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Wood density assessment to improve understanding of large wood buoyancy in rivers

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ABSTRACT: Drift wood (or in-stream large wood, LW) plays an important role in river ecosystems by influencing hydrodynamics and morphology. Wood density, therefore, buoyancy, is the main factor conditioning initial motion of wood in rivers. The better understanding of wood density and the dry-wet process and decay, may be useful to improve the knowledge of wood dynamics in rivers. We analyze wood pieces retained in a dam, in the French Rhone, and a set of freshly cut riparian trees. Different protocols were set to measure density and buoyancy of these two series of wood and to test effects of drying and wetting, species and wood decay stages. Preliminary results after seven months of experiments show different behaviors in density and buoyancy depending on species. Light wood (360–500 $kg \cdot m^{-3}$) is likely to show a buoyancy rate about 52% (half of the log emerged), medium density wood (500–700 $kg \cdot m^{-3}$) about 39%, 21% for dense wood (700–900 $kg \cdot m^{-3}$) and 12% for very dense wood (>900 $kg \cdot m^{-3}$). We observed a significant negative correlation between wood density and buoyancy and proposed a model to predict wood buoyancy. The results from this work will help to understand the evolution of buoyancy through time and estimate local conditions of entrainment and transport of wood in rivers.

1 INTRODUCTION

In-stream Large Wood (LW) plays an important role in river ecosystems by influencing hydrology, hydraulics, sedimentology, and morphology (Montgomery, 2003). An extensive literature now exists describing the influence of wood on stream ecology (Gregory et al., 2003; Kasprak et al., 2011), and more recently on stream geomorphology (Gurnell, 2012; Wohl, 2013). Recent research has focused on the mobilization of woody material during floods (Comiti et al., 2012), as transported woody material can cause a substantial increase in the destructive power of floods (Ruiz-Villanueva et al., 2012).

Various characteristics of a piece of wood affect its likelihood of movement (e.g., wood density, buoyancy, orientation, size, and form related to flow depth, velocity, and roughness; Le Lay et al., 2013).

In this study, we analyze wood buoyancy to determine whether floating or sinking of wood pieces through the water column has a fundamental impact on river dynamics. Buoyancy typically varies with tree species and decay rates. So, the most important property affecting river wood mobility and particularly the capacity of LW to float in freshwater is wood density. Wood density varies greatly among tree species, but it also varies for each of the species according to water content and degree of decay.

Therefore, the time during which wood pieces are wetting or drying can affect their dynamics when they enter the river. The final goal of this work is to improve our understanding of wood buoyancy in rivers throughout the assessment of wood density for different types of wood and decay stages and to find a model to predict wood buoyancy.

2 STUDY SITE AND METHODOLOGY

2.1 *Sampling*

The characteristics of the wood are assessed using two series of wood pieces, one extracted from a reservoir (decayed floating wood) and another from living trees used as a reference (green or fresh wood). The decayed wood analyzed was collected from wood pieces retained in the Génissiat reservoir, French Rhone (watershed area of 10,910 km^2 at Génissiat). This gravity dam has no overflow pathway so that all wood coming from two main tributaries, the Arve and Valserine Rivers, is blocked by the dam, even during floods, and must be extracted mechanically (Fig. 1).

Figure 1. Wood pile unloaded form a track at Génissiat dam.

Table 1. Experiment aspects: factors (inputs) to the process; settings of each factor in the study, and response (outcomes) of the experiment. C means calculated, M means measured; Ob observed.

Factors	Settings	Outcomes
Wood density	Different species	Buoyancy (C), density (C), weight (M), emerged height (M), Maximum moisture content (Ob); Moisture content to sink (M); Equilibrium moisture content (Ob)
Water content	Dry/wet wood	
Wood decay	Green/dead wood	

The green wood was obtained from trees cut from the riparian forest of the Ain River (tributary of the Rhone).

We collected 150 samples of green wood from 5 different trees, one per species (*Fraxinus, Acer, Populus, Alnus* and *Abies*), and 120 samples from Génissiat dam (identified as *Populus*, *Abies, Alnus, Fraxinus* and *Quercus*). From those identified samples in Genissiat 45% are *Populus*, 23% *Fraxinus*, 14% *Abies*, 9% *Alnus* and 9% *Quercus*.

2.2 *Properties of wood and experimental set up*

Wood sample size (length and diameter) and weight (using a balance with an accuracy of 10 gr.) were measured immediately after they were cut or extracted from the dam.

