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Wood density and moisture sorption and its influence on large wood mobility in rivers

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ABSTRACT

Dynamics of large wood in aquatic systems significantly influence physical and ecological processes in rivers. Wood mobility is notably becoming a critical issue, not only in the context of restoration, but also in terms of flooding and hazard potential. Although the number of studies focusing on instream wood has increased substantially over the last few years, physical properties of wood have rarely been measured in aquatic systems. Instead, forest industry-based standards are often used. In this study, we quantitatively assess properties of instream wood density using decayed samples from the Rhône River stored within the Génissiat Reservoir and green samples from the Ain River floodplain (France). Using *in-situ* and laboratory experiments, we demonstrate how wood density varies between species, how density changes with moisture sorption and decay, and how density affects buoyancy. Results illustrate that both green (e.g., 800 ± 170 kg·m^{-3}) and instream woods (e.g., 660 ± 200 kg·m^{-3}) have much greater densities than standard values used in the literature (500 kg·m^{-3}). Sorption processes differ in green versus instream wood; moisture desorption of green wood is faster than absorption, whereas for instream wood, absorption is faster than desorption. These findings and the related changes in density affect wood buoyancy and mobility and therefore influence wood dynamics in rivers. Finally, two case studies illustrate how more accurate density values can be used to improve wood transport modeling and wood budget estimates based on numerical simulation and ground video-imagery-based monitoring.

1. Introduction

The number of publications focused on large wood (LW) in fluvial ecosystems has significantly increased in the scientific and technical literature over the past two decades (Gurnell et al., 2002; Wohl, 2013; Ruiz-Villanueva et al., 2016). These studies demonstrated that the spatial distribution of wood shows significant variations depending on climate, hydrology, geological, and geomorphological setting and human interactions (Piégay et al., 1999; Wyzga and Zawiejska, 2005; Comiti et al., 2006; Andreoli et al., 2007; Wohl and Goode, 2008). However, wood properties (in terms of mechanical and physical properties) are still not commonly quantified in aquatic environments (Le Lay et al., 2013). Studies that address temporal variability are much less abundant in general due to the difficulties in estimating changes in wood storage (i.e., wood budget). Wood budgets have been estimated based on recruitment volumes, changes in storage, and then back-calculation of wood export or flux (i.e., wood in transport over a certain time or area; Benda and Sias (2003)). However quantifying wood flux is challenging and requires direct observations during different hydrological conditions (MacVicar et al., 2009; Kramer and Wohl, 2014). Usually, volume of wood, rather than mass, is required for budgeting or flux estimations. Wood volume (V_{wood}) is often estimated based on the geometrical shape of the wood (Thévenet et al., 1998). To directly quantify wood volume and compute wood budgets, different techniques have been used, such as repeat estimates of the amount of wood deposited along a given reach, or direct counts of wood pieces at a given location. One of the first attempts to compute wood fluxes was using a video camera recording wood transported during different flood events in the Ain River in France (MacVicar et al., 2009). Aside from some technical issues due to camera resolution and the possible distortion of the images, an important limitation using this technique is the accurate estimation of the detailed wood shape. For cylindrical and simple-shaped logs, length may be more easily observed, but in the images from the camera only the emergent (or above-water) part of the woody piece is observed, not its entire diameter. Therefore, an uncertainty exists when wood volume is estimated using this monitoring technique. For floating wood, the proportion of unsubmerged log depends basically on its buoyancy, and that depends on the density of the wood. Wood density is also one of the main parameters in

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controlling the initial motion and the transport mechanism of wood (i.e., floating or sliding/rolling). The incipient motion of wood pieces, assuming logs are cylinders and avoiding any influence of root wads or branches, can be described as a balance of forces (Braudrick and Grant, 2001): (i) the driving forces, including the gravitational force acting on the log, equal to the effective weight of the log in a downstream direction, and the drag force, also acting in the flow direction, which is the downstream drag exerted on the log by the water in motion; (ii) and the resisting forces, including the friction force acting in the direction opposite to flow, which is equal to the normal force acting on the log times the coefficient of friction between the wood and the river bed. Wood entrainment is therefore mainly a function of four characteristics: length, diameter, orientation, and wood density, plus three hydraulic characteristics: slope, water velocity, and depth. Once a log is put in motion, two possible transport mechanisms are possible: one analogous to bedload movement along the river bed and the second, floating. These transport mechanisms depend on the hydraulics and morphology of the river and the wood piece characteristics (i.e., density).

Finally, there is also a growing interest in estimating wood biomass and carbon storage in rivers, as large wood can contribute significantly to the carbon flux in stream ecosystems (Wohl et al., 2012). Usually direct measurements of biomass during wood inventories are not possible. Instead, the volume of individual woody pieces is estimated and biomass is calculated by multiplying this volume by an estimate of wood density (Flores and Coomes, 2011). Therefore, wood density has to be accurately estimated in order to calculate biomass accurately.

Surprisingly, for any of these calculations where wood density is required (i.e., wood budget, wood transport, or biomass estimates), a value of 500 $kg \cdot m^{-3}$ has been systematically used in the literature (Harmon et al., 1986). This is due to the fact that unlike in forestry research, wood density is infrequent assessed in aquatic studies. Wood density varies as a function of several factors including tree species, wood type (proportion of early to late wood), tree age (and proportion of heartwood to sapwood), decay status, and water sorption (Thévenet et al., 1998; Millington and Sear, 2007; MacVicar et al., 2009; Curran, 2010; Shmulsky and Jones, 2011). Environmental conditions and processes in rivers are very different than those in forests, where most of the data about wood density is obtained. For example, woody pieces in watercourses are usually exposed to wetting and drying cycles controlled by the hydrological regime (i.e., frequency, duration, and magnitude of flows). In addition, in aquatic systems, anaerobic conditions may affect decomposition rates and decay processes, significantly differing from terrestrial wood decay (Bataineh and Daniels, 2014). Therefore, using standard values or relationships extracted from inventories of wood in forests, such as the Global Wood database (density as oven-dried mass/fresh volume; Zanne et al. (2009)), or the database from the Forest Products Laboratory-USDA (2010), or those compiled by the United States Department of Agriculture (USDA; Harmon et al., 2008, 2011) may not be appropriate for large wood in rivers. Especially when wood transport is analyzed or if wood shape needs to be extracted from videos, it is more appropriate to use values of wood density that include water content, whereas for biomass or carbon stock estimations, dry wood density may be more accurate.

Despite the abundant literature on wood properties, especially for manufacturing processes (Forest Products Laboratory-USDA, 2010; Shmulsky and Jones, 2011), and studies of wood in forests (Harmon et al., 2008), few studies have been published regarding instream wood physical characteristics. As an example, Thévenet et al. (1998) analyzed wood slices from instream wood collected at the Ain River, to estimate the ability to absorb water and test how the age, decay stage, density or size of samples influence the sorption process. Díez et al. (2002) analyzed small branches of several species to quantify wood breakdown in a first order stream in the Iberian Peninsula. Macvicar et al. (2009) analyzed samples also collected from the Ain River (France) and calculated residence times using C^{14}, wood mechanical characteristics (i.e., wood resistance to penetration), decay status, and wood density to quantify temporal dynamics of wood in rivers. Cadol and Wohl (2010) analyzed wet and dry densities, decay and residence time of wood extracted from tropical streams in Costa Rica. Turowski et al. (2013) collected wood samples from a mountain stream in Switzerland, and for large wood, mass was calculated assuming a cylindrical shape and a dry density. Merten et al. (2013) analyzed the importance of breakage and decay (measuring density) of large wood in rivers, using samples extracted with increment cores from wood found within several low order streams in USA. In these studies, different types of samples were used, most of them were small samples of wood (e.g., slices, cores), making the generalization to larger pieces or comparison very difficult. Therefore, many gaps exist regarding instream wood properties, particularly in relation to wood density.

The aim of this study is to provide empirical data on instream wood density and its variability with regard to the most influential factors (i.e., species, decay and moisture content) using large samples extracted from rivers. Moreover, the goal is to better understand the differences between instream wood and green wood, and to compare measured instream wood density values with some reference values from terrestrial environments. To do this we used two different types of wood, freshly cut green wood samples and decayed instream wood samples. In addition, this study evaluates the importance of wood density in modeling wood transport in rivers and in estimating wood budgets based on tracked floating wood pieces using video records.

2. Material and methods

2.1. Study sites, sampling strategy, and laboratory experiments

We analyzed the characteristics of two series of wood pieces, one set of instream wood samples extracted from the Rhône River, stored in the Génissiat reservoir (decayed floating wood); and another set of samples collected from living trees (undecayed and never-dried, green or freshly cut wood) located in the riparian forest of the Ain River.

