Effects of deposited wood on biocomplexity of river corridors

Angela Gurnell[1], Klement Tockner[2], Peter Edwards[3], and Geoffrey Petts[4]

Under natural conditions, most rivers are bordered by riparian woodland. Many studies have highlighted the ecological importance of these wooded zones, but the impact of riparian woodland dynamics on the complexity of the active tract (the area of bare sediment adjacent to the river) has been overlooked. This paper highlights the impact of downed trees and sprouting driftwood on the development of islands and associated ponds within the active tract of large rivers and the effects of these features on the abundance and diversity of plants and animals, and points to the benefits of riparian woodland for channel restoration.

Many natural rivers are relatively wide and shallow, with an extensive tract of bare sediments during the low flow season – the active tract. Many (called braided rivers) have more than one mobile channel, bounded by bars of bare sediment, while others (island-braided rivers) are also characterized by vegetated islands. Most are lined by riparian woodlands. Along these natural rivers, floods erode, transport, and deposit not only sediment but also trees. Deposited trees, and islands that evolve from them, sustain a suite of aquatic and terrestrial habitats that would otherwise not be present on river bar surfaces. Previous research from a wide range of bioclimatic regions has focused on forested headwater catchments and on the important role of dead wood – trees eroded from hillslopes and terraces – in the ecology of streams and rivers (Maser and Sedell 1994; Gregory *et al.* 2003). The roles of wood

within large floodplain rivers have received relatively little attention. Some notable medium to large systems where the interplay between driftwood, riparian trees, and physical processes has been the focus of a great deal of research include the Queets (eg Abbe and Montgomery 1996, 2003; Naiman *et al.* 2000), Willamette (eg Sedell and Frogatt 1984; Dykaar and Wigington 2000) and Drôme (eg Piégay *et al.* 1999) rivers. We have shown that the role of wood is particularly marked when the deposited trees are able to sprout and anchor themselves to bar surfaces through the growth of adventitious roots (Gurnell *et al.* 2001); such trees are predominantly "soft-wood" riparian species and in the northern temperate zone are dominated by one family, the Salicaceae (poplars and willows; Karrenberg *et al.* 2002). Hitherto, the benefits derived from this "living wood" have been largely overlooked. Here we synthesize our findings from research on the Tagliamento River in Italy, one of the few remaining large floodplain-river systems in Europe where trees and large living-wood pieces still interact freely with river processes, forming island-braided reaches of channel (Figure 1). This paper examines the processes that lead to the formation of island-braided rivers and shows how the dynamics of these islands influence biocomplexity – the variety and arrangement of terrestrial and aquatic habitats, and the diversity and distribution of species they support – and comments on their future management and restoration.

In a nutshell:

- Deposited driftwood capable of regrowth dramatically accelerates the process of island formation along large floodplain rivers
- Deposited trees, pioneer islands, and fully developed islands are associated with a suite of adjacent and closely linked habitat types across a range of spatial scales on otherwise relatively homogenous river bar surfaces
- The suite of linked habitats supports high biodiversity and the simple index of shoreline length has been positively correlated with both abundance and diversity of animals
- These wood-cored features depend on a supply of wood capable of regrowth, space for habitat turnover, and dynamic river processes
- In river restoration, a relaxation in the intensity of river margin management could provide the space to regenerate riparian woodlands and create a sustainable supply of large wood to yield important enhancements in the biocomplexity of large-river systems

[1]*Department of Geography, King's College London, London WC2R 2LS, UK*; [2]*Department of Limnology, EAWAG, 8600 Dübendorf, Switzerland*; [3]*Geobotanical Institute, ETH, Zürich, 8044, Switzerland*; [4]*School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham B15 2TT, UK (g.e.petts@bham.ac.uk)*

■ Wood as a driver of island development

There has been extensive research on the roles of downed trees in river channels of forested headwater catchments, where dead wood induces hydraulic, morphologic, and textural complexity (Gregory *et al.* 2003). In larger floodplain rivers logjams can also form stable structures that influence local water depths and flow velocities and provide long-term protection for mature forest patches within the river corridor. From observations on the Queets River (Washington, USA), Abbe and Montgomery (1996, 2003)

