

## Sapwood Area Related to Tree Size, Tree Age, and Leaf Area Index in *Cedrus libani*

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**Abstract:** Sapwood includes the water conducting part of the stem which transports water and minerals from roots to leaves. Studies using sap flow gauges have to determine the area of the sapwood in order to scale measured sap flow densities to the tree or stand level. The aim of this study was to investigate the relationship between sapwood area at breast height and other tree parameters which are easy to measure of the montane Mediterranean conifer *Cedrus libani*, including a total number of 92 study trees of different size and age. The study was conducted at four different stands situated between 1000 and 2000 m altitude in the Elmalı Cedar Research Forest of Antalya, SW-Turkey. Sapwood area of the study trees was determined by extracting two tree cores from opposite directions of the stem using an increment borer and by visually assessing the wet part of the core. Parameters measured besides sapwood area were diameter at breast height, stem radius without bark, sapwood depth, tree basal area, tree height, tree age, and projected crown area. Furthermore, at each stand, leaf area index (LAI) was determined using hemispherical photographs of the forest canopy. The most significant relationship was found between stem radius without bark and sapwood area ( $R^2$ : 0.94) followed by tree basal area and sapwood area ( $R^2$ : 0.90). Although it was the second best predictor, tree basal area should be used to estimate sapwood area when estimating stand transpiration since it can be measured faster and without giving damage to the tree. Mean sapwood area and mean site-specific LAI showed a significant positive correlation. The findings of this study can be used in ecophysiological studies when transpiration rates of *C. libani* are measured using sap flow gauges.

**Keywords:** Taurus cedar, sapwood width, sap flow, LAI.

### 1. Introduction

Sapwood is the living and water conducting portion of the stem which transports water and minerals from roots to leaves, and where to a lesser extent energy reserves are stored (Matyssek et al., 2010). With increasing age parenchyma cells die and tracheids and vessels lose their ability to conduct water (Plomion et al., 2001). The non-conductive part of the wood (heartwood) is often infiltrated by tannins which cause a change in color. The proportion between sapwood and heartwood of a stem's cross-section vary between tree species but also among individuals of the same species or a single individual (Matyssek et al., 2010). The amount of sapwood is also an indicator of tree health since stressed trees have less sapwood (Lehmann and Becker, 1993).

In the industrial context (e.g. lumber production), it is important to know about physical and technological properties of the sapwood because they differ from those of the heartwood (Longuetaud et al., 2006). In ecophysiological studies sapwood is an important parameter when measuring sap flow rates and transpiration of single trees or whole stands (Gebauer et al., 2008; Motzer et al., 2005; Phillips et al., 1996; Wullschleger et al., 2004). The amount of sapwood area to leaf area (or leaf biomass) is an indicator about the water conducting capacity of the sapwood in relation to transpiration demand, and about the photosynthetic production relative to respiratory costs (Longuetaud et al., 2006; Mäkelä et al., 1995; Rodriguez- Calcerrada et al., 2015). Several studies have investigated the relationship between sapwood area and other parameters in

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various tree species, especially from temperate forests (Ford et al., 2004; Gebauer et al., 2008; Long and Dean, 1986). In *Picea abies* (L.) Karst. for example (Longuetaud et al., 2006), a high positive correlation was found between sapwood width and tree height, and diameter at breast height (DBH). Until now, no study was found that investigated the relationship between sapwood area and tree size, or between sapwood area and tree age of *Cedrus libani* A. Rich.

*C. libani* (Taurus cedar) is a drought tolerant and cold-resistant evergreen conifer of the Pinaceae family. Covering around 600.000 ha, today its largest distribution is found in Turkey (Boydak, 2003). *C. libani* mainly grows at altitudes ranging from 800 to 2100 m a.s.l. where montane Mediterranean climate conditions prevail (Evcimen, 1963). In a recent study published by Messinger et al., (2015), it was shown that planted *C. libani* individuals growing in the Ecological Botanical Gardens of Bayreuth under Central European climate conditions show high adaptation

and good growth performance. The good growth seems mainly to be attributed by the more humid conditions and better water supply during the summer months. In Turkey and outside its natural range, *C. libani* is used for forestation and afforestation projects and discussions about its growth and adaptation potential under different site conditions and future climate scenarios carry on (Boydak 2007; Ducci et al. 2007; Güney et al., 2017). Besides its ecological importance it is one of the most important commercial tree species in Turkey (Boydak, 2003; Kavgacı et al., 2010). Therefore it is of interest to further explore this species, especially in terms of its ecophysiology since only few studies have been carried out so far.