The Génissiat dam is located in France 50 km downstream from Geneva (Switzerland) and 160 km upstream from Lyon (Fig. 1A). The drainage area of the Rhône River at Génissiat is 10,910 km^2. With a mean annual flow of 356 $m^3\ s^{-1}$, it is characterized by summer high flows but its seasonal variations are more subdued than typical glacier-fed regimes. Lake Geneva (50 km upstream, altitude 371 m, surface area 585 km^2, volume 89 km^3) retards and attenuates the peak flows, and interrupts the transfer of wood and sediments. At Génissiat, the Rhône is supplied with driftwood from two tributaries, the Arve and the Valserine Rivers. The drainage area of the Arve is 1984 km^2, 6% being ice-covered and 50% located at an altitude of over 1360 m; it drains the massif of Mont Blanc (4807 m). In its upper reaches, it is particularly influenced by snowmelt, which occurs from the end of winter until June, and then by summer rains and storms, followed by cyclonic rain storms in the autumn. Where it merges with the Rhône, the Arve has a hydrologic regime influenced by rainfall, snow and ice-melt. The river drains an alluvial corridor for a large part of its course with a braided pattern for several kilometers. The Valserine, on the right bank of the Rhône, drains a watershed with a 374 km^2 surface area and flows through the Jura limestone massif, which reaches altitudes just in excess of 1500 m. Its hydrological regime has a very pronounced nival influence with a maximal flow in April and a secondary minimum in January, but it also has a pluvial influence with another flow maximum in the autumn. The geomorphic pattern of the Valserine is a single-thread river, flowing through a gorge and draining a more forested watershed than that of the Arve.

Génissiat dam has no overflow pathway, so all woods coming from upstream in the Rhône and from the Arve and Valserine Rivers are blocked and must be extracted mechanically, usually before they sink to the bottom of the reservoir such that significant wood accumulation against the dam wall could be avoided systematically and successfully

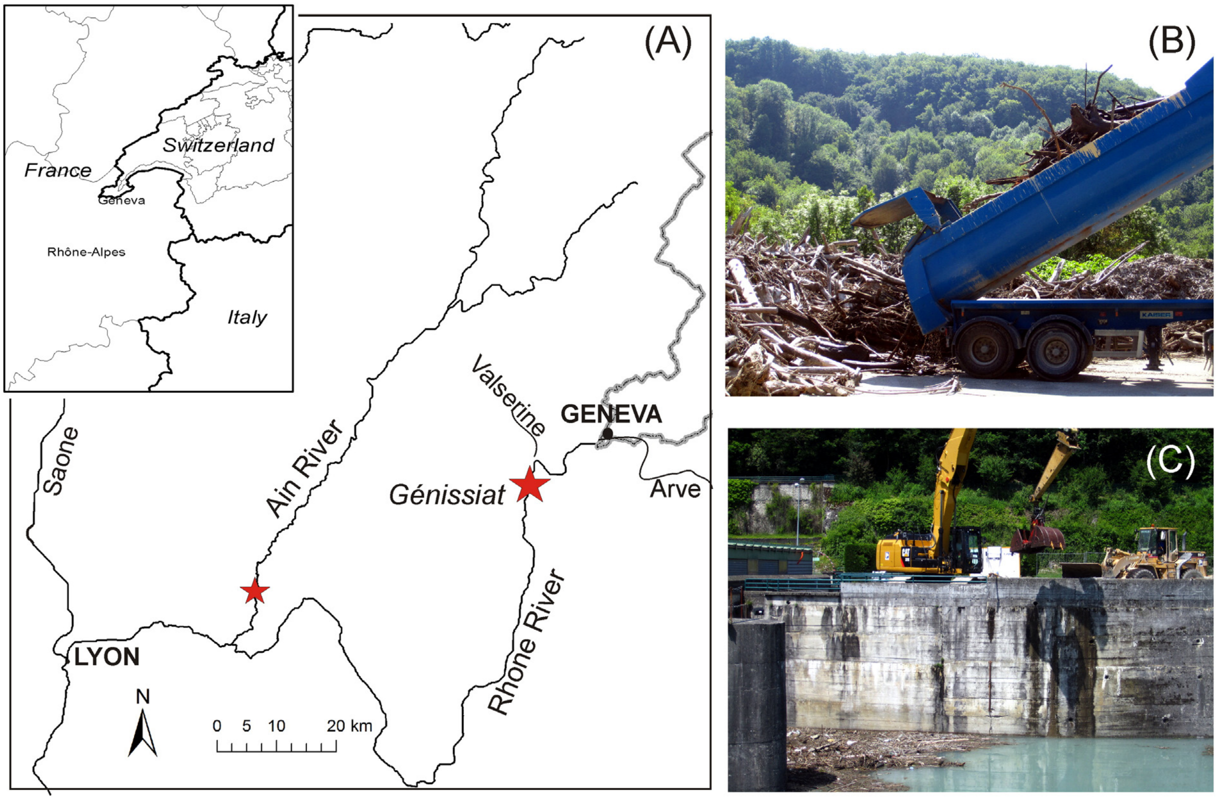

Fig. 1. (A) Location of the Génissiat dam in the Rhône River basin and the sampling site along the Ain River (red stars); (B) wood pile unloaded from a truck at Génissiat dam; (C) extraction procedure in the reservoir. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

since its construction in 1948 (see Fig. 1A). Therefore, although the wood is being in the water for some time (usually a few weeks), it is still floating. Extracted wood is stored near the dam in a pile (Fig. 1B and C). From this pile, between 200 and 300 pieces of wood were sampled randomly and measured at the time of extraction from the reservoir in June 2013, September 2013, and November 2014. In addition, we also used data obtained during previous field surveys in 1998 and 1999 (Moulin and Piégay, 2004). During extractions in June 2013, 120 samples of different genera were collected for further laboratory experiments.

Also in June 2013, 150 samples of green wood from 5 genera (*Alnus glutinosa*, *Populus tremula*, *Acer campestris*, *Fraxinus excelsior*, and *Abies pectinata*) were collected from freshly cut trees from the riparian forest of the lower Ain River (Fig. 1A), close to its confluence with the Rhône River. The Ain (3630 km^2) drains the Jura Mountains in a steep V-shaped valley. In its downstream reach (lower 40 km), between Pont-d'Ain and the confluence with the Rhône, the Ain flows through a large modern alluvial plain (200-to-1200-m wide). Floods occur mainly in the winter or in early summer. The lower Ain River was braided during the 19th century, but has adopted a wandering pattern since the middle of the 20th century and is now generally sinuous with localized meandering.

Large wood samples (diameters ranging between 15 and 20 cm and lengths between 30 and 50 cm) were cut using a chainsaw. Sampling was limited to straight, cylindrical stem sections to avoid undesirable side effects of branches or twisted shapes on the results.

The initial moisture conditions of green wood, above or equal to the fiber saturation point (*FSP*; Tiemann, 1906), were assumed to be the reference state for LW at the time of delivery into the stream. In contrast, the LW samples collected at Génissiat were considered to be representative of instream wood stored in a river, which has been fluvially transported and likely suffered phases of drying, wetting, and decaying before its arrival in the reservoir and extraction. At the time of extraction, samples were wet, although they were still floating in the water.

Identification of tree genera of decayed wood was based on characteristic cell patterns and wood features of polished samples using a microscope (Hoadley, 1990; Schweingruber et al., 2006). Most of the wood stored in the Génissiat reservoir is composed of riparian species. A large percentage comes from deciduous trees and a small percentage is comprised of conifers. For laboratory experiments, we selected samples of the most frequent genera at Génissiat, i.e., *Alnus*, *Fraxinus*, *Quercus* and *Salicacea* (including *Populus* and *Salix*), together with the samples of green wood (*A. glutinosa*, *F. excelsior*, *A. campestris*, *P. tremula and A. pectinata*). In total 7 genera were analyzed in the laboratory, of which 3 were found in both green and instream wood samples.

Sample volume (V) was determined by the external dimensions, by measuring wood sample length (L) and diameter (D) along both sides. All samples were weighed using a balance with an accuracy of ± 10 g. The term weight rather than mass is employed throughout this paper to conform to general usage.

Density (ρ_{log}) is defined as the mass or weight (m_{wood}) per unit volume (V_{wood}), usually expressed in grams per cubic centimeter or kilograms per cubic meter ($g \cdot cm^{-3}$ or $kg \cdot m^{-3}$). There is no universal procedure for calculating wood density, so it is important to specify whether the density is expressed in terms of green weight and green volume or of oven-dried weight and volume. Therefore, density can be calculated for any moisture content as:

$$\rho_{log} = m_{wood} \cdot V_{wood}^{-1} \text{ (at a given moisture content)}. \tag{1}$$

Moisture content (MC) of wood is defined as the ratio between the weight of water in wood and the oven-dried weight of wood:

$$MC = \left(m_{water} \cdot m_{dry-wood}^{-1}\right) \cdot (100\%) \tag{2}$$

$$MC = \left(m_{wet-wood} - m_{dry-wood}\right) m_{dry-wood}^{-1} \cdot (100\%). \tag{3}$$

Water in wood can exist as liquid water in the lumina of wood, often referred to as free water, or as water within the cell wall, called bound water (Shmulsky and Jones, 2011). When green wood is freshly cut, the cell walls are completely saturated with water and additional water may reside in the lumina (Forest Products Laboratory, 2010). Moisture content at which only the cell walls are saturated but no free water exits in lumina is called the *FSP*. The *FSP* is considered the moisture content above which the physical and mechanical properties of wood do not change anymore as a function of moisture content (*FSP* is usually in the range of 26–32%; Skaar (1988)). It represents the transition from unsaturated to saturated state. Further drying of the wood, below the *FSP*, results in strengthening of the wood fibers, and is usually accompanied by shrinkage. Wood is normally dried to a point where it is in equilibrium with the atmospheric moisture content or relative humidity equilibrium moisture content (*EMC*), and the wood is neither gaining nor losing moisture. As wood absorbs water above its *FSP*, air in the lumina is replaced by water until the maximum moisture content (MC_{max}) is reached. At MC_{max} both the cell lumens and cell walls are completely saturated with water. This value can be quite high naturally or through waterlogging; and can be different than the moisture content at which wood will sink in water (MC_{sink}).

