 2009; *Cadol et al.*, 2011]. Bench development has also been observed as a key process in the planform and cross-profile recovery of channelized rivers [*Hupp and Simon*, 1991; *Rhoads and Massey*, 2012]. Bench development results either in channel narrowing or in erosion of the opposite bank and an increase in channel sinuosity. Ultimately, the bench surface aggrades, resulting in local extension of the floodplain.

[82] On larger rivers, particular landforms emerge in association with the interaction between living wood and fluvial processes according to river planform. Research on the Tagliamento River, Italy, has produced the most integrated overview of the functioning of living wood in river landform development. Initially, *Gurnell et al.* [2001] proposed a model of island development along this river system (Figure 13) that was particularly concerned with braided river reaches and the way in which the different rates of early plant growth from different propagule types (seedlings, sprouting wood pieces) on gravel bars affected the likelihood of islands developing under particular fluvial disturbance regimes. In subsequent papers, other influences on the rate of vegetation growth and the fluvial disturbance regime that underpin the model have been considered, including the effect of surface water-groundwater interactions on plant growth rates, longitudinal changes in stream power within narrowing and widening reaches on vegetation disturbance and removal [*Gurnell and Petts*, 2006], and the broader significance of these factors when rivers are close to threshold conditions between river styles [*Gurnell et al.*, 2009].

[83] All of these concepts start with the initiation of pioneer landforms on open river bar surfaces. Field observations of the rates of growth of seedlings on open gravel bar surfaces and on finer sediments in the lee of wood accumulations, and regeneration from living wood (trajectories A, B, and C, respectively, Figure 13) suggest that regeneration from living wood pieces (i.e., wood pieces capable of sprouting) is the only mechanism by which vegetation can establish sufficiently rapidly in rivers where fluvial disturbances are relatively strong and frequent. Regeneration from living wood pieces gives rise to the development of pioneer islands on open bar surfaces [*Edwards et al.*, 1999]. Similar pioneer features have been observed on river systems in South Africa and the U.S. [e.g., *Pettit et al.*, 2006; *Pettit and Naiman*, 2006; *Rood et al.*, 2011]. If the pioneer islands are sufficiently closely spaced and survive for long enough, they enlarge and coalesce by trapping more sediment and propagules so that on the Tagliamento they form large building islands on gravel bar surfaces [*Gurnell et al.*, 2005]. This process maintains a dynamic island-braided morphology that is distinctly different from the morphology of nearby bar-braided reaches [*Bertoldi et al.*, 2011a]. The island-braided morphology develops in reaches where vegetation regeneration proceeds at a sufficiently rapid rate to interact effectively with the flood disturbance regime. *Gurnell and Petts* [2006] hypothesized that tree growth rate was not only dependent on propagule type (i.e., regeneration from living wood pieces) and species but also on groundwater conditions in the alluvial aquifer. Therefore, they hypothesized that in a specific environmental context, there would be an optimum combination of depth to water table (induced by river active width and alluvial sediment caliber) and stream power (induced by river active width and gradient) to maintain high vegetation growth rates that could support a free interaction with disturbance events and a maximum but dynamic cover of building islands. In unconfined reaches, river active width is maintained by the forested floodplain, and so a second type of island, called a floodplain dissection island, is created by avulsions from the main channel during floods. *Gurnell et al.* [2001] hypothesized that once created, floodplain dissection islands could be modified by pioneer and building island development, and similarly, building islands could become incorporated into the floodplain. Thus, building, complex, and floodplain dissection islands could coexist in the same reach, but their form and tree age structure would be different. Building islands tend to be curved in their vertical long and cross profiles, whereas floodplain dissection islands tend to be more tabular with sharper and steeper margins. The age structure of building islands tends to be graded with the youngest shrubs and trees at the upstream and downstream ends and the oldest trees toward the upstream end of the island. In contrast, floodplain dissection islands have a more random, patchy age structure but very few young trees. Complex islands show intermediate morphology and tree age structure [*Gurnell et al.*, 2001].

[84] In wandering and meandering reaches, similar regeneration processes operate, but living wood pieces are often incorporated into scroll bars on the inside of meander bends or along the margins of some straighter reaches rather than being deposited on open bar surfaces [*Gurnell and Petts*,

2006]. As in the case of dead wood, whole trees and wood pieces are incorporated into these elongated sediment ridges during their deposition by flood events. The living wood pieces then sprout to create elongated ridges of shrubs that aggrade and may also funnel flows leading to bar surface scour between the ridges during subsequent floods [e.g., *McKenney et al.*, 1995]. Ridges are built by each succeeding large flood, leading to the development of parallel ridges supporting trees of different ages, particularly on the inner bank of meander bends. The ridges gradually aggrade to floodplain level, and the channel migrates through corresponding erosion of the opposite bank. It is possible that the scoured areas between ridges could be activated during heavy flooding, potentially triggering the formation of cutoffs.

[85] Lastly, in periods without major floods, levée-like features (i.e., elongate ridges of mud and/or silt that are deposited next to the river) have been observed to develop around dense stands of riparian tree seedlings adjacent to low-flow channels along the Tagliamento [*Gurnell et al.*, 2012]. This process is similar to the riparian tree recruitment process described for many North American rivers (see section 3), whereby seedlings germinate in bands on gravel bars where there is an optimum combination of moist exposed gravel, gently falling water table, and low flood disturbance during initial vegetation establishment. On the Tagliamento, this process was observed to lead to the construction of fine sediment levées up to 60 cm high, reinforced by the root systems of a dense cover of riparian tree seedlings. These features developed over 3 years during which there were no bankfull floods. Similar features have been observed on the River Tech, France [*Gurnell et al.*, 2012], and are probably characteristic of other braided and wandering rivers during periods without major flow disturbance events and where there is sufficient suspended load to support strip aggradation.