Wood density can be calculated as the ratio of its mass to its volume. Both mass and volume depend on moisture content (Table 1).

Moisture content of wood is defined as the weight of water in wood expresses as a fraction, usually a percentage, of the ovendry weight of wood. Since we do not ovendry samples, we referred as initial moisture content the first measurement (just after cutting or extraction from the dam).

Moisture can exit in wood as liquid water (free water) or water vapor in cell lumens and cavities and as water held chemically (bound water) within cell walls. The moisture content at which both the cell lumens and cell walls are completely saturated with water is the maximum moisture content (M_{max}). 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 (M_{sink}). However, we finish the experiment when the piece of wood is sunk, so M_{sink} is the maximum moisture content value we consider. Conceptually, the moisture content at which only the cell walls are saturated but no water exits in cell lumens is called the fiber saturation point. The moisture content of wood below this fiber saturation point is a function of both humidity and temperature. The moisture content at which the wood is neither gaining nor losing moisture is defined as Equilibrium Moisture Content (EMC).

Samples were divided into different groups to analyze drying and wetting processes to observe the variability in moisture content (density) and therefore in buoyancy. A total of 220 samples were stored outside protected from rainfall and where air temperature was recorded, and 50 samples were placed in plastic boxes in water (Fig. 2).

Weight (moisture content) and buoyancy of wood samples belonging to both categories were measured every month.

To measure wood buoyancy, samples were placed in sinks filled with water, and using a point gauge the emerged height was measured at both

Figure 2. Samples submerged in water and stored in plastic boxes.

ends of the wood sample, thereby obtaining buoyancy (B) as the percentage (%) or ratio (0-1) of emerged height (h) from the entire log diameter (D). In case that the log was not perfectly straight, several stable floating positions could be observed. In this case, we measure the emerged height in all stable positions.

3 PRELIMINARY RESULTS

Preliminary results after six months of running the experiments show different behaviors in density and buoyancy depending on species and decay stage.

As expected, *Abies* samples show the lowest average wood density just after cutting, ranging from 590 to 890 kg·m^{-3}; whereas *Acer, Alnus, Fraxinus*, and *Populus* showed densities between 720 and 1080 kg·m^{-3}. The dead wood samples extracted from Génissiat dam exhibit a much larger spread in wood density ranging from 350 to 910 kg·m^{-3}. After six months of wetting, the samples placed in the containers increased their water content up to 66%; whereas the samples that were stored in dry conditions reduced their water content by 42% (Fig. 3).

Large variability was observed in samples, point to significant differences in water content as compared to initial conditions in both the wetting and drying experiments. As Figure 2 shows, the wetting and drying curves are not symmetric. Between 94 and 109 days the maximum moisture content (M_{max}) and Equilibrium Moisture Content (EMC) are reached.

In general terms light wood specimens (*Abies* and *Populus*) lost the highest MC (up to 42%), while *Alnus, Acer* lost around 35–36%, and *Fraxinus* lost a lower percentage of MC (23%) when drying. The drying process could be accelerated at the beginning of the experiment (summer) because of the air temperature. But, the conditions were homogenous for all samples, so we can compare different behaviors among the samples.

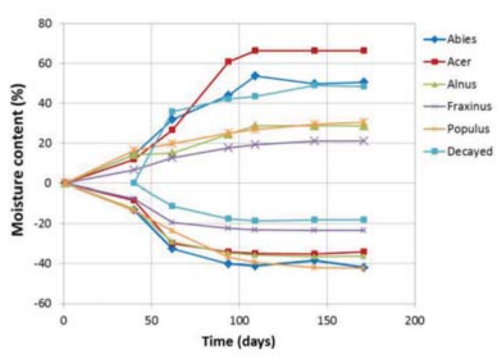

Figure 3. Temporal variability in average mass (due to increase or decrease in water content) of the samples.

On the other hand, hard wood samples (*Alnus* and *Fraxinus*) gained the lowest percentage of MC when wetting (28% and 21% respectively), while *Populus* (30%), *Abies* (53%) and *Acer* gained up to 66%.

In terms of average wood density this variability is also observed. Figure 4 shows some examples, for *Abies* and decayed wood (Fig. 4 A–B and E–F), which underwent significant differences in density, and *Fraxinus*, with less variability (Fig. 4C–D).