Density, including water content, was calculated as the ratio between the weights of wood divided by the volume of the log. We used the density reduction factor (*DRF*), defined as the ratio of the decayed density of a piece of dead wood as compared to its initial green density (Miles and Smith, 2009) as a proxy for the degree of decay in dead wood (expressed with values ranging from 1 to 5, from "not decayed" to a "very advanced decay" class; Harmon et al. (2011)).

All samples (green and decayed wood) were divided into two groups, with 220 samples being stored in a rain-sheltered location but exposed to ambient air humidity and temperature fluctuations (for which values were recorded as well), and 50 samples were placed in water tanks (Fig. 2A and B). These two different conditions were used to analyze sorption processes (wetting and drying) and its influence on wood density. Sorption was measured regularly over more than one year up to the *EMC*, for drying samples, and until wood samples were sinking in water (MC_{sink}).

In addition to density, we measured wood buoyancy (*B*) defined here as the ratio between the emerged or above-water height of a log (h) divided by its diameter (D; $B = h \cdot D^{-1}$). To measure *B*, samples were placed in water, and a point gauge with an accuracy of 1 mm was used at both ends of the wood sample. In the case that the log was not perfectly straight, several stable floating positions were observed. In these cases, we measured the emerged height for all stable positions.

Results were analyzed using the Statistical tool R (www.r-project.com). Differences in the datasets were tested with the Kruskal–Wallis rank test, assuming significance when p-value < 0.05. Regression models were fitted to explain relationships between wood density and other properties. A bootstrap version (with 1000 Monte Carlo simulations) of the univariate two-sided Kolmogorov–Smirnov test (Sekhon, 2011) was used to test differences in distributions (i.e., between surveys). The Kolmogorov–Smirnov test compares two cumulative distribution functions and computes the maximum discrepancy with the statistic *D* (if *D* is close to 0, the distributions are overlapped) and the significance with the p-value < 0.05.

2.2. Influence of wood density and moisture on mobility and budgeting calculations

To analyze the influence of wood density on wood mobility in rivers, we designed a scenario-based numerical model analysis of wood transport.

Following the balance of forces (Braudrick and Grant, 2001):

$$\begin{aligned}&(g \cdot \rho_w \cdot L_w \cdot A_w - g \cdot \rho \cdot L_w \cdot A_{sub}) \cdot (\mu_{bed} \cdot \cos\alpha - \sin\alpha)\\ &= {U_{flow}}^2/2 \cdot \rho \cdot C_d \cdot (L_w \cdot h \cdot \sin\theta + A_{sub} \cdot \cos\theta)\end{aligned} \tag{4}$$

where L_w is the piece length, ρ_w and ρ are the wood and water densities, respectively, α is the angle of the channel bed in the direction of the flow, g is gravity, A_w is the area of the log perpendicular to the piece length, h is the water depth, Cd is the drag coefficient of the wood in water, μ_{bed} is the coefficient of friction, and A_{sub} is the submerged area

Fig. 2. (A) Samples drying, stored outside, protected from rainfall; (B) samples wetting, stored in water containers; (C) detail of the point gauge used to measure buoyancy; (D) two samples floating in water, the small one is an instream wood sample from Génissiat and the big one is a green sample.

of the log, as a governing equation, large wood transport was numerically simulated with the model developed by Ruiz-Villanueva et al. (2014a).

This model fully couples a two-dimensional hydrodynamic model based on the finite volume method with a second-order Roe Scheme with a Lagrangian model for wood dynamics. Details about the model and applications to real rivers are described in Ruiz-Villanueva et al. (2014a, 2014b, 2014c, in press-a, in press-b). Along with river morphology, flow conditions, and wood shape, wood density has a strong influence on the mobility of logs, therefore, a proper value has to be assigned to reproduce reliable scenarios.

In the model, we designed a river reach (2.5 km long) with characteristics similar to those of the Rhône or Ain Rivers. The river reach is a single thread channel, with an average width of 100 m, an average slope gradient of 0.002, and a uniform roughness value of 0.029 (i.e., coarse sand, fine gravel, and sparse grass material) along the riverbed. A flood scenario of 100 $m^3 \cdot s^{-1}$ was designed under steady stage conditions, so as to simulate a close-to-bankfull discharge. Under this scenario, wood is transported in the main channel without deposition along the floodplain.

We defined the number of logs-per-minute to enter the simulation, assuming that wood recruitment only occurs upstream of the study reach. Logs are characterized in the model using length, diameter, and density. To characterize each piece of wood entering the reach, we established a stochastic variation of ranges of maximum and minimum values for wood lengths and diameters (2–5 m in length, 10–30 cm in diameter). We ran several scenarios modifying only wood density values. To analyze impacts on wood dynamics, we calculated the traveled distance and the transport ratio, defined as the ratio between the outlet and inlet numbers of logs (*Tr = pieces transported downstream of the studied reach / total inlet logs*).

In order to monitor wood and calculate wood budgets, a video camera was installed in 2007 at the gauging station at Pont de Chazey on the Ain River. The camera has a view of the entire river width and it is located on the side of the river closest to the thalweg to provide a maximum image resolution where the majority of wood is expected to pass. Using records from the camera during several flood events, the total volume of wood was calculated (MacVicar et al., 2009; MacVicar and Piégay, 2012). As pointed out by the authors, the most likely source of error was the measurement of wood diameter. First, measurements may be distorted because the image compression algorithm used by the camera results in color bleeding into neighboring pixels. Second, because floating wood is partially submerged, the entire log diameter is not visible to the camera. Therefore, wood shape must be estimated. Variance in wood buoyancy and density would impact these estimates and subsequent wood budget calculations. We tested how this source of error could affect the final volume calculations, using our experiment's results regarding wood buoyancy and density.

3. Results

3.1. Instream wood extracted from the reservoir and comparison with green wood samples

The size of the wood pieces extracted from the reservoir in June 2013 ranged between 19 cm and 7 cm (median = 12 cm and SD = 3). Lengths were also recorded, but most of pieces are broken or cut during extraction, so the values are not representative of the real lengths, thus they are not provided here. Initial wood density (density and moisture content at extraction) of all samples ranged between 408 and 1054 $kg \cdot m^{-3}$, with a median of 651 $kg \cdot m^{-3}$ (SD 131 $kg \cdot m^{-3}$). In September 2013, wood density ranged from 321 to 1184 $kg \cdot m^{-3}$ (median value 703 $kg \cdot m^{-3}$, SD 150 $kg \cdot m^{-3}$). In November 2014, the range of wood density was between 441 and 1076 $kg \cdot m^{-3}$ (median value 771, SD 169 $kg \cdot m^{-3}$). Differences in wood density were related to differences in species distribution, decay stage, and water content.

Green wood had an average density at the time of cutting close to 900 $kg \cdot m^{-3}$ for all genera (median 930 $kg \cdot m^{-3}$, SD 127 $kg \cdot m^{-3}$). *Abies* samples showed the lowest average wood density just after cutting ranging from 590 to 890 $kg \cdot m^{-3}$ (median value 712, SD 91 $kg \cdot m^{-3}$); whereas *Acer* (median value 785, SD 75 $kg \cdot m^{-3}$), *Alnus* (median value 897, SD 71 $kg \cdot m^{-3}$), *Fraxinus* (median value 810, SD 70 $kg \cdot m^{-3}$), and *Populus* (median value 804, SD 119 $kg \cdot m^{-3}$) had densities between 720 and 1080 $kg \cdot m^{-3}$. Mean values of wood density (including water content) differed significantly (p-value < 0.05) between species of green wood and instream wood. Table 1 summarizes the initial wood density values as observed immediately after extraction from the reservoir and cutting for instream and green wood samples, respectively.

According to our findings, green wood has an average density value of 800 $kg \cdot m^{-3}$ ($\pm$170), whereas instream wood exhibits much lighter values with an average of 660 $kg \cdot m^{-3}$ ($\pm$200). Instream wood is less dense than green wood (16–24% lighter) in general and exhibits a *DRF* ranging between 0.76 and 0.84 (equivalent to decay class 2 for riparian species, not a very advanced decay class).