[86] The last group of vegetated landforms are found in very low energy river systems. In these systems, aquatic plants are able to grow to high abundances [*Gurnell et al.*, 2010]. Stands of emergent aquatic plants, in particular, can retain and reinforce fine sediments to build shelf, bench, and island features within low-energy river systems [e.g., *Liffen et al.*, 2011; *Gurnell et al.*, 2012]. In extremely low energy environments, peat can accumulate to form river banks [e.g., *Gradzinski et al.*, 2003] or to completely line river channels [e.g., *Smith and Prez-Arlucea*, 2004; *Watters and Stanley*, 2007; *Nanson et al.*, 2010]. The form and dimensions of these channels is constrained by the properties of the peat and aquatic plants that form the banks, which are in turn maintained by a near-surface water table within the banks. These channels possess a characteristically low width:depth ratio [*Watters and Stanley*, 2007; *Nanson et al.*, *Nanson et al.*]. The anastomosing Narew River system, Poland [*Gradzinski et al.*, 2003], is a well-documented example of a lowland, low-energy anastomosing system developed in peat and heavily influenced by aquatic plant growth. In this system, channels have peat banks and a sand bed. Aquatic plants interact with the fine bed sediment to build a variety of bar and bench forms, including vegetated point, concave bank, side, linguoid and midchannel bars, and also channel plugs. Vegetation forms an important part of all of these features, providing sediment reinforcement and also a substantial aboveground biomass, which can induce channel change and blockage.

[87] In conclusion, similar landforms and channel adjustment processes are initiated by dead and living vegetation across a spectrum of river energy and styles. In all cases, characteristic vegetated landforms occur at the interface between the active channel and the vegetated floodplain. These play a crucial role in maintaining characteristic morphodynamics and also in leading transitions between landform assemblages and river planform styles in time and space.

6. QUANTITATIVE MODELS

[88] In this section, we review the main quantitative models that have been proposed to describe the interactions between river morphodynamics and riparian vegetation dynamics. We consider models for multi- and single-thread rivers separately; however, first, we review the seminal work by *Millar* [2000] which concerned the effects of riparian vegetation on alluvial channel patterns and, in particular, on how vegetation can also induce changes in river morphology between braiding and meandering.

[89] *Leopold and Wolman*'s [1957] criterion is usually adopted to describe the transition between meandering and braided morphology

$$S^* = 0.013Q^{-0.44}, \tag{18}$$

where S^* is the transition slope that separates meandering from braided rivers and Q represents bankfull discharge. Although it is widely used, relation (18) does not always work well since it is based on a single discriminant function that fails to take into account uncertainty both in terms of the original measurements underpinning it and in bank resistance to erosion, which is an important factor for the transition between meandering and braiding rivers. A body of subsequent research has introduced sediment size as an additional important property that influences both bank and bed stability (for an overview, see *Church* [2002]), but vegetation is also able to increase the stability of bank sediments and so can be crucial for the type of morphology that is established (see section 5.1). The stabilizing effect of vegetation is taken into account in the model proposed by *Millar* [2000]:

$$S^* = 0.0002D_{50}^{0.61}\,\Phi'^{1.75}Q^{-0.25}, \tag{19}$$

where D_{50} is the median sediment diameter and Φ' is the bank friction angle.

[90] This transition criterion (equation (19)) has been tested with field data and incorporates the sensitivity of channel planform to changes in bank vegetation by means of different values of the friction angle ranging from $\Phi' = 40°$ for sparse vegetation to $\Phi' = 70°$ for dense vegetation. A planform stability diagram can be developed by plotting the

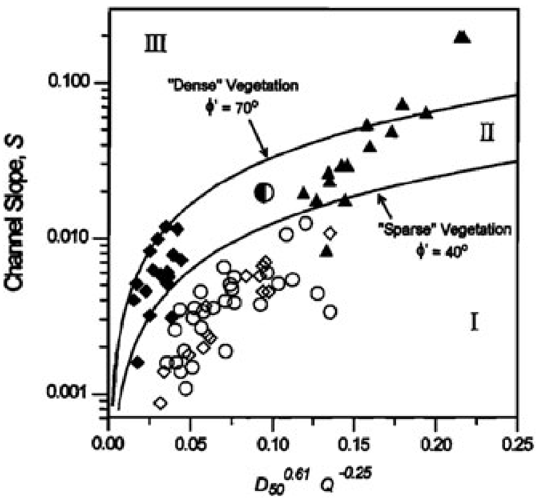

Figure 14. Planform stability diagram derived from the model proposed by *Millar* [2000], with superimposed data for a river with "sparse" vegetation (see equation (19)). The open symbols correspond to meandering rivers, while the solid symbols denote braided rivers. From *Millar* [2000].

slope S^* against $D_{50}^{0.61}Q^{-0.25}$, and three regions can be delimited, as shown in Figure 14. The rivers in region I "are predicted to be relatively insensitive to changes in riparian vegetation, and would develop a single-thread or meandering pattern irrespective of the bank vegetation density" [*Millar*, 2000, p. 1116]. The rivers in region II "are potentially the most sensitive to changes in the characteristics of bank vegetation" [*Millar*, 2000, p. 1116]. A wide and shallow braided channel would be expected to form where riparian vegetation is sparse, whereas meandering channels can only develop where riparian vegetation is dense and deeply rooted (i.e., high Φ'). A reduction in vegetation density, a change from deep to shallow rooted vegetation, or vegetation clearance is likely to lead to channel widening and potential morphogenesis to a braided channel. According to *Millar* [2000], the rivers in region III are likely to remain braided, irrespective of the riparian vegetation, because of their relatively high gradient.