The specific objectives of this study were to investigate (1) the relationship between sapwood area at breast height (1.30 m) and other tree parameters of *C. libani*, and (2) to test if there is a relationship between mean sapwood area and mean leaf area index in *C. libani* stands.

**Table 1.** Characteristics of the study trees selected at four different sampling sites (T1 – T4) within the Elmalı Cedar Research Forest and site-specific leaf area index (LAI). Differences between sites were tested using ANOVA. Significant differences ( $P < 0.05$ ) are indicated by lower case letters.

|   | T1_1960 m               | T2_1665 m                   | T3_1355 m                    | T4_1050 m                | F-value | P     |
|---|-------------------------|-----------------------------|------------------------------|--------------------------|---------|-------|
| Latitude  | 36.58422°N              | 36.58520°N                  | 36.57771°N                   | 36.57800°N               | -       | -     |
| Longitude   | 30.03077°E              | 30.02035°E                  | 29.98542°E                   | 29.96881°E               | -       | -     |
| Number of trees (n)                               | 23                      | 24                          | 23                           | 22                       | -       | -     |
| Sapwood area (m <sup>2</sup> )                    | 0.22±0.20 <sup>a</sup>  | 0.40±0.19 <sup>b</sup>      | 0.38±0.24 <sup>ab</sup>      | 0.34±0.26 <sup>ab</sup>  | 3.20    | 0.027 |
| Diameter at breast height (cm)                    | 20.1±9.7 <sup>a</sup>   | 33.9±10.3 <sup>b</sup>      | 31.3±11.9 <sup>b</sup>       | 27.8±15.1 <sup>ab</sup>  | 5.96    | 0.001 |
| Radius without bark (cm)                          | 9.0±4.9 <sup>a</sup>    | 14.6±4.5 <sup>b</sup>       | 14.1±5.5 <sup>b</sup>        | 12.6±7.3 <sup>ab</sup>   | 4.66    | 0.005 |
| Sapwood depth (cm)                                | 4.7±1.2                 | 5.1±1.2                     | 4.9±1.4                      | 5.1±1.1                  | 0.63    | 0.596 |
| Tree basal area (m <sup>2</sup> )                 | 0.039±0.05 <sup>a</sup> | 0.099±0.06 <sup>b</sup>     | 0.087±0.07 <sup>ab</sup>     | 0.078±0.08 <sup>ab</sup> | 3.67    | 0.015 |
| Height (m)  | 7.3±1.8 <sup>a</sup>    | 18.4±4.8 <sup>b</sup>       | 18.7±4.7 <sup>b</sup>        | 12.4±5.3 <sup>c</sup>    | 35.51   | 0.000 |
| Age (years)                                       | 44.8±25.6 <sup>a</sup>  | 92.4±23.8 <sup>b</sup>      | 87.3±25.2 (n=8) <sup>b</sup> | 52.2±28.6 <sup>a</sup>   | 17.23   | 0.000 |
| Projected crown area (m <sup>2</sup> )            | 12.9±8.2 <sup>a</sup>   | 10.7±9.7 (n=9) <sup>a</sup> | 30.2±15.6 <sup>b</sup>       | 22.4±17.6 <sup>ab</sup>  | 7.81    | 0.000 |
| Leaf area index (m <sup>2</sup> m <sup>-2</sup> ) | 1.04±0.45 <sup>a</sup>  | 2.93±0.46 <sup>b</sup>      | 3.22±0.89 <sup>b</sup>       | 2.37±0.65 <sup>c</sup>   | 42.26   | 0.000 |