3.2. Variability of wood density and moisture sorption

During the drying experiment the desorption process decreased wood density significantly, with a reduction in moisture content between 17 and 34% in both green and instream wood pieces (Fig. 3).

As Fig. 3 shows, the largest variability (or variance) in the initial density for green wood was observed in *Abies* and *Acer* samples, and the lowest variability in *Fraxinus*. The largest change in moisture content occurred very quickly, observed within the first month of drying, for both green and instream woods. Within green wood, the largest change was observed in *Alnus* and *Populus* and the smallest change in *Fraxinus*. In the case of instream wood, the largest variance in initial density was observed in *Populus* (besides the undefined samples, which are a mixed of different species). The largest changes resulting from moisture changes was observed in *Alnus* and the smallest in *Salix* (however, the smaller number of samples of the latter could in fact influence this interpretation).

When compared to standard values for these species, we observed that green wood density values were in general higher than those provided in the analyzed databases. This is because most of these databases use oven-dried densities. The desorption process lowered moisture content so that by the end of the experiment, when samples reached the *EMC*, values of wood density were closer to the published oven-dried density values (although our samples were not oven-dried and they still had a low water content). Instream wood density values were mostly within the range of published oven-dried densities, even when they were recently extracted from the reservoir (as examples *Fraxinus* and *Populus*) and the moisture content was quite high. This was due to their state of decay before they were extracted from the dam for the analysis.

In general, the wood density of green soft or light wood, such as *Abies*, decreased after drying out to an average value of 500 $kg \cdot m^{-3}$, while green hardwoods, such as *Fraxinus* or *Acer*, had air-dried values

Table 1
Average initial wood density calculated for all instream and green samples and density reduction factors for common genera.

Genus	Initial ρ_{log} ($kg \cdot m^{-3}$, SD)		*DRF*
	Instream	Green	
Abies	–	693 (102)	–
Acer	–	794 (79)	–
Alnus	667 (83)	874 (73)	0.76
Fraxinus	686 (35)	816 (70)	0.84
Populus	616 (110)	793 (118)	0.78
Quercus	843 (150)	–	–
Salix	789 (10)	–	–
Unidentified	585 (106)		–

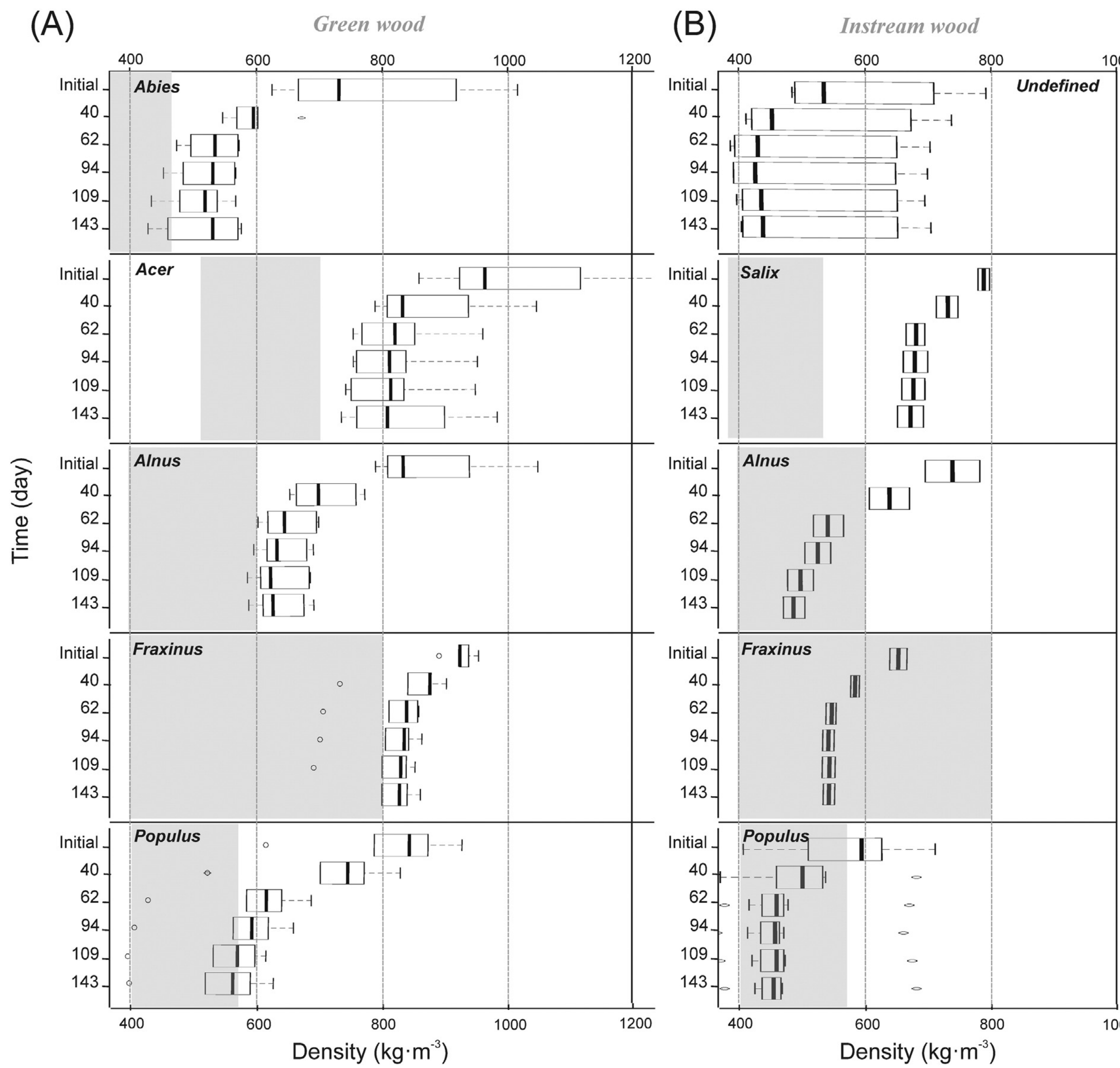

Fig. 3. Boxplots for wood density after drying process. In gray are ranges of standard values for wood density (Zanne et al., 2009; Forest Products Laboratory, 2010).

of around 800 $kg \cdot m^{-3}$. *Alnus* and *Populus* had final dry values around 600 $kg \cdot m^{-3}$. *Alnus* and *Populus* samples extracted from the reservoir showed different ranges. Instream *Fraxinus*, *Populus* and *Alnus* samples with decreased moisture contents reached density values closer to 500 $kg \cdot m^{-3}$, although *Salix* showed final dry densities above 600 $kg \cdot m^{-3}$.

The absorption process during wetting, by contrast, increased moisture content between 11 and 25% for green wood and by 19 to 36% for instream wood (Fig. 4).

The largest variability observed in green wood samples was in *Abies* and *Acer* (as it was during the drying process), and the lowest variability was observed in *Fraxinus* and *Populus* samples. Final water content density values, when green wood samples sank in the water tanks reaching the MC_{sink}, increased up to 1200 and 1100 $kg \cdot m^{-3}$ for *Acer*, *Populus* and *Alnus*, and to approximately 1000 $kg \cdot m^{-3}$ for *Fraxinus* and *Abies* species. In comparison, instream wood samples achieved lower values of final density after wetting. *Populus* samples had the highest values (between 1100 and 1200 $kg \cdot m^{-3}$) and the other samples had density values between 900 and 1000 $kg \cdot m^{-3}$.

Table 2 summarizes the initial and final values of average wood density for green and instream woods before and after drying and wetting experiments.

We found that moisture or water content increased (or decreased) wood density following an exponential function with time with exponents ranging between −0.00009 and −0.003 for water desorption (for both green and instream woods) and 0.0009 and 0.0031 for water absorption (Fig. 5). The exponents, and thus the temporal variability of density, were species-dependent. In the case of instream wood, the median value of the exponents was 0.0028 for wetting and −0.001 for drying. For green wood samples, the median exponent for the wetting process was equal to 0.001 and for drying was equal to −0.002. These exponents reflected that green wood gained moisture more slowly than instream wood, but green wood lost moisture a bit faster than instream wood during the drying process.