6.1. Multi-Thread Channels

[91] Only a few quantitative mathematical models have been developed to simulate the impacts of flow on plants in river channels and their feedback effects in multi-thread channels [e.g., *Murray and Paola*, 2003; *Coulthard et al.*, 2007; *Jang and Shimizu*, 2007; *Benjankar et al.*, 2011]. They are all cellular automata models that have successfully been developed to model braiding morphogenesis. Only the models by *Murray and Paola* [2003] and *Coulthard et al.* [2007] consider the dynamic growth of vegetation and its feedbacks in the floodplain. *Benjankar et al.* [2011] provide a dynamic vegetation model where field data are included to represent the assumed critical values of stress of riparian vegetation species. However, floodplain morphodynamics are not dynamic since they are not updated with vegetation change.

[92] In the model developed by *Murray and Paola* [1997, 2003], vegetation roots influence bank erosion by decreasing the magnitude of lateral sediment export from a vegetated cell. Plants are destroyed when the sediment deposition rate or the erosion rate rises above a cutoff value for longer than a threshold time period. Some model results are shown in Figure 15. The numerical simulations have also allowed *Murray and Paola* [1997] to obtain a stability diagram that indicates whether a modeled river will exhibit a single- or multiple-channel pattern.

[93] Another model, CAESAR (Cellular Automaton Evolutionary Slope and River model), provides coupled information on the dynamics of the riparian system and floodplain morphodynamics by means of a cellular approach that represents a good compromise between speed and accuracy at useful time and space scales [*Coulthard et al.*, 2007]. The vegetation module describes dynamic growth by a linear growth model, with erosion resistance of riverbed surfaces (e.g., bar tops) increasing with vegetation development maturity until a maximum level is reached. Applications of this model demonstrate the key role of vegetation in braiding river morphodynamics.

[94] Finally, *Hooke et al.* [2005] developed a cellular automata model to simulate channel and vegetation dynamics in ephemeral streams in the Mediterranean region over decadal time scales with a monthly time step. Both erosion and deposition processes occur in each step, in association with flow events, while the growth of vegetation and evapotranspiration take place according to the weather conditions during the month. The model is quite sophisticated and incorporates both deterministic and stochastic process rules. In particular, vegetation has a major role in modulating the impact of floods and the extent of morphological change: erosion and deposition patterns are very sensitive to vegetation patterns, and a dense cover of shrubs or phreatophytes generally prevents erosion except when flow velocities are very high. When flow velocities are high, vegetation is destroyed and a new cycle of colonization restarts. For vegetation regeneration, germination is considered stochastic, and seeds germinate with a fixed probability. The model also takes into account changes due to plants that grow in neighboring cells.

6.2. Single-Thread Channels

[95] Several quantitative morphodynamic models of single-thread channels have been developed, especially for meandering rivers [e.g., *Ikeda et al.*, 1981; *Smith and McLean*, 1984; *Johannesson and Parker*, 1989; *Mosselman*, 1998; *Imran et al.*, 1999; *Zolezzi and Seminara*, 2001; *Seminara et al.*, 2001; *Camporeale et al.*, 2007]. Meandering rivers are very common in nature, and, due to their planimetric migration in the floodplain, they interact closely with human structures and influence the riparian ecosystem. They can therefore be important from both an engineering and environmental point of view. However, in spite of the evident influence of riparian vegetation on the meander migration rate [e.g., *Micheli et al.*, 2004], bio-morphodynamic models have only been proposed recently [e.g., *Brookes et al.*, 2000;

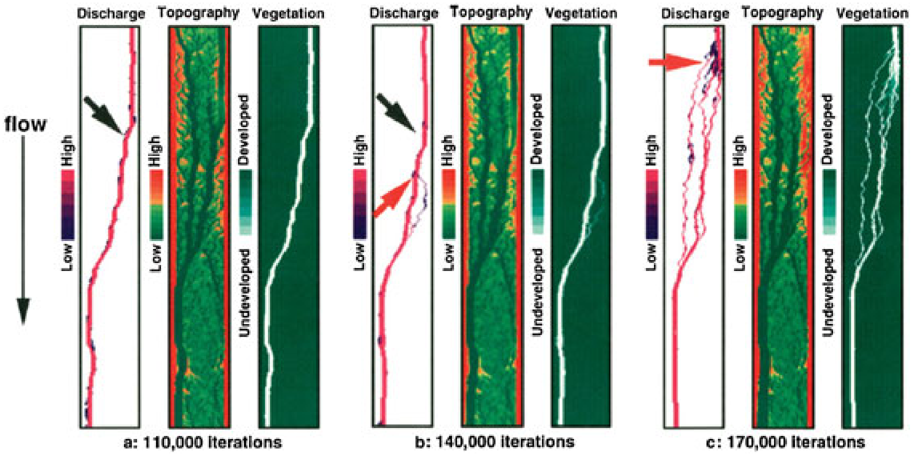

Figure 15. Output of the model developed by *Murray and Paola* [2003] with different river-vegetation time scales. (a) 110,000 iterations; (b) 140,000 iterations; and (c) 170,000 iterations. A slow migration of the channel, due to vegetation which increases bank strength, is visible comparing Figures 15a and 15b, which are separated by 30,000 iterations. More dynamic changes occur where the flow avulses over the banks and vegetation is destroyed. The black arrows in Figures 15a and 15b mark the location of minor channel migration. The red arrows in Figures 15b and 15c point out avulsions. From *Murray and Paola* [2003].