Figure 1. *An island-braided section of the Tagliamento River, Italy. Pioneer islands surround the established island, with newly deposited trees draped across the bar adjacent to the main channel (foreground). The inset shows trees deposited across an expanse of bare gravel by a recent flood.*

our observations on the Tagliamento River, we have demonstrated an additional mechanism for island growth, where regrowth from living driftwood dramatically accelerates the process of island formation. This mechanism appears to be important for sustaining islands within river corridors characterized by rapid channel migration and frequent disturbance by floods (Gurnell *et al.* 2001; Gurnell and Petts 2002). Along the Tagliamento, rates of tree growth from living wood (Figure 2) can be four times faster than growth from seeds and small vegetative propagules and islands of more than 200 m in length can form in less than 20 years (Francis *et al.* in press). The availability of riparian tree species capable of regenerating in this way is obviously a key component of this system, but appropriate local conditions are also required, especially adequate moisture levels. On the Tagliamento, dynamic braided reaches lacking islands have a similar supply of wood but occur where regrowth from drift-

developed a model of island formation downstream from an initial deposited tree or wood jam at the head of a mid-channel bar and eventual integration of the island into the floodplain. This island development model was driven by the accumulation of dead wood and the growth of vegetation from propagules deposited in the protected lee of the wood. In such locations, the wood supports vegetation growth by acting as a "resource node" (Pettit and Naiman 2005), where fine sediments accumulate, retaining moisture and nutrients from the decomposing plant material. From

wood is severely limited by locally arid conditions caused by deeper alluvial groundwater levels and rapid drainage from surface waters.

■ Wood as a driver of physical complexity

Trees transported by floods become snagged on river bars, typically with their root bole oriented upstream. The hydraulic impact of an individual tree creates a set of closely linked topographic habitats (Figure 3a) on what would otherwise be a relatively homogeneous and smooth surface of bare sediments. Deep hollows are often scoured at the upstream flow divergence around the root bole of the tree; scouring exposes lag deposits of coarse sediment. Plumes of sand are deposited in the sheltered area bordering, and in the lee of, the tree's stem and canopy. Large wood pieces and large sediment particles become trapped, forming jams against the upstream face of the root bole, and reinforcing the hydraulic impact of the tree.

The build-up of wood and coarse sediment around the root bole, the adjacent scour hole, and sand plume may develop over a sequence of inundations. Given suitable tree species and environmental conditions, some wood pieces and the core deposited tree may sprout, developing root networks that reinforce the accumulating sediments and a canopy that


Courtesy of R Francis

Figure 2. *Early regrowth of poplar (Populus nigra) from a tree deposited by floodwaters along the Tagliamento in the second growing season, showing over 2m of growth.*

further enhances the hydraulic impact of the tree (Figure 3b). As a result, the area of hydraulically induced scour, sedimentation, and growing vegetation may enlarge to form a patch of vegetation or "pioneer island" (Edwards *et al.* 1999; Figure 4). Such pioneer islands may subsequently continue to grow and coalesce to form larger, more mature islands (Figure 3c; Gurnell *et al.* 2001).

Individual deposited trees, pioneer islands, and more mature islands all support the same suite of linked habitats, but the relative size of these habitats increases with the size of the vegetated area. For example, deposited trees and pioneer islands (length typically < 30 m) are often associated with small shallow scour holes supporting ephemeral ponds (Figure 5). Established islands (length typically > 100 m) are often associated with large, deep scour holes extending below the alluvial water table and sustaining ponds for prolonged periods (see Figure 6). These ponds provide an important addition to the range of habitats within the active tract. They are different from those associated with remnant cutoff channels, contributing thermal heterogeneity by damping diel (ie within a 24-hour cycle) fluctuations. Along the middle of the Tagliamento, scour pools associated with wood accumulations at the head of islands have a lower average daily temperature (18 °C) and lower diel variation (5 °C) than ponds located on open gravel (20.5 °C and 9.5 °C, respectively; Karaus *et al.* 2005). Because scour and deposition of sediment during bar-inundation can cause rapid creation, infilling, and lateral displacement of the low-lying ponds around the margins of aggrading islands, the turnover of ponds is an order of magnitude more rapid than islands (Van der Nat *et al.* 2003).