Differences in moisture (water) content clearly affect buoyancy (Figs. 5–6), which is ranging from 38% (38% of the log is emerged; *Abies*) to 20–17% (*Acer* and *Fraxinus*) as initial values, and increased up to 49% (*Abies*), 33% (*Acer*) and 23% (*Fraxinus*) for dry samples; or decrease between 0% (completed submerged; *Acer, Alnus* and *Fraxinus*) to 15% (*Abies*), 5% (*Populus*) for wet wood.

From the wetted samples, all Acer specimens sank within two months (62 days), as did all Alnus, after 3 months (109 days), and all Fraxinus after 4 months (143 days). Only 33% of the Populus samples are sunk so far, the rest are close to sink with buoyancy around 2%, while all Abies did not

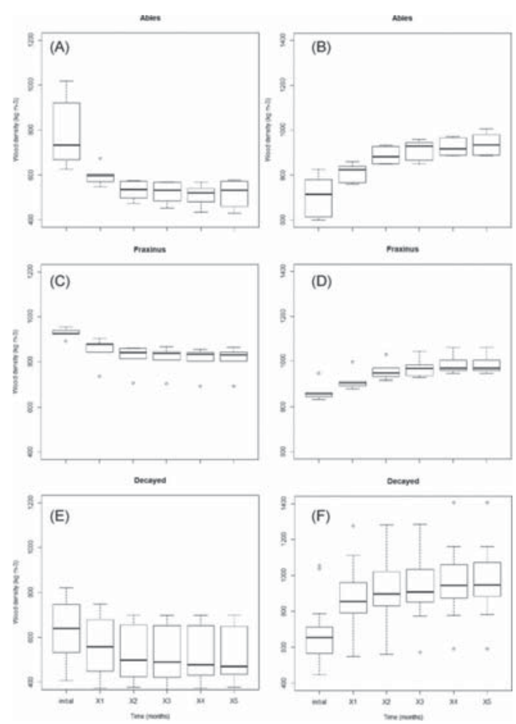

Figure 4. Temporal variability of average wood density (including water content) for *Abies* (A and B), *Fraxinus* (C and D), and the decayed wood from Génissiat dam (E and F; all species combined), and for drying (left) and wetting (right) process.

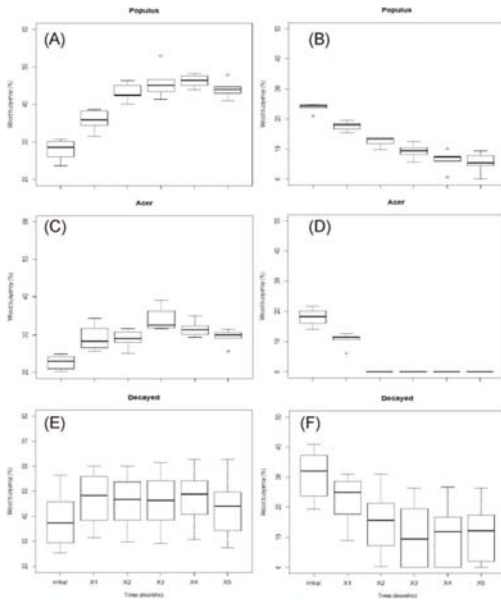

Figure 5. Temporal variability of wood buoyancy (%) for *Populus* (A and B), *Acer* (C and D) and decayed wood from Génissiat dam (E and F; all species combined), and for drying (left) and wetting (right) process.

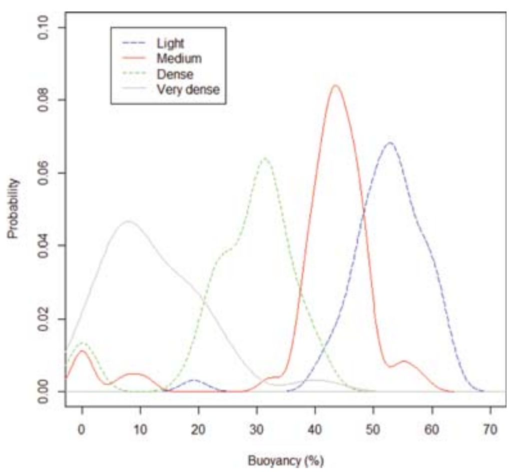

Figure 6. Probability density functions of buoyancy (%) for different ranges of average wood density (light: 360–500 $kg \cdot m^{-3}$; medium: 500–700 $kg \cdot m^{-3}$; dense: 700–900 $kg \cdot m^{-3}$; very dense: >900 $kg \cdot m^{-3}$).

sink and exhibit a buoyancy rate of ca. 10%. The already sunk samples are drying again to analyse how they recover buoyancy.