Based on these findings we present a generalized function to estimate the temporal variability of density based on changes in moisture content as follows:

$$\rho_f = \rho_i \cdot e^{-K \cdot t} \tag{8}$$

where ρ_f and ρ_i are final and initial density values (in $kg \cdot m^{-3}$), K is the exponent with averaged values equal to 0.0019 (according to our findings) for wetting (wood in water tanks) and −0.0016 for the drying

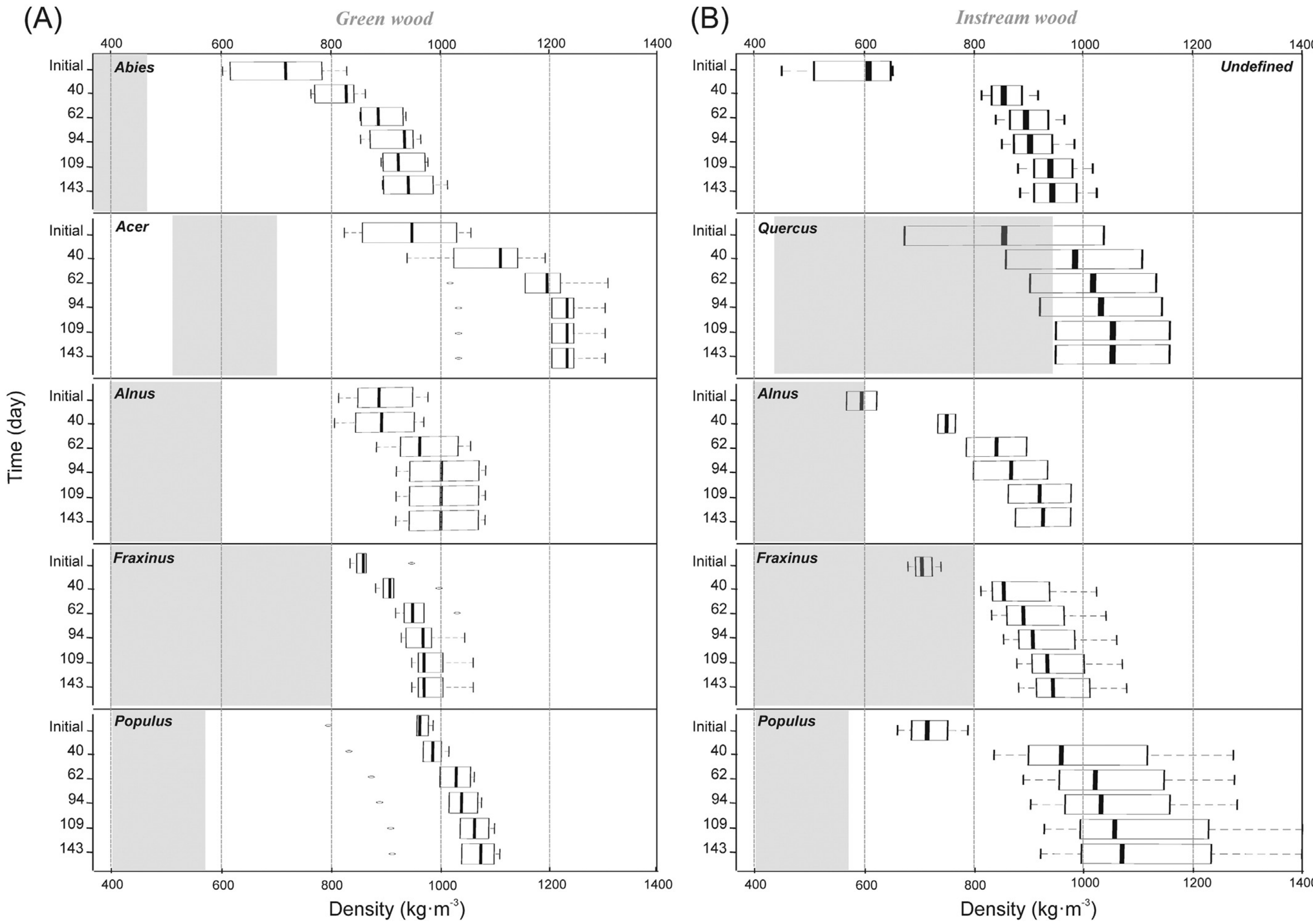

Fig. 4. Boxplots for wood density after wetting process. In gray are ranges of standard values for wood density (Zanne et al., 2009; Forest Products Laboratory, 2010).

process (at air temperature conditions); and *t* is time (in days). Table 3 summarizes all the exponents.

The end of the wetting experiment was determined when most of the wood samples sank to the bottom of the water tanks and were completed submerged. Among the green wood, some of the *Acer* samples sank within two months (62 days), all *Alnus* samples sank after 3 months (109 days), and all *Fraxinus* samples sank after 4 months (143 days). Only 33% of all the *Populus* samples were totally submerged when the experiment finished, and all of the *Abies* logs were still floating in the water. Instream wood samples sank slightly more slowly in all cases. *Quercus* and *Fraxinus* samples were the first to sink (between 62 and 109 days), followed by *Salix* samples (94 days), *Populus* samples (between 109 and 143 days), and finally *Alnus* samples (after 143 days). These observations showed instream wood samples were generally floating considerably longer than green wood samples (even of the same species).

The sorption processes exhibited a hysteresis effect, and the degree of hysteresis was greater for instream wood. Green wood *Populus* samples, for instance, lost up to 42% of water content but gained just 23% (Fig. 6A and C). Comparable results were found for *Abies*, whereas *Alnus* and *Acer* lost around 35–36%, and *Fraxinus* lost only 23% when drying. *Alnus* and *Fraxinus* samples gained the lowest percentage of *MC* when wetting (22% and 17% respectively), whereas *Populus* and *Abies* gained 23 and 34%, respectively. In the case of instream wood, we observed a larger variability, especially in the absorption process (Fig. 6B and D). *Populus* samples gained the highest *MC* with up to 46%, whereas *Alnus* samples gained around 37%, *Fraxinus* 25% and *Quercus* 20%. In the desorption process, instream *Alnus* samples lost

Table 2
Averaged and standard deviation (in parentheses) of initial and final wood density (kg·m^{-3}) calculated for drying and wetting experiments and for green and instream samples.

Genus	Drying				Wetting			
	Green		Instream		Green		Instream	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Abies	782 (140)	517 (55)	–	–	708 (85)	939 (50)	–	–
Acer	1053 (191)	833 (85)	–	–	942 (92)	1203 (91)	–	–
Alnus	876 (90)	636 (36)	742 (44)	487 (18)	894 (56)	1004 (60)	592 (27)	928 (51)
Fraxinus	980 (121)	811 (55)	652 (14)	545 (10)	867 (37)	984 (39)	709 (24)	962 (81)
Populus	814 (99)	544 (73)	572 (98)	476 (90)	944 (66)	1058 (66)	719 (53)	1135 (200)
Salix	–	–	789 (10)	671 (21)	–	–	–	–
Quercus	–	–	–	–	–	–	855 (182)	1057 (104)
Undefined	–	–	589 (119)	503 (123)	–	–	651 (84)	948 (51)

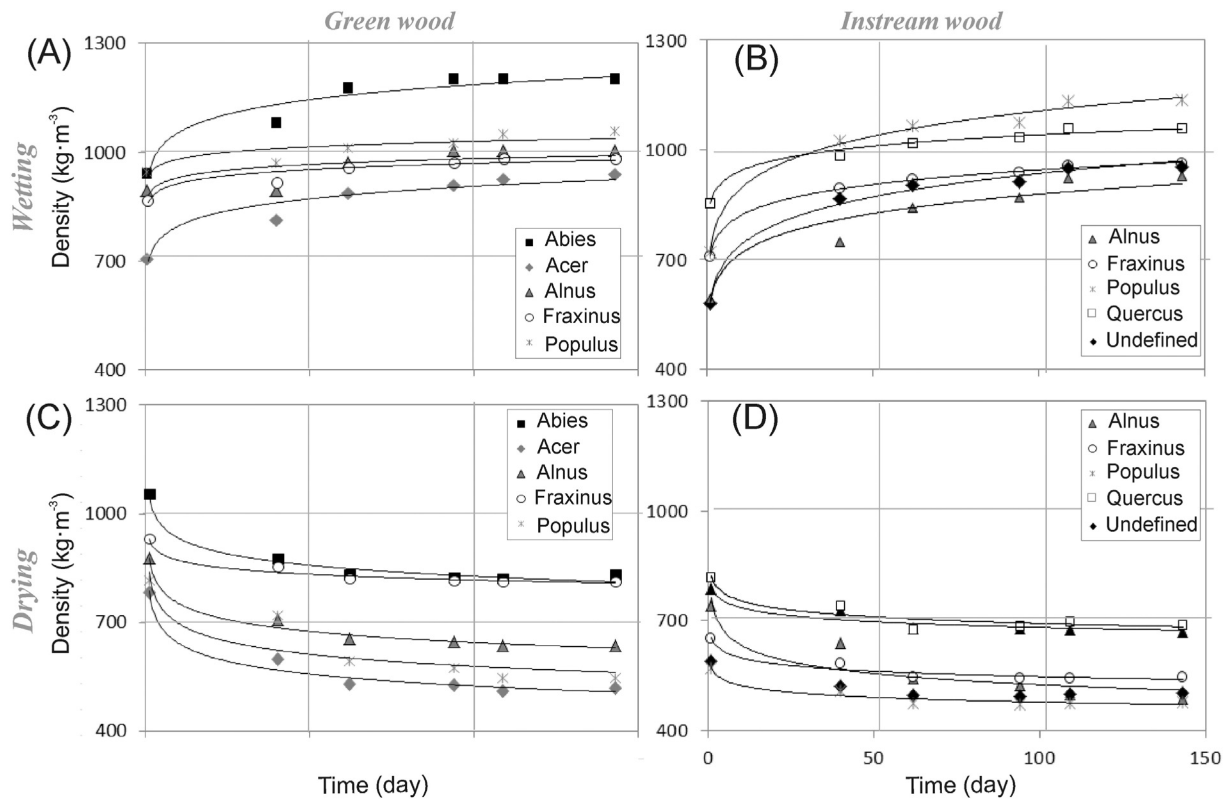

Fig. 5. Average wood density for green and instream samples during wetting (A, B) and drying experiments (C, D).

the highest *MC*, whereas *Populus*, *Salix* and *Fraxinus* lost between 15 and 17% of *MC*.