Whereas individual trees and islands have an important local effect on flow resistance and bar surface form, clusters of deposited trees can have an important aggregate effect across entire bars. We hypothesize that as the density of snagged trees and pioneer islands increases across a bar surface, their aggregate effect on flow resistance can change a bar surface from a fine sediment source to a fine sediment sink during flood events (Figure 7). In the former case, a low density of trees and pioneer islands allows fine sediment particles to be flushed from the bar surface and washed downstream by floodwaters, leaving a coarse gravel pavement (Figure 7a). In the latter case, closely spaced trees and pioneer islands filter fine sediments from the water and create backwaters that enhance the rate of sedimentation. The deposition of fine sediments and vegetation propagules around vegetated patches can lead to rapid extension of the vegetated surface (Figure 7c). We
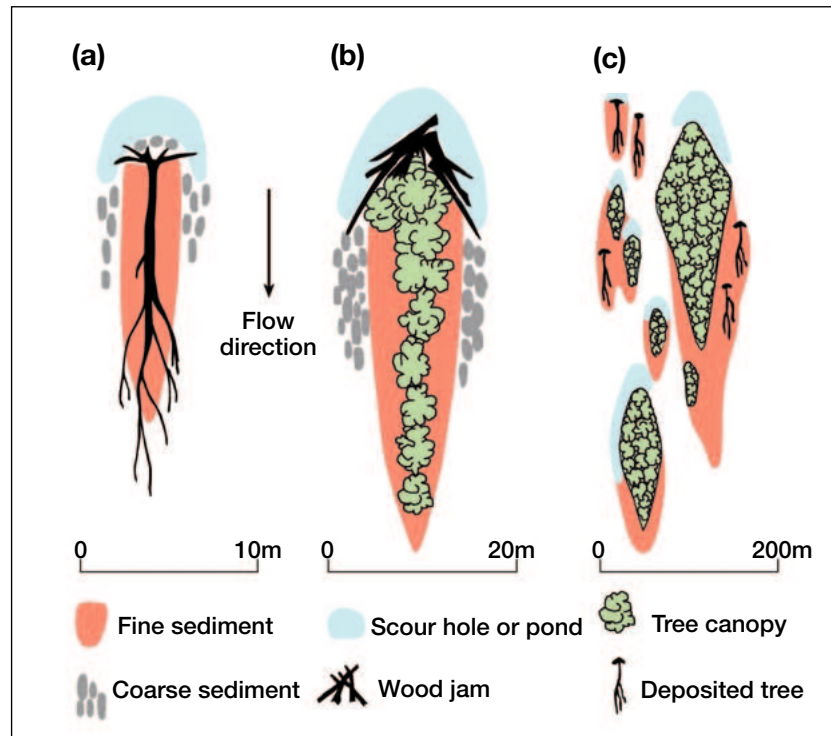
Figure 3. Island development from living wood. (a) A deposited tree inducing the development of a suite of linked habitats; (b) a tree sprouting and inducing scour, deposition of fine sediment, and trapping of wood pieces to form a pioneer island; (c) an island complex with deposited trees, pioneer islands, and established islands distributed across an extensive gravel surface.

also suggest that an intermediate density of trees and pioneer islands could maximize habitat diversity by causing the scouring of fine sediments along high-velocity flow pathways between sedimentation zones of closely spaced patches of wood, trees, and pioneer islands (Figure 7b).

■ Wood and biocomplexity

It is well established that wood jams in streams provide: flow and habitat heterogeneity; refugia for fish and invertebrates; sites of biofilm production that serve as food for grazing organisms; high organic matter retention; nursery habitat for fish; and perches for birds and other animals. Within large dynamic rivers, such as the Tagliamento, the suite of habitats created around individual deposited trees and islands form complex patches of high biodiversity within a relatively barren landscape of exposed sediment (Figure 6). Seed germination and sprouting wood produce a diverse vegetation cover on the building, fine-sediment surfaces. In addition, the root bole of deposited trees often contains soil, established plants, and a seed bank. This increases plant species diversity and greatly accelerates and influences the initial trajectory of succession, not least because some species may be "alien" to the particular location along the river continuum (Tockner *et al.* 2003).

As deposited trees evolve into pioneer islands, the number of plant species increases with vegetated area. On the Tagliamento, Kollmann *et al.* (1999) surveyed 89 recently

Figure 4. A pioneer island developing from a single buried willow, showing the features described in Figure 3b with wood debris accumulating around the root bole, gravel scour around the growing debris jam, and fine sediment deposition downstream.

deposited trees (< 1 year since deposition) and 22 pioneer islands (2–5 years) and showed that, on average, 17.3 (sd = 1.1) plant species were associated with the former and 26.2 (sd = 2.1) species with the latter. They also showed that the association between the number of plant species and habitat area was sustained across the developmental sequence of island types (deposited tree → pioneer island→ building island → established island).