## 2. Material and Method

### 2.1. Study area and tree selection

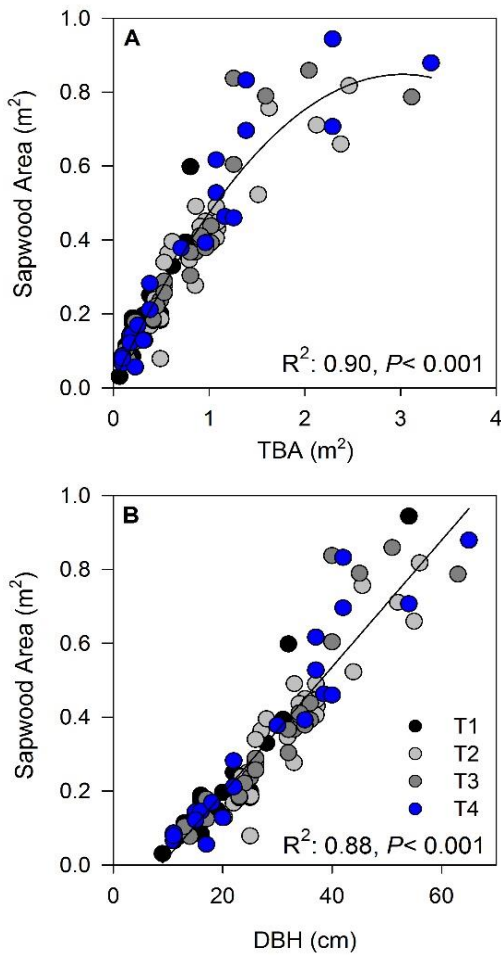
The study was conducted during March 2013 and end of 2014 within the Cedar Research Forest in the Elmali district of Antalya located in the southwestern Taurus Mountains. The forested parts exhibit mostly pure stands of *C. libani*, which are sometimes partly mixed with *Juniperus sp.* individuals. The area is characterized by an oro-Mediterranean climate with cold winters and drought periods during summer (Atalay, 1987) with a mean annual precipitation of 640 mm and mean annual temperature of 7.5 °C (Basaran et al., 2008). Our sampling sites (abbreviated as T1, T2, T3, and T4) were located along an altitudinal gradient ranging from approximately 1000 to 2000 m a.s.l. (Table 1). For further details about the characteristics of the sampling sites see Güney et al., (2017).

For analysis of sapwood area, between twenty-two and twenty-four mature *C. libani* trees of different size and age were randomly chosen per sampling site. None of the selected tree individuals had any visible damage (Güney et al., 2016). DBH was measured in two directions and then averaged. Tree height was measured with an ultrasonic distance meter with inclinometer (Vertex III, Haglöf Sweden AB, Langsele, Sweden). Tree basal area (TBA) was measured at breast height (1.30 m) including the bark. The projected crown area for each sample tree was determined by measuring the radius from stem to end of crown perimeter in eight directions (North, Northeast, East, Southeast, South, Southwest, West, and Northwest). Projected crown area was then estimated as a circle of which the diameter was calculated as an average of the eight measured radii (Kantola and Mäkelä, 2004). For T2, data of projected crown area is only available for nine trees.

### 2.2. Sampling and determination of sapwood area

To determine the sapwood area of all sample trees, tree cores were extracted at breast height using an increment borer (Suunto 300/400 mm, Finland). For each tree, two cores were extracted from the north and south facing side of the stem reaching to the pith. Since tree cores were taken during early spring and early winter the stems were assumed to