We can classify all the green wood samples according to the average wood density (wet and dry samples included) in light wood, medium, dense and very dense wood, and analyse how the buoyancy varies among these groups (Fig. 6).

In addition we can compare the probability distribution of buoyancy between green wood and decayed wood samples (Fig. 7).

According to this analysis, light wood is likely to show a buoyancy rate about 52% (half of the log emerged), medium density wood about 39%, 21% for dense wood and 12% for very dense wood. Green wood shows lower values of buoyancy (mean 27%, SD 16%), and lower variability than buoyancy in decayed wood samples, which shows higher variability and higher values (mean 32%, SD 18%).

A significant ($p\text{-value} < 0.002$) negative correlation between wood density and buoyancy is observed in all cases (Fig. 8). For a linear regression model the coefficient of determination (R^2) is ranging

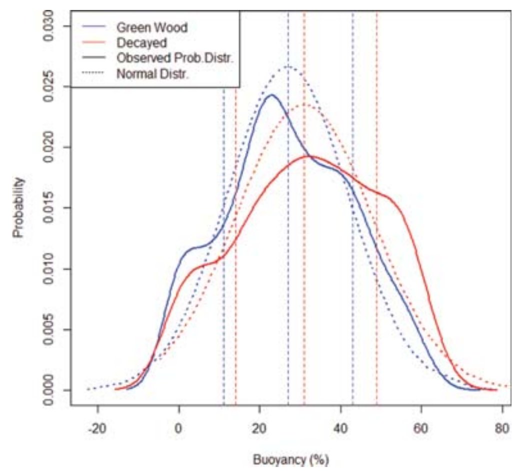

Figure 7. Probability density functions (observed and fitted to normal) of buoyancy (%) for green wood and decayed wood samples (wet and dry samples combined). Vertical lines shows mean and standard deviation values.

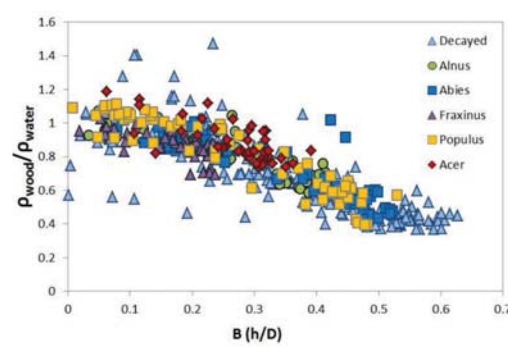

Figure 8. Relationship between density and buoyancy ratios for all green and Génissiat samples.

Table 2. Main results obtained after six month of experiments. SD means standard deviation, EMC equilibrium moisture content, MC moisture content. Highlighted in grey are the species still floating.

Specie	Wood density (SD) ($kg \cdot m^{-3}$)	Days to sink	Days to EMC	% MC lost	% MC gained	Initial buoyancy (SD) (%)
Abies	693 (102)	>180	109	42	53	36 (8)
Acer	794 (79)	62	94	35	66	22 (4)
Alnus	874 (73)	109	109	36	28	23 (4)
Fraxinus	816 (70)	143	109	23	21	19 (4)
Populus	793 (118)	>180	171	42	30	25 (5)
Decayed	706 (151)	>180	109	18	49	34 (10)

from 0.54 to 0.86, depending on the specie and for all samples combined; and the exponential model, R^2 was ranging from 0.51 to 0.82. Abies, Alnus and Populus showed the best correlations (both linear and exponential, with R^2 ranging from 0.76 to 0.86), Génissiat wood and all samples together showed R^2 from 0.55 to 0.68, and Acer and Fraxinus revealed the lowest correlation of wood density and buoyancy, with R^2 equal to 0.55 and 0.64 for the linear and exponential model respectively.

All samples combined from the green wood revealed a correlation of 0.71 both linear and exponential, and for all samples analysed (green and dead wood) the determination coefficient was 0.63 and 0.68 (linear and exponential).

According to this the relation between wood buoyancy and wood density can be assumed as linear following the model:

$$B = -0.7 \cdot \rho_{wood} + 0.86$$

Table 2 summarizes the preliminary results explained above.

4 PRELIMINARY DISCUSSION AND ONGOING WORK

Despite the fact that a limited number of samples have been selected from a few tree species is unlikely to be representative for all different tree species and forest types; samples allowed analysis of different behaviours of wood in water, in terms of buoyancy depending on 5 freshly cut species, decayed wood and different water content. Density of wood varies significantly between species, but we also observed variability among samples of the same species, so the estimated values of wood density should be considered representative of the specie, but they can be different from another study. These differences exist because of anatomical characteristics such as the ratio of early wood to latewood and heartwood to sapwood. In addition minerals and extractable substances may also affect density.