3.3. Wood buoyancy, mobility, and budgeting

The instream wood extracted from Génissiat had initial buoyancy between 25% and 44%, and the green wood samples buoyancy was between 18% and 30%, depending on the density. In line with the Archimedes principle, we observed a significant (p-value <0.05) linear relationship between wood density and buoyancy. The wetting and drying processes and related changes in density revealed dispersion in this relationship, which was species-dependent. Nevertheless, the linear relationship explained between 44% and 90% of the variance (Table 4, Fig. 7).

The largest variance was observed for the higher values of wood density and the denser samples. Some of the samples with high density were still floating and only partially submerged in the water. Green *Fraxinus* and *Acer* samples had the largest variance and lowest correlation (with determination coefficients of 0.44 and 0.63, respectively).

Table 3
K exponents of the generalized functions for wetting and drying and for green and instream woods.

Genus	Drying		Wetting	
	Instream	Green	Instream	Green
Abies	–	−0.002	–	0.002
Acer		−0.003	–	0.002
Alnus	−0.003	−0.002	0.0031	0.001
Fraxinus	−0.001	−0.00009	0.0019	0.0009
Populus	−0.001	−0.003	0.0028	0.0009
Quercus	−0.001	–	0.0014	–
Salix		–	–	–
Unidentified	−0.001	–	0.0031	–
MEAN	−0.0014	−0.0018	0.0025	0.0014

Instream wood samples, generally lighter in density, showed stronger correlations, with determination coefficients greater than 0.8 in all cases.

The results of the numerical simulation of wood transport highlighted the strong influence of wood density on wood mobility, illustrated here by the strong negative correlation between wood density and the wood transport ratio (Fig. 8). As wood density increased, the wood transport ratio decreased in such a way that under identical flow conditions, the number of transported pieces in a river was significantly reduced for very dense logs. However, the relationship was not linear; it was better explained by a quadratic function (Fig. 8).

According to our results from the experiments, green wood, which is representative of freshly recruited trees during a flood event, showed average density values of 800 $kg \cdot m^{-3}$, whereas instream wood, representative of wood stored in the river and transported during a flood, showed average density values of 660 $kg \cdot m^{-3}$. Our simulations demonstrated that these two different types of wood move very differently in rivers, both in terms of distance traveled and with regard to transport mechanism (i.e., buoyancy, depending on the flow conditions). According to modeling results, lighter wood (less than 600 $kg \cdot m^{-3}$, representative of instream wood) traveled longer distances floating, unless interactions occurred with river morphology. When wood density values reached around 850 $kg \cdot m^{-3}$ (a value representative of green wood), the transport ratio decreased more quickly (the slope of the linear relation in Fig. 8 is higher in the gray function than in the black one, the latter representing lower values of wood density).

For pieces of wood with densities lower than 500 $kg \cdot m^{-3}$, model results calculated mean traveled distance of 1880 m along the simulated river. Traveled distance decreased when wood density increased, according to the simulations results. Wood pieces with wood densities of 650 and 850 $kg \cdot m^{-3}$ traveled mean distances of 1660 and 1521 m along the simulated river, respectively. Very dense pieces, with densities higher than 850 $kg \cdot m^{-3}$, moved less than 900 m, and some logs did not move at all at a discharge of 100 $m^3 \cdot s^{-1}$ and in the simulated river when wood density was extremely high (>1200 $kg \cdot m^{-3}$).

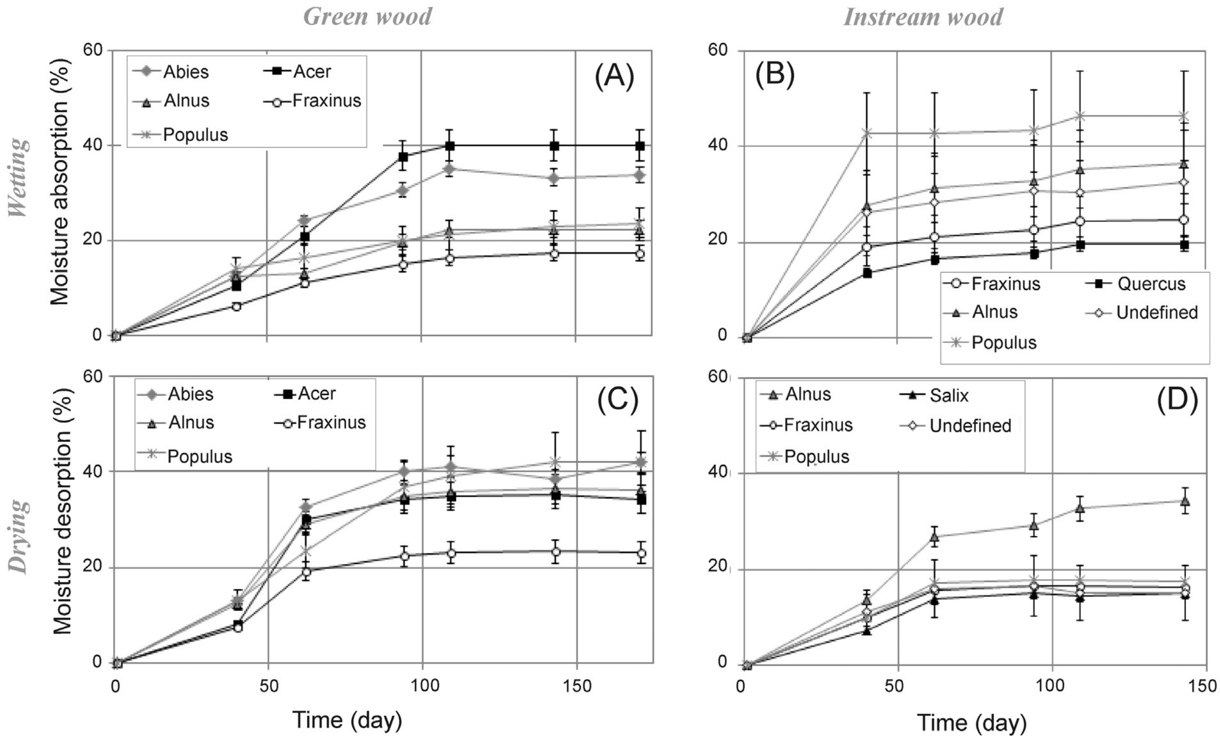

Fig. 6. Sorption curves showing moisture content variations: for samples in water: (A) green wood (B) instream wood; and samples drying: (C) green wood (d) instream wood.

These outcomes were then used to test the error associated with the diameter and the wood volume estimation from images recorded by cameras. A piece of wood transported in the river with enough discharge to be transported floating was recorded by a camera installed on the floodplain. When the image recorded by the camera showed just the emergent part of the log, this was used to estimate the log diameter, the wood volume, and later to calculate the wood budget. According to the results of our experiments, we cannot assume the emergent log height to be similar to the log diameter. Only very lightweight pieces with density values lower than 500 kg·m^{-3} would float halfway out of water, i.e., at the diameter level (buoyancy around 50%), however this density value was found to be unrealistic in our samples. On the other hand, freshly-cut wood (green wood) had an average buoyancy of 26% (between 18 and 34% of the log above water) and instream wood had an average buoyancy value of 37% (27 to 66% of the log above water). Based on these results, a piece of wood with an emergent height recorded by the camera equal to 1 m would have a real log diameter between 2.7 m and 5 m, depending on its level of decay. The estimated volume for this piece would range between 0.79, 5.72, and 19.63 m^3 if the log was considered well-decayed, partially-decayed, or green, respectively. Therefore, the error in the budget estimation could be significantly large with an assumption of 50% buoyancy, or if density was under- or overestimated.

The results presented here could be used to set ranges of density values, depending on the type of transported wood (green or decayed) and the species (if this is known), as well as ranges of buoyancy in order to calculate the probable range of piece diameter, volume, and wood budget.

Table 4
Regressions of the measured wood density (g·cm^{-3}) and buoyancy for all the species of green and in-stream woods (wetting and drying); determination coefficient (R^2), intercept and slope of the linear regression, and mean and standard deviation (in parentheses) of averaged values for all the specimens of all species.