Baptist et al., 2004; *Van De Wiel and Darby*, 2004; *Baptist et al.*, 2005; *Hooke et al.*, 2005; *Larsen et al.*, 2006; *Perucca et al.*, 2006, 2007; *Benjankar et al.*, 2011; *Crosato and Saleh*, 2011].

[96] Different approaches to modeling single-thread rivers can be found in the literature: (i) models which take into account only the effects of vegetation on river morphology, (ii) models that take into account only the impact of the river on vegetation, and (iii) complete bio-morphodynamic models.

[97] For example, *Van De Wiel and Darby* [2004] developed a model where vegetation has only a passive role. This model considers the presence and density of vegetation but not vegetation temporal dynamics, i.e., its active role (see Figure 2). The geomorphological model is based on a two-dimensional depth-averaged model (mRIPA) of bed topography and bank erosion for single-thread meandering rivers [*Darby et al.*, 2002]. The effect of vegetation in the model is to alter both the stability of the banks, by increasing bank cohesion, and the flow field, by means of the drag coefficient. In the parametrization of the vegetation, all the trees are mature, identical, and static. Moreover, the vegetation is positioned in simple (and quite artificial) wide strips along the banks, parallel to the river, and extending from the bank toe to the floodplain. *Van De Wiel and Darby* [2004] show how vegetation is able to induce morphological changes in the channel bed and in the planform (bank retreat and total floodplain area loss).

[98] Another model which considers only static vegetation effects on the river has been proposed by *Larsen et al.* [2006]. The model was devised to evaluate the effects of different floodplain scenarios on the dynamics of the Sacramento River. *Larsen et al.* [2006] used the *Johannesson and Parker* [1989] meander migration model, which assumes that the local bank erosion is proportional to velocity according to an erodibility coefficient, whose value is varied for agricultural land and for natural vegetation. *Larsen et al.* [2006] produced 100 year forecasts under the influence of natural scenarios and scenarios constrained by erosion control measures (riprap) to provide some indication of the impact of management on meander dynamics. In particular, they observed that riprap and léeves set back less than one to three river widths from the channel, limit the formation of point bars and oxbow lakes, and hinder the maintenance of the corresponding plant communities.

[99] *Baptist et al.* [2004, 2005] proposed a modeling approach which incorporates the impact of hydrology on vegetation evolution, with vegetation development and succession controlled by four variables: (i) inundation duration, (ii) former land use, (iii) grazing intensity, and (iv) sedimentation rate. In this way, and within the limitations of the model, they demonstrated that the duration of floodplain inundation strongly influences vegetation types.

[100] Finally, *Perucca et al.* [2006, 2007] and *Crosato and Saleh* [2011] proposed two bio-geomorphological models. In the first, river-induced vegetation patterns are investigated but the active role of vegetation is not considered. The second model couples the dynamics of river morphology and riparian vegetation.

[101] The main effects of the river-induced processes on riparian vegetation can be summarized by three typical distributions of biomass densities along a river transect [*Perucca et al.*, 2006]. These biomass distributions (Figure 16) depend on the dominant hydrological mechanisms that affect riparian vegetation [e.g., *Fonda*, 1974; *Nanson and Beach*, 1977; *Bradley and Smith*, 1986]. A first typical distribution of biomass emerges when the water table depth is the main control on riparian vegetation growth and shows a maximum in biomass at the river bank and a decrease with distance from the channel edge (curve A in

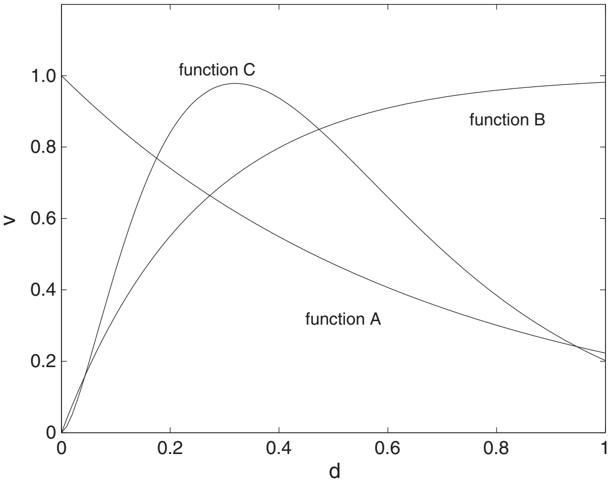

Figure 16. Example of (normalized) vegetation density functions A, B, and C, where d is the distance of a generic vegetation plot from the river bank.