A combination of the geometrical approach to obtain average wood density and physically-based measurements are yet to be implemented and will allow estimation of calculation errors.

In addition, a detailed characterization of wood extracted from Génissiat dam is in progress to better set buoyancy in real in-stream wood. The size of 312 samples was measured and 100 samples were also weighted (Fig. 9).

Several species were identified during the sampling campaigns with several decay stages. Additional analysis will be carried out to identify some undetermined samples.

The estimated mean average density for all samples is 706.25 $kg \cdot m^{-3}$ ($\pm$150.48 $kg \cdot m^{-3}$). Regarding the size, for pieces larger than 10 cm in diameter the average was 16.71 cm ($\pm$9.1 cm), and the maximum was 65 cm. In general we could classify the wood extracted from Génissiat as medium to dense regarding its density (ranging from 600 to 800 $kg \cdot m^{-3}$). Following our experiment findings, for medium to dense wood buoyancy is likely ranging between 39 and 21% (mean of 30%). Indeed we found an average value of wood buoyancy for all samples extracted from the dam of 32%, which agrees with the experiment results. Knowing wood buoyancy we could improve the estimation of wood size (diameter) from video cameras used for wood budgeting. In the records only the emerged part of the log is observed, and this is normally used to estimate log diameter. To be considering this observed part the real log diameter, buoyancy should be at least 50%, and this is unlikely (according to our findings). If buoyancy is around 30%, we could be underestimating wood budget in a 20%. If buoyancy is around 10%, then the error in the wood budget estimation increases up to 40%.

Moreover, and according to the experiment results so far, samples from Génissiat are sinking slower than freshly cut samples. This may be related to the species (mainly softwood species, such as *Populus*), the drying and wetting history and the residence time in the reservoir before extraction. From the

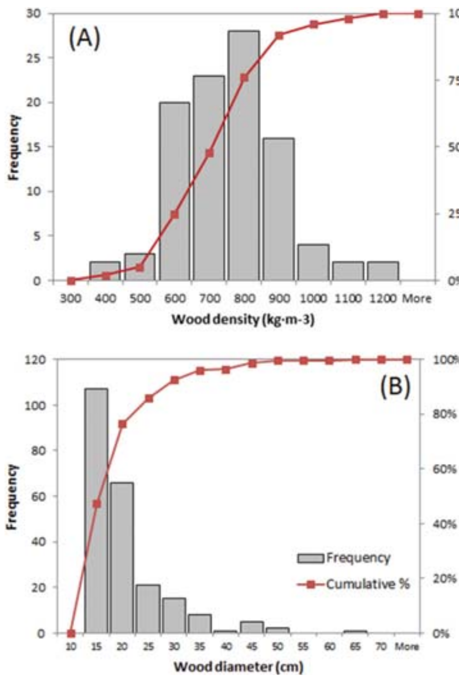

Figure 9. Frequency distributions of (A) average wood density and (B) wood diameter.

freshly cut we observed that *Acer*, *Alnus* and *Fraxinus* are likely to sink faster than *Abies* and *Populus*. The observed times to sink are highly influenced by the fact that the samples are cut for both sides and this may increase the flow of water through the cells. But, since this is the same for all samples, we can compare different behaviors. The likelihood of sinking for different species can be useful information for the reservoir and dam managers.

In addition, wood density, therefore, buoyancy, is one of the main factors conditioning initial motion of wood in rivers. The better understanding of wood density and the dry-wet process and decay, may be useful to improve accuracy when initial motion is calculated, in hydrodynamics models for instance.

Wetting and drying processes and relation to wood density can be useful to understand wood mobility in rivers and the influence of antecedent floods. In a river where wood recruitment is mainly controlled by bank erosion during extreme floods, when one of this event occurs fresh wood is expected to be recruited, so in general terms dense wood (depending on the species). While after ordinary flood when mainly the previously deposited wood is transported, this wood will be lighter (after drying) or heavier (if it is stored floating and wetting in the river). We could expect that lighter wood will travel longer distances floating in the flow, unless interactions with the riverbed, bars or infrastructures happened; while dense wood will be rapidly deposited. Of course the transport and deposition will depend also on the presence of roots or branches, and not only on the wood density.

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