	Slope	Intercept	R^2	Density (mean; SD) (g·cm^{-3})	Buoyancy (emerged height/diameter)
Green wood					
Abies	−0.73	0.85	0.90	0.71 (0.18)	0.34 (0.14)
Acer	−0.43	0.66	0.63	0.89 (0.12)	0.28 (0.06)
Alnus	−0.75	0.87	0.80	0.77 (0.14)	0.29 (0.12)
Fraxinus	−0.52	0.62	0.44	0.86 (0.07)	0.18 (0.06)
Populus	−0.63	0.79	0.84	0.78 (0.21)	0.30 (0.3)
Mean	−0.61	0.76		0.80 (0.14)	0.28 (0.10)
All	−0.67	0.81	0.75	0.80 (0.17)	0.26 (0.13)
In-stream wood					
Alnus	−0.72	0.82	0.86	0.54 (0.12)	0.44 (0.09)
Fraxinus	−0.70	0.80	0.90	0.76 (0.18)	0.27 (0.13)
Populus	−0.78	0.84	0.90	0.66 (0.24)	0.33 (0.20)
Quercus	−0.40	0.66	0.89	0.84 (0.25)	0.32 (0.11)
Salix	−0.82	0.92	0.80	0.59 (0.13)	0.44 (0.12)
Undefined	−0.57	0.74	0.89	0.37 (0.13)	0.66 (0.21)
Mean	−0.67	0.80		0.63 (0.17)	0.41 (0.14)
All	−0.69	0.81	0.72	0.66 (0.20)	0.37 (0.15)

4. Discussion

This study was designed to improve the scientific understanding of wood dynamics in rivers. In particular, the aim was to provide empirical values of wood density from wood extracted from rivers and to test the reliability of standard wood density values (500 kg·m^{-3}) for aquatic system studies. According to our results, green wood showed an average density value of 800 kg·m^{-3} (±170 kg·m^{-3}), whereas instream wood exhibited much lighter values with an average of 660 kg·m^{-3} (±200 kg·m^{-3}), although values varied among species. We believe that these values, and the values we reported for each genus, are indeed representative of the studied tree species (for green and decayed woods) and of the geographical and climatic regions. When compared to standard values for the same species, we observed that green wood density values were in general higher than those provided in the analyzed databases. On the other hand, instream wood density values were closer to the range of oven-dried densities due to the degree of decay, however the ranges varied significantly. Overall, the standard value of 500 kg·m^{-3} currently used in the literature should be used with caution when it comes to the analysis of wood dynamics in rivers. As an example, Nakashima and Yamanaka (1999) observed a wood density value of 1500 kg·m^{-3} for logs transported by a flood, measured

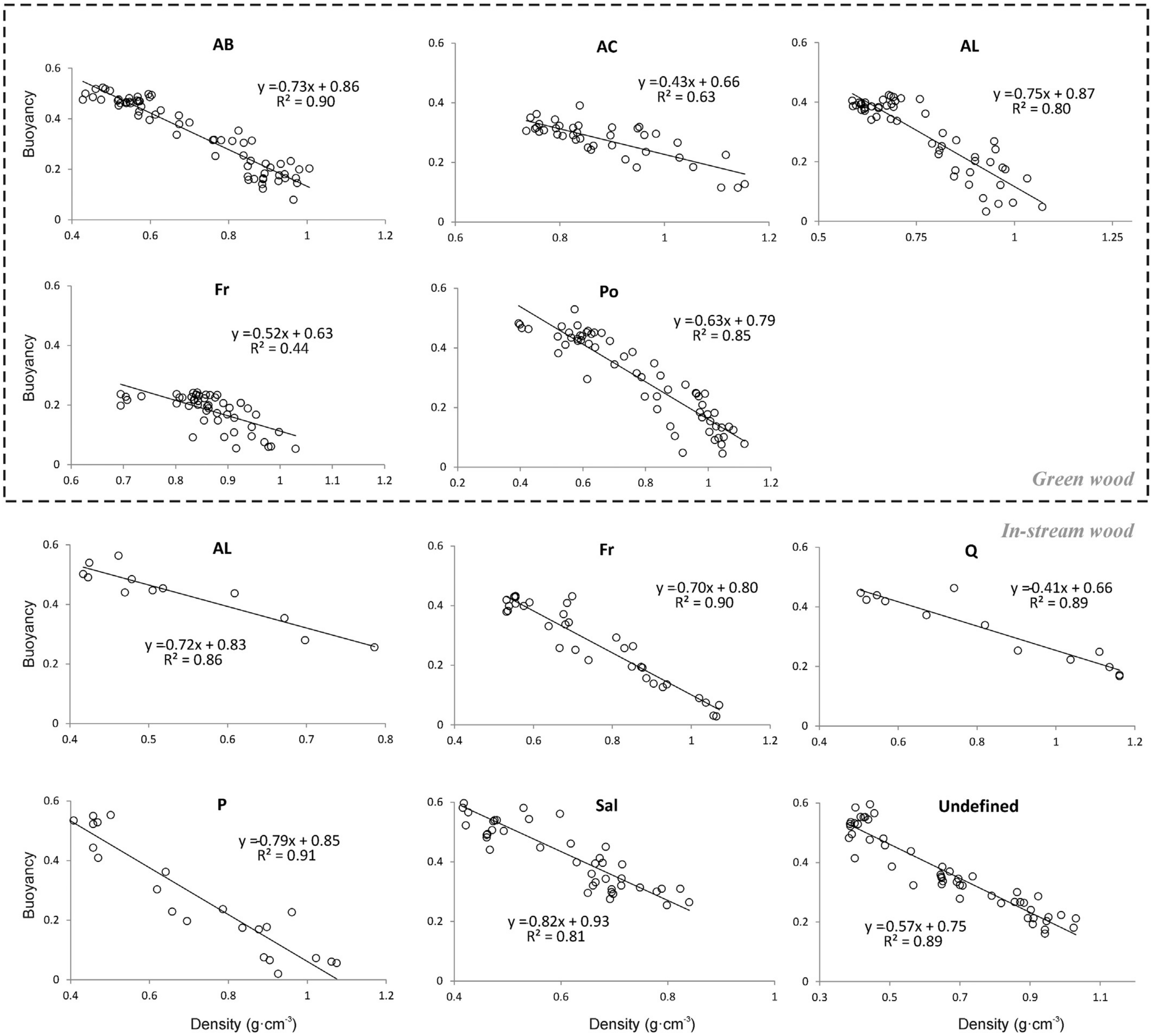

Fig. 7. Relationships between buoyancy and wood density for green wood samples for all wetting and drying samples and the 5 species: AB: *Abies*, AC: *Acer*, AL: *Alnus*; Fr: *Fraxinus*; Po: *Populus*; Q: *Quercus*; Sal: *Salix*.

immediately after the flood in a forested stream in western Japan. Shields et al. (2004) observed dry wood densities between 390 kg·m^{-3} and 760 kg·m^{-3}, while wet densities ranged between 980 kg·m^{-3} and 1150 kg·m^{-3} in Little Topashaw Creek (Mississippi, USA). Turowski et al. (2013) found a large fraction of wood samples with densities >1000 kg·m^{-3} in a mountain stream in Switzerland. Cadol and Wohl (2010) calculated dry densities for wood ranging between 239 kg·m^{-3} and 1057 kg·m^{-3} and wet densities ranging between 879 kg·m^{-3} and 1379 kg·m^{-3} (median = 1152 kg·m^{-3}, SD = 144 kg·m^{-3}) in two streams in Costa Rica. Merten et al. (2013) calculated an average wood density of 780 kg·m^{-3} in wood samples analyzed in 12 streams in Minnesota (USA), with more than 84% of the samples having densities >500 kg·m^{-3} (23% had densities >1000 kg·m^{-3}, 27% had densities between 900 kg·m^{-3} and 800 kg·m^{-3} and 36% between 700 kg·m^{-3} and 500 kg·m^{-3}).

We observed statistically significant differences in wood density between surveys at Génissiat. These differences might be due to different associations of species probably related to the flood that transported the wood and the source of the wood in the catchment (Benacchio et al., 2015). It was out of the scope of this study to analyze this in detail, so only some general comments are given here. For Génissiat, the main sources of wood during floods are the stored wood within the fluvial corridor and the recruited wood from bank erosion along the Rhône River and the two main tributaries, the Arve and Valserine Rivers. Depending on the flood conditions (which watershed contributes more water to the main stem) and the different recruitment processes in the region (i.e., landslides and other mass movements, bank erosion), the mix of wood found stacked behind the dam could contain different species (e.g., more conifers in the case of wood recruited from slopes by mass movements), tree ages (e.g., older trees can be expected to be recruited during a very intense flood producing significant bank erosion), or exhibiting different levels of decay (Moulin and Piégay, 2004; Benacchio et al., 2015).