Figure 16). The distribution is typical of semiarid regions, where the main water supply comes from the river [*Carr*, 1998], but it has also been observed in mild or humid climate zones [*Brooks and Brierley*, 2002]. If the destructive action of floods is the main factor affecting the distribution of riparian vegetation, a second form of density functions applies: biomass is smaller close to the river bank and increases with distance from the river margin (curve B in Figure 16) [*Bradley and Smith*, 1986]. Finally, the combined impact of the water table, sedimentation, and flooding is considered. In this case, the riparian vegetation close to the river banks is mainly influenced by flood disturbances, while vegetation far from the river suffers from a declining water table. As a consequence, riparian vegetation biomass reaches a maximum at a distance from the river margin before declining (curve C in Figure 16). A density function shaped in this way was observed by *Nanson and Beach* [1977] and analytically derived by *Camporeale and Ridolfi* [2007] (see section 7).

[102] When the river migrates, the position of vegetation relative to the river margin changes and riparian vegetation tends toward a stationary density value that corresponds to the actual distance from the river bank. This temporal evolution of biomass density is described by a logistic curve when the biomass tends to increase (e.g., the river becomes closer in the case of function A) or by an exponential decay when the biomass density tends to decrease. Thus, the planimetric evolution of a river and its riparian vegetation dynamics are coupled, and the riparian vegetation continuously changes in space and time forced by river migration. This latter feature has been evaluated using the physically based model proposed by *Zolezzi and Seminara* [2001], which gives the most accurate linear description of the flow field in a meandering river [*Camporeale et al.*, 2007].

[103] Figure 17 shows some results obtained from the numerical simulation of the model, illustrating the development of vegetation patterns due to river movement in the case where the temporal scale of vegetation evolution and the temporal scale of the river are comparable [*Perucca et al.*, 2006].

[104] In order to model the active role of vegetation, *Perucca et al.* [2007] introduced vegetation-dependent bank erodibility. This implies coupling between vegetation and river dynamics. As the river comes into contact with sites of different vegetation density or biomass during migration across the floodplain, different levels of bank erodibility influence river migration. According to *Ikeda et al.* [1981], the rate of meander migration, ξ, is generally taken to be proportional to the perturbation, u', of the flow field near the outer bank, with respect to the bulk velocity, by means an erodibility coefficient, E: $\xi = E \cdot u'$. For simplicity, *Perucca et al.* [2007] used a linear dependence of erodibility on dimensionless biomass, so that $E = E_0 + q \cdot v$, where E_0 is the erodibility of bare banks (i.e., $v = 0$), and $q < 0$ is the parameter that weights the dependence of erodibility on biomass density, v.

[105] Figure 17 illustrates the impact of introducing a linear variation in erodibility with vegetation density. The

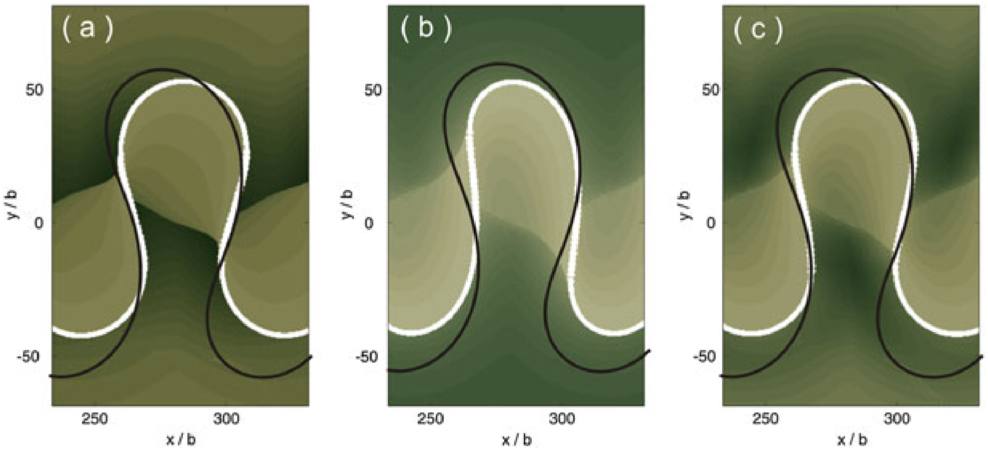

Figure 17. River planforms and corresponding vegetation patterns for transversal biomass distributions (a) function A, (b) function B, and (c) function C. The green intensity is proportional to the vegetation biomass. The black lines indicate the planform obtained assuming a constant erodibility [from *Perucca et al.*, 2007].

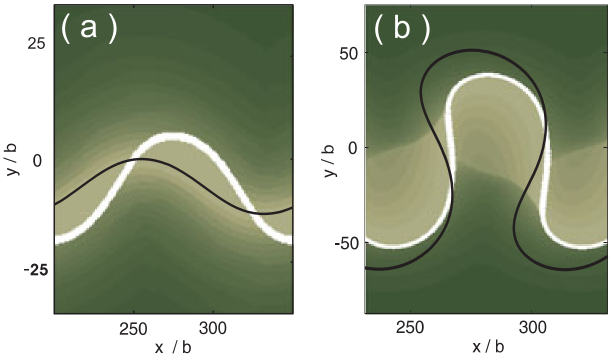

Figure 18. Two steps of river evolution with a vegetation density given by function B. The black lines indicate the planform obtained assuming a constant erodibility [from *Perucca et al.*, 2007].

remarkable differences between this simulation in comparison with a constant erodibility simulation demonstrates the degree to which meander shape depends on the vegetation density function. Another important aspect of the impact of vegetation dynamics on river evolution is shown in Figure 18, where two steps of meander evolution under variable erodibility are compared with evolution under constant erodibility. In the first stage of evolution, the bend with variable erodibility migrates faster, but during subsequent migration this is reversed.