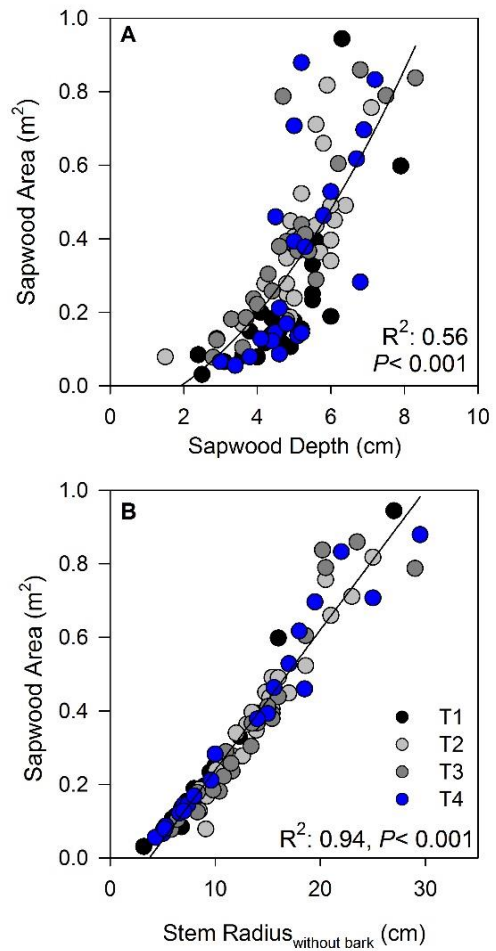
be fully hydrated and the sapwood was marked right after tree cores were taken as the visibly wet part of the xylem (Long and Dean, 1986). The natural change of color (the heartwood was more reddish brown) did not directly correspond with the boundary of wet to dry wood in most cases and was located closer to the pith. Additionally, several tree cores were stained with Lugol's solution (Rodriguez- Calcerrada et al., 2015) which showed a slight reaction close to the previously marked wet proportion of the cores. Nevertheless, the visibly wet outer part of the cores was taken as the sapwood depth since staining methods can result in high error rates. From the two cores, an average sapwood depth was determined for each tree. Sapwood area at DBH was then calculated as the area of the outer stem ring with a radius that is equal to the average sapwood depth while assuming a uniform circular sapwood (Horna et al. 2011). From the tree cores used for determination of sapwood area, tree age at breast height was defined by counting the number of tree rings, and radius without bark was measured. For mean values of each parameter at each sampling site see Table 1. At T3, exact determination of tree age was only possible for eight trees.



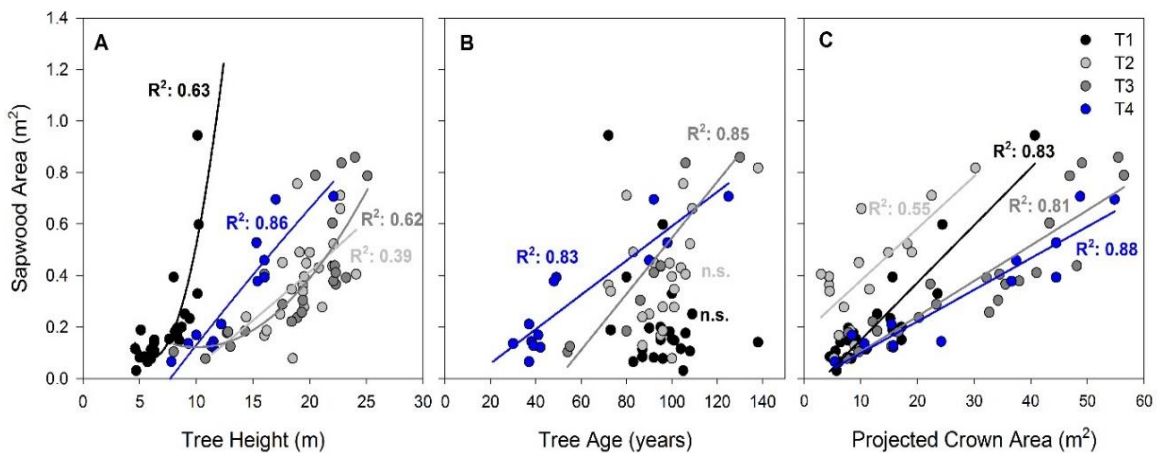
**Figure 1.** Relationship between Sapwood area and (A) tree basal area (TBA), and (B) diameter at breast height (DBH) of *Cedrus libani* at four different sampling sites (black circles: T1\_1960 m; gray circles: T2\_1665 m; dark gray circles: T3\_1355 m; blue circles: T4\_1050 m).

### 2.3. Determination of leaf area index

Leaf Area Index (LAI) is defined as “one half of the total leaf area per unit ground surface area” (Jonckheere et al., 2004). LAI was determined at seventeen different locations within each sampling site. Hemispherical photographs of the forest canopy were taken from the ground which were later analyzed via HemiView image analysis software (1999 Delta-T Devices Ltd, Cambridge, UK). The presented LAI values were published in Güney et al. (2017).



**Figure 2.** Relationship between Sapwood area and (A) sapwood depth, and (B) stem radius without bark of *Cedrus libani* at four different sampling sites (black circles: T1\_1960 m; gray circles: T2\_1665 m; dark gray circles: T3\_1355 m; blue circles: T4\_1050 m).