Moisture or water desorption and absorption significantly changed the values of wood density during drying and wetting experiments. We observed that green wood gained moisture more slowly than

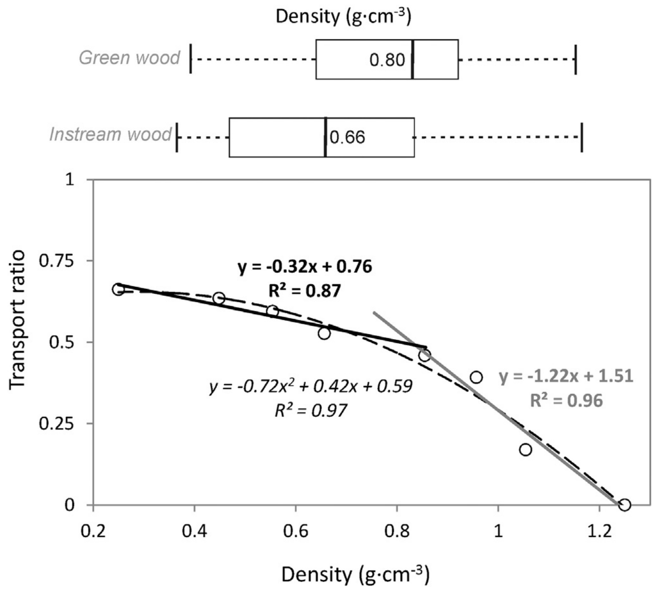

Fig. 8. Relationship between wood density and wood transport ratio. Result from numerical modeling. Boxplots show wood density ($g\cdot cm^{-3}$) values obtained for samples of green and instream woods during our experiments (green wood shows an average density value of 0.8 $g\cdot cm^{-3}$ ($\pm$0.17 $g\cdot cm^{-3}$), whereas instream wood exhibits much lighter values with an average of 0.66 $g\cdot cm^{-3}$ ($\pm$0.20 $g\cdot cm^{-3}$).

instream wood, but green wood lost moisture a bit faster than instream wood during the drying process. We also observed that instream wood samples stayed afloat considerably longer (instream wood samples sank more slowly in the water tanks) than green wood. And for instream wood samples, absorption was faster than desorption, while the opposite was true for green wood samples (desorption was faster than absorption). In general terms, the rate of water absorption depends on the difference between the saturation water content and the water content at a given time. As sorption proceeds, water content increases, and this difference diminishes. A higher difference between the saturation water content and the water content in the case of instream wood would explain a higher capacity to gain moisture content. Therefore, the initial moisture content and the effect of immediate past history control the wetting and drying processes (Skaar, 1972). When drying wood, free water is lost first because it is held with weaker capillary forces. This fact may explain our observations that moisture desorption of green wood is faster than absorption, since green wood generally contains water in free forms. This is also one of the reasons why desorption from a green condition is considered different than from any subsequent desorption, even from the saturated condition (Engelund et al., 2013). On the other hand, instream wood may contain less free water, and absorption is therefore faster than desorption. In addition, other wood properties may influence moisture sorption, such as the age of individual wood pieces as was found by Thévenet et al. (1998). During their experiments, Thévenet et al. (1998) also observed a difference among absorption and desorption processes. In their case, desorption was faster than absorption, and they did not observe differences between oven-dried samples and air-dried. This illustrates that results from these types of experiments are influenced by the analyzed samples (small size) and experimental design (previous oven dry). In our study, we analyzed instream samples taken from the Génissiat reservoir in the Rhône River and trees living in the floodplain of the Ain River. Clearly, recruitment processes and fluvial dynamics determine the type, amount, and size of instream wood, and the riparian forest ecosystem and management determine the green wood species. Moreover, wood is a biological, porous material that is both anisotropic and heterogeneous with a complicated internal cell structure making generalizations unreliable. However, we believe that our findings represent a big step forward in the analysis of LW density and mobility and that the values presented here can be useful especially for similar piedmont rivers of Europe. Therefore, despite the fact that a limited number of samples are unlikely to be representative of all different types of LW (Swenson and Enquist, 2008), an improved understanding of the wetting and drying patterns and the estimated wood density values are likely to be helpful in predicting other unsampled species or similar types of LW.

The analysis of real logs, with relatively large size (compared to disks, slices, wood veneers, twigs or cores), forced us to design manageable laboratory and in-situ experiments, occasionally less complex than other approaches published in the literature (Williamson and Wiemann, 2010). Therefore some limitations should be discussed here. One challenge in our experiments was related to the determination of volume. While determining volume using water displacement is probably the most accurate method, it is relatively slow and works best for small volumes. Volumes determined by external dimensions, although less precise, can be taken rapidly in the field or for very large volumes of wood (Harmon et al., 1986, 2011). We assumed that wood was dimensionally stable, as it is when moisture content is greater than the fiber saturation point (Tiemann, 1906; Skaar, 1988). This assumption might have influenced the final calculations of wood density, affecting the ranges and dispersions observed in our results.

The samples we analyzed (both, green and instream wood logs) were cut using a chainsaw, and both sides were freshly cut in all cases. This may also have had an influence on the water absorption and desorption processes. In addition, there are other characteristics which may influence the density values we obtained in our study. In general terms, wood density increases as the proportion of cells with thick cell walls increases, and in riparian species, density also depends on the amount of void space occupied by vessels and parenchyma. Moreover, the proportion of heartwood to sapwood influences density as well, and this relationship depends on species, age of the tree, and size of the log. Sapwood has a higher density, higher green moisture content, and is more permeable to moisture movement than the heartwood (Harmon and Sexton, 1996; Bütler et al., 2007). Thus sapwood normally dries more quickly, but the higher volume of moisture present means that after the same period of drying, the sapwood might be still wetter than heartwood. However, Pichler et al. (2012) analyzed average moisture differences between heartwood and sapwood, and they found that differences were lower than expected. In addition, wood density may also decrease from the stem base to the top of the trunk (Repola, 2006; Sandström et al., 2007; Köster et al., 2009). The highest values of density we observed in our samples were those of *Fraxinus*, *Acer*, and *Alnus* compared with the other species. This is related to the wood anatomy of these species, and specific characteristics and conditions in the region. However, we did not analyze wood anatomy in detail, neither the age of samples nor the ratio between heartwood and sapwood, which may have influenced our final results.

Decay is another factor influencing wood density. According to our observations and the RDF, the samples extracted from Génissiat were slightly decayed. Wood decay in aquatic systems might be very different than in forests. Submersion in water may reduce or even stop decay (Borgin et al., 1979), whereas changes in moisture conditions and dry and wet cycles (due to changes in the hydrological regime) can accelerate decay. With advancing decay, water may also more easily saturate logs (Braudrick et al., 1997).

The numerical experiment carried out in this work was designed to be simple but representative of rivers like the Rhône or Ain Rivers. As the goal was to test the influence of wood density on transport of logs, very few scenarios were tested, keeping all parameters constant except for wood density. However, many other variables affect wood mobility and transport (Ruiz-Villanueva et al., 2015a), such as the morphology of the river, flow conditions (i.e., flow depth and velocity) and wood shape (i.e., the presence of roots or branches). Based on our findings, we can hypothesize that wood deposited on floodplains or bar crests during floods begins to dry and decay, decreasing moisture content and wood density. If mobilized during the next high flow episode, the same piece of wood would be transported more easily, at least at the beginning of movement. This wood element may again become wet during transport, changing density during the flood (although we found this process to be slower than the duration of most floods, i.e., taking days rather than hours). The model proposed for density change due to changes in the moisture content (Eq. (8)) could be used to estimate the influence of this on wood buoyancy (e.g., to calculate the time to sink) and it could be added to numerical models to analyze wood transport under a variable density. Increased density influences mobility, as we demonstrated with our findings, therefore higher water levels and/or flow velocities would be required to keep a wetter log in motion. The same effect can be expected for very fresh recruited wood (almost green wood) and for a high density (e.g., *Acer*) dominant tree species on transport and retention in streams, which would need higher discharges than decayed and lighter density trees (e.g., *Abies*) to be transported downstream.

5. Conclusions

In this study, we illustrate that conditions and processes in rivers, such as wetting and drying as a result of flow variability, may significantly impact wood properties including density. Our results demonstrate that wood density values taken from global databases should be used with caution when it comes to the characterization of instream wood density, especially when analyzing wood mobility, as they are calculated based on oven-dried samples or in the context of forest inventories. We analyzed the variance in density related to tree species, decay state, and recent history of wetting and drying. Our experiments show that absorption and desorption processes depend on the initial moisture content, and both processes can be explained by an exponential model, which can be used to analyze wood density variability due to changes in moisture. According to our findings, differences in density and sorption processes have a substantial impact on wood buoyancy and mobility. Thus, the ability of wood to be transported during high flows can be very different between (partly) decayed instream and freshly recruited green wood. Therefore, variability in wood properties needs to be taken into account more carefully in future LW studies. In particular, when analyzing dynamics and mobility of wood in rivers, standard values for density can no longer be considered to be representative for instream wood, not even for the same species.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.catena.2016.02.001.

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