[106] *Perucca et al.* [2007] have also shown that the shape of meanders affected by the presence of vegetation combined with the effect of a decreased friction factor does not always produce the usual downstream skewness that is typical for a constant mean erodibility and that reversed skewness induced by vegetation dynamics can occur.

[107] The importance of river-vegetation interactions has been recognized also by *Crosato and Saleh* [2011]. Their model showed that different vegetation planforms (braided, transitional, or meandering patterns) can occur depending on different vegetation densities.

7. MINIMALIST MODELS

[108] In the minimalist approach, only the key processes of the investigated dynamics are modeled while keeping the model mathematically tractable. The aim is to obtain analytical and semi-analytical solutions that are able to elucidate the quantitative links among the main variables that regulate the dynamics. To achieve this, a number of simplifications are necessary in comparison with more detailed models, but the results need to be clear to provide evidence for the skeleton of the dynamics. This approach has been successfully followed in several branches of bio-geosciences [*Ridolfi et al.*, 2011], such as vegetation pattern formation [*Lefever and Lejeune*, 1997; *Klausmeier*, 1999; *D'Odorico et al.*, 2006; *Rietkerk and Van de Koppel*, 2008], ecohydrology [*Rodriguez-Iturbe et al.*, 1999; *D'Odorico et al.*, 2005; *Rodrigez-Iturbe and Porporato*, 2005; *Laio et al.*, 2006], and plant physiology [*Hutt and Luttge*, 2002]. A few minimalist models have recently also been proposed to describe some aspects of riparian vegetation ecosystems [*Camporeale and Ridolfi*, 2006, 2007, 2010; *Muneepeerakul et al.*, 2007; *Perona et al.*, 2009a, 2009b; *Perucca et al.*, 2009; *Crouzy and Perona*, 2012; *Tealdi et al.*, 2010, 2013], and the main results are reviewed in this section.

[109] Minimalist models capture the overall vegetation biomass of the phreatophyte riparian species and neglect interspecies interactions and geomorphological processes, such as sedimentation and erosion, but rather consider a steady river morphology [*Auble et al.*, 1994]. Under these hypotheses, the local stochastic dynamics of the dimensionless biomass density, v, of single-species riparian vegetation can be modeled as a generic plot of the riparian transect according to the following dichotomous process [*Camporeale and Ridolfi*, 2006]

$$\frac{\mathrm{d}v}{\mathrm{d}t} = \begin{cases} -\alpha v & h \geq \eta \qquad (20a) \\ v(\beta - v) & h < \eta, \qquad (20b) \end{cases}$$

where h and η are the water level of the river and the topographic elevation of the plot, respectively (see Figure 19). Equation (7a) models the decay of the vegetation biomass caused by flooding (i.e., anoxia, burial, uprooting, etc.). Equation (7b) is a generalization of the commonly used Verhulst-logistic function which simulates the growth of a phreatophyte species that taps the groundwater [*Botkin et al.*, 1972], where β is the *carrying capacity* (i.e., the maximum sustainable biomass).

[110] Equations (7a–b) switch, according to whether the site is inundated or not. The statistical characteristics of the dichotomous switching are dictated by the river stages and are described by the probability distribution, $p(h)$, and the correlation time scale, τ, of the water level time series, the latter representing "memory" hydrological forcing. Model (7) can be rewritten as a single stochastic differential equation, driven by multiplicative dichotomous noise [*Kitahara et al.*, 1980], whose solution in steady state conditions is the probability distribution of the vegetation density, $p(v)$

$$p(v) = \frac{N}{\alpha} v^{\frac{\beta(1-\alpha\tau)-(\alpha+\beta)P_I}{\alpha\beta\tau}} (\beta - v)^{\frac{P_I}{\beta\tau}-1} (\alpha + \beta - v), \qquad (21)$$

where $v \in [0, \beta]$, P_I is the inundation probability (with $P_I < \beta/(\alpha + \beta)$) and N is the normalization constant.

[111] The analytical relation (equation (21)) can be used to study how the transverse distribution of riparian vegetation depends on the hydrological, morphological, and biological parameters involved in the model. *Camporeale and Ridolfi* [2006, 2007] considered the quasi-trapezoidal river cross section shown in Figure 19 and assumed a standard Gamma distribution to model the probability distribution, $p(h)$, of river water stages. The lower inset of Figure 19 shows some examples of the behavior of the mean, μ_v, and standard deviation, σ_v, of $p(v)$ along the riparian transect. The average vegetation biomass value varies along the x direction, increasing from zero close to the river to a maximum value and then decreasing asymptotically to approach the average value of the carrying capacity, $\beta(x)$, at high values of x. This behavior of the mean along the riparian transect agrees with field observations

