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R. S. Sigafoos's 1961 and 1964 papers on botanical evidence of paleofloods

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Abstract

The interaction between vegetation and fluvial processes leaves many possibilities for research. Since the publication in the early 1960s of the US Geological Survey Professional Papers by R.S. Sigafoos, numerous contributions in paleohydrology and riparian ecology have deepened the interaction between vegetation and fluvial geomorphology. In this article, we briefly review the impact of Sigafoos' research in past and current scientific developments. We highlight the importance of the botanical evidence described by Sigafoos and the need for further work in this research line.

Keywords

classics revisited, paleohydrology, dendrogeomorphology, tree rings, botanical evidence, Sigafoos

1 Introduction

The application of tree rings in hydrological science started in the early decades of the 20th century, when Hardman and Reil (1936) reconstructed past annual streamflow of the Truckee River (Nevada, USA) based on the existing correlation between ring widths of Ponderosa pine and river flow records. But tree-ring analysis was not used to date specific paleoflood events and fluvial sediment landforms until the early 1960s. In his seminal studies, Robert S. Sigafoos (1961, 1964) described, for the first time, botanical evidence of past floods events in the Potomac River of Washington, DC (USA) and highlighted its utility in paleohydrologic analysis to explore the hydrologic history of rivers (Leopold, 1953). Beyond the suggested economic value of botanical evidence (i.e. to improve flood-frequency analysis in poorly ungauged rivers; p. A32), research conducted by Sigafoos (1964) enabled the ecological interpretation of interactions between riparian vegetation and fluvial geomorphology, stimulating further research in the field (e.g. Hupp and Osterkamp, 1996; Osterkamp et al., 2012; Stoffel and Wilford, 2012).

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Since their publication, the Sigafoos papers (1961, 1964) have been cited more than 313 times, and have especially been widely cited since the 1990s (84% of citations; Google Scholar, accessed 08 August 2014). Our purpose here is twofold: to examine how the novel research conducted by Sigafoos, published in two United States Geological Survey (USGS) Professional Papers in 1961 and 1964, led to the subsequent development of standard dating procedures in tree-ring-based paleoflood research; and how his work has contributed to the definition of conceptual models of riparian vegetation and fluvial geomorphology interaction.

II The significance of botanical evidence of floods and relationship between tree establishment and fluvial geomorphology

Working for the USGS in the late 1950s, botanist Robert S. Sigafoos focused his applied research on the interaction between vegetation and fluvial geomorphology. He was well aware of the problem of the lack of hydrologic data necessary for the design of reliable hydraulic structures on rivers. Therefore, in agreement with his colleague Leopold (1953), he understood the technical and economic needs for obtaining information on past flood events from indirect evidence.

Consequently, in his initial publication on this field, Sigafoos (1961) examined the relationship between vegetation patterns and the frequency and duration of flooding. He performed a quantitative study along the Potomac River to analyse differences in the vegetation before and after flood events that had occurred early in 1961. His observations on damaged riparian trees allowed him to reinforce the hypotheses about the interrelationship between tree species and floods. He concluded that trees were not always killed by floods. Instead, he suggested that some tree species presented a major adaptability to growth on frequently flooded floodplain. He concluded that the establishment of new seeds on floodplains was dependent on fluvial conditions (as a driver to supply viable seeds on favourable beds of fresh mineral soil) and favourable environment condition (both climate and subsequent hydrologic regime). Finally, he suggested that floods were the cause of different bottomland-vegetation banded patterns along the Potomac River which clearly were linked with the past flood activity and fluvial dynamics (see Figures 1 and 2).

These observations were the basis for carrying out his study on botanical evidence of past floods and their physiological effects on trees a few years later (Sigafoos, 1964). Although some authors had previously described the harmful effects of floating ice chunks colliding with trees (e.g. Cribbs, 1917; Lindsey et al., 1961), Sigafoos related for the first time several lines of botanical evidence of a flood and deposition event with flow records. Specifically, the main contributions were: i) improving interpretation of flood-inflicted damages on trees (i.e. scar on stems) in relation to their hydrologic origin and physiological effects on trees as a basis for dendrochronological dating; ii) the description of the steps involved in the generation of multi-sprouted flood-felled trees as evidence of different floods events responsible for periodic crown losses; iii) reporting the utility of trees buried by alluvium for dating flood events by dating burial-induced anatomical changes in the stem and the generation of adventitious roots that allowed an estimate of the amount of alluvium deposited; and, iv) illustrating the value of relating trees with flood-exposed roots to erosional phases during flood events. These observations formed the basis of dendrogeomorphology (Alestalo, 1971; Shroder, 1978; Stoffel and Corona, 2014; see Butler and Stoffel, 2013 for a historical interpretation) and today still represent a reliable source of information for paleo-reconstructions in mountain areas (Stoffel et al., 2010) (see Figure 3).