**Figure 3.** Relationship between sapwood area and (A) tree height, (B) tree age at breast height, and (C) projected crown area of *Cedrus libani* at four different sampling sites (black circles: T1\_1960 m; gray circles: T2\_1665 m; dark gray circles: T3\_1355 m; blue circles: T4\_1050 m). Level of significance  $P < 0.05$ . Please note that the scaling of the y-axes are identical.

#### 2.4. Data analysis

Simple regression analysis was used to compare the relationship between sapwood area and other measured parameters. Differences between sites in means of sapwood area and other measured parameters (e.g. DBH, sapwood depth, tree height, LAI, etc.) were tested using ANOVA. Analyses were performed with Sigma Plot 10.0 (Systat software, Inc.) and SPSS 20.0 (SPSS Inc., Chicago, IL, USA) software.

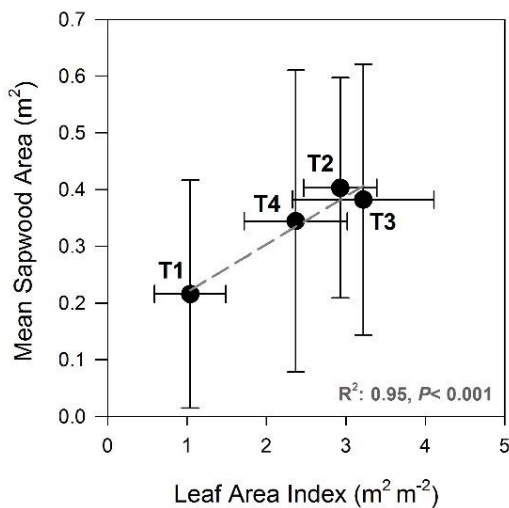
#### 3. Results

ANOVA resulted in significant differences between sites for tree age, LAI, and all measured tree size parameters except for sapwood depth. At all sites, mean sapwood depth was approximately 5 cm (Table 1). Resulting means of the other parameters were generally similar between the sampling sites T2 and T3.

Sapwood area was positively related to TBA and DBH using non-linear (exponential rise to maximum) and linear regression, respectively (Figure 1). Regarding the values obtained from all study trees, TBA was the best predictor for sapwood area explaining 90% of the variation. A high correlation was also found for DBH which accounted for approximately 88% of the variation in sapwood area.

Sapwood area was further related to the tree size parameters sapwood depth and stem radius without bark using non-linear (quadratic) and linear regression, respectively (Figure 2). Stem radius without bark was overall the best predictor for sapwood area explaining 94% of the variation. The quadratic relationship between sapwood area and sapwood depth explained only 56% of the variation.

Regression analysis between sapwood area, tree height, tree age, and projected crown area was done for each sampling site separately (Figure 3). The relationship between sapwood area and tree height was very variable explaining between 39 and 86% of the variation. While no significant correlation was found between sapwood and tree age at the sampling sites T1 and T2, linear regression explained 85 and 83% of the variation for T3 and T4, respectively.



**Figure 4.** Relationship between site-specific mean leaf area index (LAI) and mean sapwood area of *Cedrus libani*. Values are given with standard deviations. T1-T4: Sampling sites, see Table 1.

A high positive correlation was found between sapwood area and projected crown area at T1, T3 and T4. At T2 (values only available for nine trees) it accounted for only 55% of the variation in sapwood area.

A significant positive linear relationship ( $R^2=0.95$ ) was found between site-specific mean sapwood area and LAI (Figure 4). An altitudinal trend for sapwood area was not found.

#### 4. Discussion and Conclusions

In this study, sap wood area of *C. libani* individuals growing at different altitudes in the Elmalı Cedar Research forest was determined by visually assessing the wet part of extracted tree cores. The relationship between sapwood area and different parameters (tree size, age, LAI) was investigated.