On the Tagliamento, ponds associated with islands pro-

duce large amounts of algal biomass that may drive metabolism and provide habitat for a high proportion of juvenile fish. However, it is the physical proximity of the different habitats (scour holes, accumulations of sediment of different caliber, wood jams, vegetated patches; eg Figures 4, 5, and 6) that is of particular importance. For example, islands provide a source of organic matter for adjacent ponds and are a habitat from which the pond can be recolonized. Ponds are a food source for island fauna and algae can be an important food source for grazers, while the range of linked habitats are important for amphibians. Snags and islands provide stable habitat for invertebrates and are often areas of high secondary production, which may be important as drift. The islands are characterized by a high proportion of rare species of some taxa, such as ground beetles (Carabidae) that have high dispersal capacity, but the highest abundance is found along shorelines (up to 150 individuals m^{-2} on the Tagliamento), where prey organisms (ie emerging insects and aquatic drift) are concentrated. Moreover a study of amphibians within one reach of the Tagliamento found that amphibian richness within a given habitat type decreased with distance from islands (Tockner *et al.* in press). At a large scale, one simple index that appears to be helpful in demonstrating the impact of islands and channel complexity is shoreline length. This index has been positively correlated with both the abundance and diversity of animals. Table 1 provides comparative data for two adjacent reaches of the Tagliamento River (a bar-braided and adjacent island-braided reach; the latter is shown in Figure 1) and provides indices of their overall physical complexity, richness, and diversity of animal species.

It is also important to realize that any particular bar will not sustain the same position along the spectrum described in Figure 7 indefinitely. In particular, a bar surface that has been the subject of heavy accumulation of fine sediment and vegetation growth can be reset to a lower cover of vegetation and fine sediment during large, erosive floods. In natural settings, rivers have space to move, so that at the landscape scale different zones of the river corridor can support different densities of snagged trees, vegetated patches, and islands. The spatial distribution of both individual features and zones of features of different age, profile, and density, are highly dynamic. Dynamic zones, similar to those depicted in Figure 7, can be present

Figure 5. A well-established pioneer island with a large wood debris jam trapped against its upstream face and an adjacent scour hole that contains an ephemeral pond. The scour hole is bordered by fine sediment deposited by receding floodwaters and also by wind that has redistributed sand from the surrounding bar surface.

within and between reaches and are subject to major contrasts in habitat turnover rates that promote substantial variations in biodiversity. For example, along the middle Tagliamento, aquatic habitat change caused by individual floods was observed to be 35% in the island-braided compared to 56% in the bar-braided reach (described in Table 1), showing that woody vegetation slowed turnover in these habitats, whereas habitat composition remained relatively stable (Arscott *et al.* 2002).

■ Conclusions and management implications

Our observations on the Tagliamento River highlight the important role played by the transport and deposition of downed riparian trees, particularly species that can sprout, in enhancing biocomplexity within valley corridors along large, multi-thread gravel-bed rivers. Deposited trees create biocomplexity from the scale of the individual tree to the entire river corridor. Islands and their associated ponds are a dominant habitat couplet within the otherwise bare expanses of gravel (see Figure 6); the range of mesohabitats associated with this primary couplet (eg log piles, sand drapes, algal mats, and patches in different stages of succession) contribute to the high physical complexity of island-dominated reaches. The large size, braided pattern, relatively unmanaged riparian woodland, and large wood load of the Tagliamento River may be unique within Europe, and we have proposed that the future conservation of the Tagliamento should provide a benchmark for the European Water Framework Directive (Tockner *et al.* 2003). However, we also believe that our observations are applicable to other multi-thread and meandering systems and are germane to restoring reaches of larger rivers. Indeed, along large sand-bed rivers, wood deposition may be the only mechanism for creating habitat diversity (Erskine and Webb 2003).