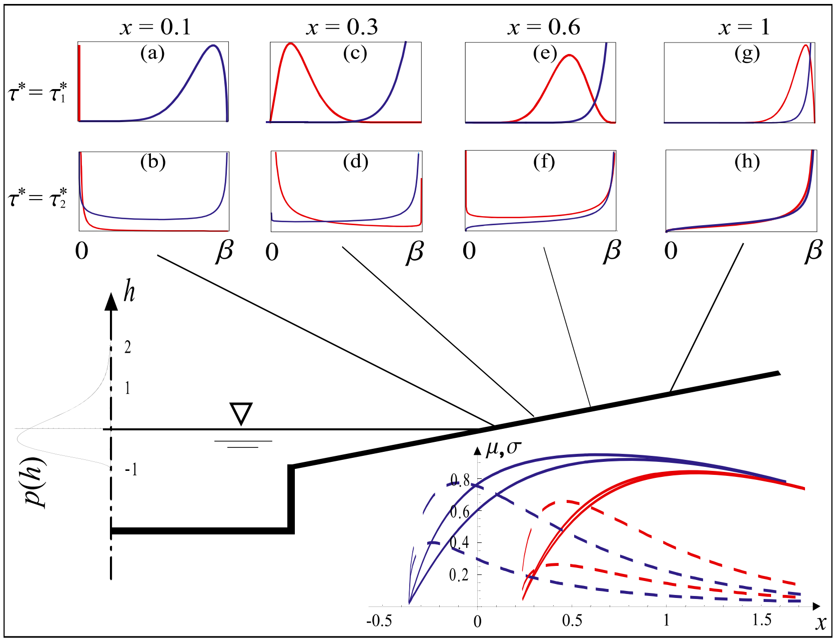

Figure 19. Probability density functions in four plots along a quasi-trapezoidal riparian transect (x is made dimensionless with the river half width). The lower inset shows the mean (solid lines) and standard deviations (dashed lines) along the transect, respectively. For the mean values, the upper curves refer to correlation $\tau = \tau_1 = 15$ days and the lower curves refer to $\tau = \tau_2 = 180$ days, while for the standard deviation, the correspondence is inverted [from *Camporeale and Ridolfi*, 2007].

[e.g., *Johnson et al.*, 1995]. The monotonic decrease in the carrying capacity along the transect is due to a progressive increase in water table depth, while inundations frequently destroy vegetation close to the river. The dependence of σ_v on x indicates important fluctuations in the time series of the vegetation biomass near the river.

[112] The minimalist approach allows the role of stochasticity in vegetation dynamics to be studied analytically [*Camporeale and Ridolfi*, 2007]. For example, the insets (a)–(h) in Figure 19 show the probability distribution of vegetation biomass for two different species in four plots along a transect, considering two different dimensional river correlation time scales. A flood-tolerant species (represented by the blue curves) and a less tolerant species (red lines) are considered. The flood tolerance (i.e., low values of α) can be due both to a high resistance to the negative effects of floods (uprooting, anoxia, etc.) and to a high resilience, because of a short vegetation growth time scale. If the insets are compared vertically and a single species is considered, an increase in the correlation time does not significantly affect μ but can drastically alter the shape of the distribution, as is also testified by the increase in the standard deviation. When the upper insets shown in Figure 19 are compared horizontally, the dependence of the distribution on the position of the plot along the transect clearly emerges: not only the quantitative characteristics but also the shape can change, and different noise-induced phenomena [*Ridolfi et al.*, 2011] can emerge along the same riparian transect and for the same species [*Camporeale and Ridolfi*, 2007].

[113] *Muneepeerakul et al.* [2007] followed the modeling approach by *Camporeale and Ridolfi* [2006] but introduced some small changes in order to obtain a finite width for the riparian belt. In this way, they were able to study the relationship between the geomorphological scaling rules that are typical of the river flow [*Rodriguez-Iturbe and Rinaldo*, 1997] and riparian zone width. Starting from the scaling relation between the standard deviation of the river discharge, σ_Q, and the drainage area, A, (i.e., $\sigma_Q \sim A^s$), *Muneepeerakul et al.* [2007] showed the key role of the scaling exponent s on riparian vegetation patterns. When discharge fluctuations increase rapidly with the drainage area (i.e., high values of s), high-order streams could be poor in riparian vegetation, whereas low values of s entail riparian belt widths that increase with the link magnitude. Stream magnitude order is a key geomorphological characteristic of each stream link: order magnitude 1 denotes links (called sources) without upstream tributaries, while higher-order magnitudes are defined as the number of sources that drain through a link. Figure 20 shows an example of field data relating stream order (magnitude) and riparian width: a positive correlation emerges, due to a low value of s, which confirms the theoretical results of *Muneepeerakul et al.* 2007.

[114] The minimalist approach introduced by *Camporeale and Ridolfi* [2006] has also been used (i) to investigate the subtle interplay between the geomorphology of meandering rivers and the corresponding vegetation biomass stored in the riparian corridor [*Camporeale and Ridolfi*, 2010] and (ii) to explore the effects of (natural or anthropic) changes of river discharge regime on riparian vegetation biomass [*Tealdi et al.*, 2011]. In particular, this latter work provided a theoretical framework to describe the vegetation narrowing/widening process induced by river damming.

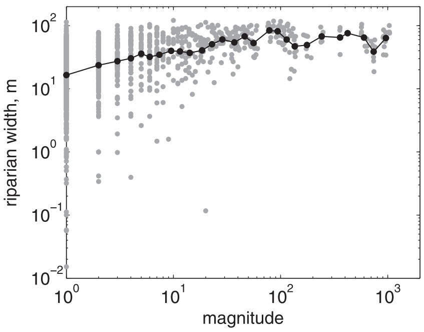

Figure 20. Empirical relation between the stream magnitude and the riparian width of the Sand Creek, Oklahoma (USA), obtained from remote sensing data. The black circles connected by the line represent average binning values [from *Muneepeerakul et al.*, 2007].

8. CONCLUSIONS

[115] Field evidence collected over the last 30 years has illustrated the remarkable significance of riparian vegetation for river morphodynamics. This knowledge, together with the need to evaluate how hydrological and/or morphological changes can influence riparian environments, has led to the development of several models.