##### 4.1. Determination of hydro-active sapwood area

Many techniques and methods are available to determine the sapwood area of the stem, either using tree cores, trees' cross sections or whole tree stems, depending on the study objectives. Determining the sapwood area using computer tomography (portable devices) is non-destructive but measurement devices are expensive. Another

method is to measure the resistance to penetration but it is restricted to areas where frost occurs (Rust 1999). Staining methods are more economical but cannot be performed without causing damage to the tree (Kutscha and Sachs, 1962). Furthermore they are prone for overestimating the sapwood proportion when the transition zone between sapwood and heartwood is also stained, although it almost entirely lost its ability to transport water (Köstner et al., 1998; Rust, 1999). This in turn may lead to overestimating transpiration rates when calculated based on sapwood area. In studies measuring transpiration of trees, a common method is to extract a tree core to the pith of the stem in the early morning hours before transpiration rates rise. Right after coring, a solution including staining reagents (e.g. indigo carmin) is injected into the hole. If necessary the hole is refilled. After a few hours, when the xylem sap including the staining solution should have moved upward, a second core is taken a few cm above the hole of the first extracted tree core. The sapwood can then be determined based on the stained depth of the tree core (Gebauer et al. 2008; Meinzer et al., 2001). It is to mention that in such studies methods including extraction of tree cores should be carried out after all measurements are completed. This way unnecessary disturbance that may influence the measurements can be avoided. If the sapwood area has to be determined in a fast and economical way visual assessment of the wet part, as used in this study, may be the preferred method (Long and Dean 1986; Rust 1999). However, this method should be used only when the stem is fully hydrated (e.g. after rain events, in the early morning hours, preferably during early spring) and the wet part of the tree core has to be marked immediately after extraction. In further studies, different methods could be used to determine the sapwood area of *C. libani* to improve our knowledge in this regard.

##### 4.2. Relationship between sapwood area and different parameters in *C. libani* and its use in ecophysiological studies

Several parameters were measured to find the best predictor to determine sapwood area in *C. libani*. Stem radius without bark explained 94% of the variance, total basal area explained 90%. DBH which is often used as a predictor in other studies, accounted for approximately 88% of the variation in sapwood area. In the study of Vertessy et al. (1995) DBH explained 96% of the variation in sapwood area of mountain ash (*Eucalyptus*

*regnans* F. Muell.). Mean sapwood depth of *C. libani* (approximately 5 cm) was higher than that of Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) with approximately 3 cm and lower than sapwood depth of Ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws.) with approximately 12 cm (Barnard et al., 2011). The larger fraction of sapwood area in *P. ponderosa* is hypothesized to be an advantage under drier conditions. Similar sapwood depths (averages mostly range between 4 and 6 cm) were found in mountain pine (*Pinus uncinata* Ram.) trees growing in the Iberian Peninsula (Galván et al., 2012). Tree age, tree height and projected crown area resulted in different good correlations. Especially correlations between sapwood area and tree age were not significant if tree age values did not cover a wide range. Projected crown area was a better predictor, especially when the sampling number was high. The relationship between mean sapwood and mean LAI resulted also in a high positive correlation. Since LAI was not always measured in close proximity to the sampling trees it is only an approximation but it clearly shows the trend how leaf area and sapwood area are correlated. In this context, projected crown area can also be used as an estimator for leaf area. Furthermore, these relationships show the physiological balance between water requirement of the tree (from shoots or leaves) and the water conducting sapwood (Kaufmann and Troendle, 1981).

In studies using sap flow gauges, sapwood area is an important parameter to determine single tree and stand transpiration (Gebauer et al., 2008; Meinzer et al., 2001) or to investigate water storage and transport properties in trees. A study conducted by Rodriguez- Calcerrada et al., (2015) showed how amongst six deciduous species, dominant individuals had higher transpiration rates per unit basal area compared to suppressed individuals mainly because the latter had lower sapwood depth. The findings of this study can be used in ecophysiological studies on *C. libani* to calculate single tree and stand transpiration and to answer other questions related to water use or water transport in this tree species, especially when site and stand characteristics area similar to those in this study.

In conclusion, sapwood area of *C. libani* was visually assessed in extracted tree cores and resulted in significant correlations with the other measured parameters in this study. Stem radius without bark and tree basal area where the best

predictors, but the latter should be preferred since it causes no damage to the tree. Further studies at different sites and using different methods should be carried out to improve our knowledge about *C. libani* sapwood and to enable upscaling of measured sap flow densities from the single tree to the stand level in this species.

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