We contend that island-braided rivers, although rare today, would have been a common style of gravel-bed river before the introduction of river engineering and flow regulation for water supply, flood control, hydroelectric power production, and navigation. Historical records support this contention for Europe (Gurnell and Petts 2002; Tockner *et al.* 2003) and North America (Maser and Sedell 1984), and research on impacts of dams has illus-

Figure 6. A deep pond at the head of an island on the Tagliamento River, showing a massive wood jam. The islands form a complex patch within an extensive expanse of bare gravel (view looking downstream).

trated how island-braided rivers have changed to single-thread ones over the historical period (eg on the Peace River, British Columbia and Alberta, Canada; Church 1995). However, the loss of island-braided reaches is not only related to increased intensity of river management over the past 200 years; it is also likely to have been part of a longer, slower change in large river dynamics, whereby island complexes disappear from sections
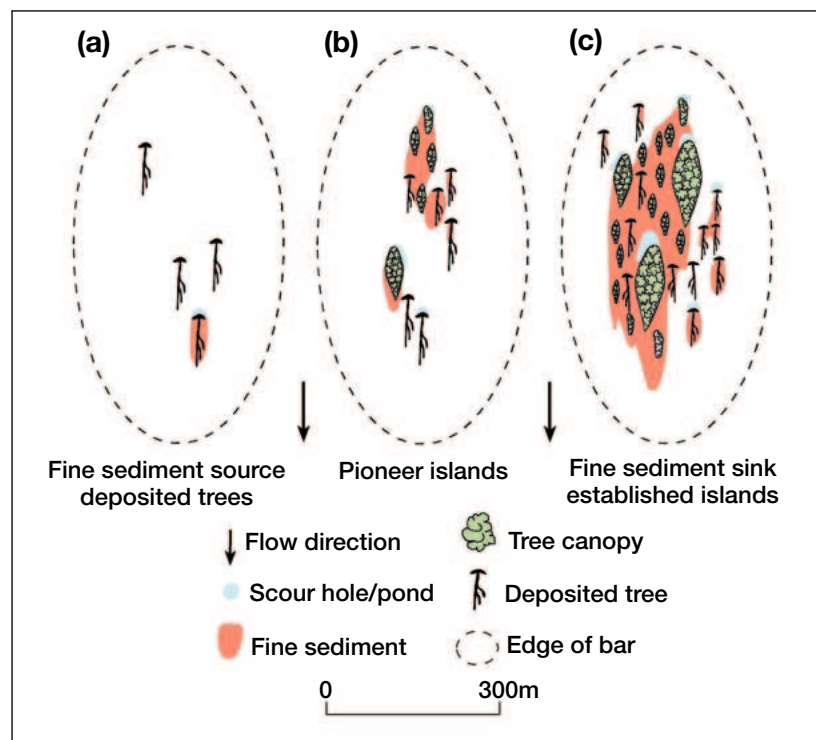
Figure 7. Hypothetical impact on the character of a large bar as the number of snagged trees and pioneer islands increases, and in the functioning of the bar surface from (a) a fine sediment source to (c) a fine sediment sink during flood events.

Table 1. Biocomplexity of the active zone of an island-braided compared to a bar-braided reach, Tagliamento River, Italy.

Approximate reach dimensions	Bar-braided	Island-braided
Channel slope (m m^{-1})	0.0035	0.0029
Reach length (km)	1.4	1.8
Width of active zone (m)	1000	800
Physical characteristics		
Large wood (t ha^{-1})	15–73	102–158
Channels (half-life expectancy; months)	4.1	7.7
Aquatic habitat diversity (H')	1.6	2.0
Average number of ponds	7	22
Average shoreline length (km km^{-1})	13.7	20.9
Animal species richness and diversity		
Amphibian species: γ-diversity	5	7
Carabid beetle species: γ-diversity	34	47
Benthic invertebrates: α-diversity	30	27
Benthic invertebrates: β-diversity	10.5	21
Benthic invertebrates: γ-diversity	50	53

Diversity indices: α-diversity - the number of species in each habitat; β-diversity - the turnover of species between habitats; γ-diversity - the total species pool.

starved of wood. Wood-cored islands of the type described in this paper are dynamic structures that can only exist where there is space for habitat turnover and a supply of downed trees of species capable of regrowth, as well as suitable environmental conditions for regrowth. In river restoration, a relaxation in the intensity of river margin management could provide the space to regenerate riparian woodland and create a sustainable supply of large wood to yield important enhancements in the biocomplexity of any large-river system. Island development through the incorporation of trees and wood, would have a major impact in enhancing habitat and biodiversity at both local and reach scales, especially where the tree species concerned are capable of sprouting from driftwood.

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