Figure 1. Left: R. S. Sigafoos examining an Ash sprout growing from tilted stem due to flood in 1928; Right: R.S. Sigafoos measuring the diameter of an Alder sprout growing from the parent stem knocked over in 1956 (locations: Potomac River, Scott Run, Virginia). Pictures originally published as Figures 25 and 26 in US Geological Survey Professional paper 485-A, 1964 (available resources from: US Geological Survey, Department of the Interior/USGS).

III The impact of Sigafoos's research on subsequent development

The observations conducted by Sigafoos (1961, 1964) were quickly accepted. Therefore, their influence on science can be temporally tracked by distinguishing: i) those subsequent contributions focused on dating past flood events (i.e. paleohydrology), and ii) those research efforts aimed at the analysis of the interaction between riparian forests and fluvial geomorphology.

In the paleohydrology field, several researchers understood the potential of this new source of information for documenting past flood history (Harrison and Reid, 1967; Helly and LaMarche, 1973; Phipps, 1970). Since the formal foundation of dendrogeomorphology (Alestalo, 1971; Shroder, 1978, 1980) and paleoflood hydrology (Kochel and Baker, 1982; Baker, 1987), the use of botanical evidence was widely spread in North America. Yanosky (1983, 1984) picked up the baton and extended the anatomical studies of Sigafoos on *Fraxinus* species affected by floods in the Potomac River, analyzing the anatomical abnormalities between earlywood and latewood of annual tree rings which could be

Figure 2. R.S. Sigafoos in the field employing an increment borer in order to date past geomorphic events. Credit: US Geological Survey, Department of the Interior, US Geological Survey.

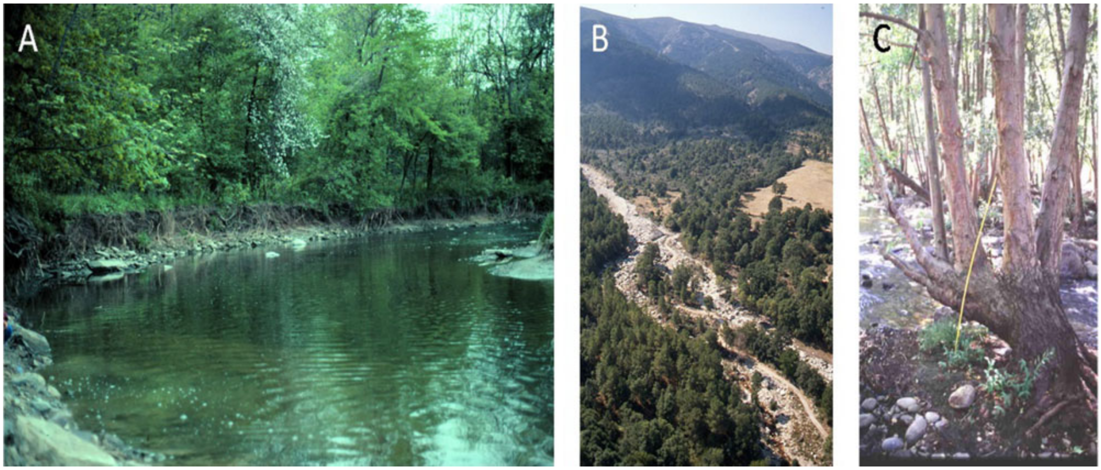

Figure 3. A) Riparian vegetation and tilted trees with exposed roots outside Toronto, Ontario; B) Aerial view of damages on vegetation due to intense flash flood event in Venero Claro, Spain; C) Example of multi-spruced Alder growing in the floodplain of the Alberche river, Spain (Credit: Andres Díez-Herrero).

used for more precise dating of event occurrence (i.e. for identifying flood events with intra-annual precision). Contemporaneously, Bryan and Hupp (1984) studied adventitious roots to report episodic deposition events related to floods.