[116] The first step in modeling the fluvial environment was the development of conceptual and semiquantitative models that rely on accurate field observations and describe, mainly in a qualitative way, the complex picture of interactions and feedbacks that drive the riparian bio-morphologic environment [e.g., *McKenney et al.*, 1995; *Nanson and Knighton*, 1996; *Tooth and Nanson*, 2000; *Gurnell et al.*, 2001; *Collins et al.*, 2012; *Gurnell et al.*, 2012].

[117] More mathematical treatments have recently been proposed, and some quantitative models have been developed. Cellular automata [e.g., *Murray and Paola*, 1997, 2003; *Hooke et al.*, 2005; *Coulthard et al.*, 2007], physically based differential models [e.g., *Van De Wiel and Darby*, 2004; *Perucca et al.*, 2006, 2007], and minimalist models [e.g., *Camporeale and Ridolfi*, 2007; *Muneepeerakul et al.*, 2007] are three mathematical approaches that have been adopted to describe and study the processes between channel evolution, river hydrology, and vegetation dynamics.

[118] All three approaches have proved to be important for exploring interactions in riparian environments, because natural riparian environments are so complex that they are difficult to reproduce with a single model, which is, by definition, a simplification of reality [e.g., *Nicholas and Quine*, 2007]. Nevertheless, comparisons between model outputs and the evolution of real rivers, their plan geometry, and changes in river patterns are very positive, indicating that the main processes have been correctly identified, in both multi-thread and single-thread rivers. Some of the key points that the models have shown are as follows: the importance of comparable temporal scales of vegetation evolution and river dynamics for the occurrence of significant morphodynamic interactions, the role of the stochastic variability of river discharge in the ecological succession of riparian plants, and the significant effect that vegetation can have on river planform evolution and on channel shape.

[119] In spite of these positive indications, quantitative modeling of river eco-geomorphology is still in its infancy, and many aspects are not yet completely understood and, as a consequence, have not been mathematically modeled. We believe that the following points, in particular, require research attention to gain a deeper understanding:

[120] 1. The first is the effect of different types or growth stages of vegetation (rigid or flexible) and different vegetation densities on the turbulence structure and secondary currents of a stream. This point is of crucial importance to evaluate all the transport processes in the riparian corridor, and its development can greatly benefit from scientific results obtained in the aeolian and plant canopy literature.

[121] 2. The second is the effect of vegetation on over-bank flooding and on the kinematics of over-bank flow. This knowledge is essential for the evaluation of deposition and erosion processes.

[122] 3. The third is the relationship between riparian plant growth rate and hydrological processes, such as water table oscillations and flooding. In particular, the role of river-driven stochasticity in influencing the temporal and spatial patterns displayed by riparian vegetation has to be explored and quantified in a similar manner to research on ecosystems [e.g., *Rodrigez-Iturbe and Porporato*, 2005].

[123] 4. The threshold tangential stresses that plants of different species and at different growth stages withstand before being scoured. This is important for modeling the interplay between vegetation, sediment transport, and the flow field.

[124] 5. The next is the formulation of quantitative ecological succession models in order to better describe riparian vegetation dynamics (in particular under stochastic forcings). This is a very complex topic—where fluid dynamical, morphological, and bio-ecological processes interact to a great extent—but it is crucial if we are to describe riparian ecosystems properly.

[125] 6. The next is the influence of roots on the geotechnical characteristics of vegetated banks in order to correctly model the erodibility of alluvial soils and bank stability.

[126] 7. The next is the spatial and temporal dynamics of soil moisture and groundwater near the river and the role of chemical and biological filtering played by riparian vegetation in the exchange processes that occur between a river and upland vegetation. These processes can have a significant influence on the dynamics of plant colonization and plant survival.

[127] 8. Last is the coupling of vegetation dynamics with topography, in order to elucidate the capability of vegetation to create favorable growing conditions through its impact on sediment transport processes.

[128] Eco-morphodynamics is an extremely challenging and fascinating topic, which has to be pursued with two key points in mind. First, any modeling development and improvement can only be possible by means of long and accurate field observations, which are fundamental for providing an insight into appropriate modeling approaches, providing the necessary data that are so rarely available at

the scale or level necessary for morphodynamic models [e.g., *Brookes et al.*, 2000] and for validating the realism of modeling outputs. Nevertheless, ground and air photographs and other airborne data sets are providing important landscape scale information at rapidly increasing spatial and temporal resolution. Such data sets can be used to extrapolate field observations across space and time and thus to supply a wealth of new information to support modeling. For example, recent research on the Tagliamento River illustrates how field observations can be very successfully combined with historical maps and air photographs [*Zanoni et al.*, 2008]; repeat, automated oblique photographs [*Bertoldi et al.*, 2013]; airborne lidar data [*Bertoldi et al.*, 2011a]; and multispectral satellite data [*Bertoldi et al.*, 2011b; *Henshaw et al.*, 2013] to yield new insights at many different scales into the eco-morphodynamics of this complex river system. At the same time, models are necessary to inform field studies, to demonstrate the understanding of the processes, to elucidate mechanisms that are difficult to extract from the complexity of real cases, and to make quantitative forecasts.

[129] Second, it is a *conditio sine qua non* to study river-vegetation interactions in a multidisciplinary way, with the strict cooperation of the different scientific expertise, where qualitative and quantitative modeling converge toward a unifying description.

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