The influences of Sigafoos were also present on developments conducted during the 1990s on: i) understanding the anatomical response upon affected trees by floods; ii) reporting flood-chronologies and understanding their climate and land use controls; and iii) using scar height for flood-magnitude estimation (see reviews in Stoffel and Wilford, 2012). The wide acceptance and extensive application of procedures described by Sigafoos (1964) have motivated others to extend his initial wood analysis of buried trees to other affected tree species to improve the reliability of dating procedures by analyzing the 3D anatomical signals related with wounded trees (Arbellay et al., 2012; Stoffel and Klinkmüller, 2013), buried trees (Kogelnig et al., 2013) and persistently flooded trees (Wertz et al., 2013). These updated wood anatomy observations from those carried out by Sigafoos (1964), and later on by Yanosky (1983), reflect the current interest in using tree rings to reconstruct flood histories in poorly or ungauged rivers (St George and Nielsen, 2003). However, beyond the interest of flood dating using botanical evidence, the early relations between scar height and flow discharge observed by Sigafoos (1964) provided the incentive for subsequent studies performed in other environments to determine their reliability to be used as paleostage indicators (e.g. Gottesfeld, 1996). This has allowed the creation of flood-magnitude estimates of extreme event (Ballesteros-Cánovas et al., 2011a), and has consequently improved the flood-frequency for risk assessment (Ballesteros- Cánovas et al., 2011b).

Concerning the interaction between riparian forest and fluvial geomorphology, there is no doubt that the observations described by Sigafoos (1961, 1964) in the Potomac River resulted in subsequent contribution on floodplain ecology. After its publication, several authors used the conceptual models based on the establishment of trees in the floodplain in relation to flow regimen to describe the floodplain (Keller and Swanson, 1979) and meander formation (Hickin, 1974; Nanson and Beach, 1977). Later, Osterkamp and Hupp (1984), and Hupp and

Osterkamp (1985), confirmed that the vegetation bands observed by Sigafoos (1961, 1964) on the Potomac River were related to bankfull, floodplain and terrace levels in a classical river cross profile. This concept was then updated to provide a dynamic channel-evolution model based on five stages of adjustment where channel incision, erosion and aggradation phases were related with tree establishment (Hupp, 1992). Throughout a comparative analysis in different fluvial environments, Hupp and Osterkamp (1996), explained changes in vegetation patterns with diverse causes, although all of them were related to the hydrologic regimen. Nowadays, riparian forests are considered a key component of river landscapes. The current state-of-knowledge has demonstrated the interaction of riparian forests with a broad spectrum of hydrogeomorphic processes, illustrated how they help in regulating the water and soil budget and shown the ecological value of river corridors (Osterkamp and Hupp, 2010; Osterkamp et al., 2012: Simon et al., 2004).

IV The legacy of Sigafoos' studies

Although botanical evidence has not been developed in the same fashion as other 'geological' evidence used in paleohydrology (e.g. slackwater deposits; Baker, 2008), the potential of this evidence has been repeatedly demonstrated. Over the last decade, several new applications using tree rings have been introduced in paleohydrology. New advances in the understanding of botanical evidence contained in heretofore un-studied species of riparian trees (Arbellay et al., 2012; Stoffel et al., 2012; Wertz et al., 2013), and their utility for flood-magnitude reconstruction in combination with numerical models (Ballesteros-Cánovas et al., 2011a; Ballesteros-Cánovas et al., 2014) might ensure greater applicability and worldwide adoption. Therefore, botanical evidence could be greatly advantageous especially in mountain areas, where the lack of data and the difficulty of locating slackwater deposits have so far largely precluded the spatio-temporal reconstruction of past hydrogeomorphic activity. Similarly, research in riparian corridor geomorphology and river flows has also undergone considerable development (Naiman et al., 2010). Retrospective analysis of vegetation changes and longer flow records have allowed demonstration of the impact of vegetation changes on magnitude and variability of river flows as well as on sediment retention processes (Marston et al., 1995; Simon and Rinaldi, 2000; Garófano-Gómez et al., 2012). Therefore, the idea that good ecological status could improve river ecosystems, and consequently provide benefits to societies, has now become a compulsory task for river managers (e.g. European Water Framework Directive WFD 2000/60/EC). The short historical review of the impact of Sigafoos' research on science presented here also illustrates the importance of continuing and developing those research lines into the future.

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