In order to shed light on the insect part involved in the forest decline associated with Atlas cedar (Cedrus atlantica (Endl.) Carriere.), an etiological study was carried out on eight representative stations in the Aures mountains located in Eastern Algeria. 1,728 woodlogs was prospected, representing three levels of tree's health status (healthy, decaying, and moribund) and four heights (base, medium, crown, and branches) over three years (2010, 2013 and 2016). From this large-scale investigation, it was found that beetles caused the most important damages on Atlas cedar trees, 22 species of which belong mainly to the Scolytidae (Cryphalus numidicus, Scolytus rupicola, Crypturgus cedri, Phloeosinus cedri, and Hylastes batnensis); the Buprestidae (Melanophila marmottani and Anthaxia martini) as well as the xylomycophage Ciidae (Cis corioli) were found to be the most significant decline agents who impacted most of the phytosanitary status of Cedrus atlantica. The thorough examination of the infestation level and the manner of how these insects affected each stage of decline (taking into account the various specimens collected at different high levels) showed an intra and inter-specific heterogeneity, as well as a succession of the xylophagous entomofauna when comparing various stations.

Endemic to the Maghreb Mountains, Atlas cedar is one of the noble trees of the of the Maghreb (Morocco and Algeria) forest. However, this typical forest species has shown in the last few years a worrying sanitary state that is threatening its durability in the region (Quezel 1998; Harfouche and Nedjahi 2003).

The decline of the cedar forests in the Aures areas started at the end of the 20th century. In Algeria, cedar rapid degradation is noteworthy, especially in the southern part of Aures and Belezma forests, where decline—expressed through dead standing trees—can reach 95% incidence in some stands. This state of facts expresses probably the fragility of the Atlas cedar in its natural habitats (Bentouati 2008; Beghami 2010).

Several authors pinpointed the preponderant effect of drought, which is an eliciting factor that triggers outbreaks in Aures forests (Boudy 1950; Landmann 1994; Touchan et al. 2008, 2011, 2014; Allen et al. 2010; Beghami 2010; Williams et al. 2013). However, the good relative phytosanitary state of some water demanding woody species, such as the common yew (Taxus baccata L.) brings other factors into play and causes collective and synchronous senescence of Atlas cedar trees which are known for their plasticity (Beghami 2012).

In this context, Manion (1991), M'hirit (2008), and Mouna (2009) indicate that cedar dieback is a complex phenomenon where various spatio-temporal (biotic and/or abiotic) factors interact. These interdependencies make difficult to identify and prioritize these factors.

Bark and wood boring (BWB) insects considered as one of the main biotic factors inciting and aggravating decline process that often leads to tree death. Once the decline of trees has begun, a loss in vigor follows,
resulting in increased susceptibility to secondary pests and pathogens agents (Wargo 1995; Sallé et al., 2014).

Indeed, these remarkable insects present special challenges to researchers worldwide, since their effects are usually indirectly visible on hosts as they are difficult to rear outside of their normal environments; they affect both biogeophysical and biogeochemical processes, disrupt the physiological processes of hosts, inoculate fungal diseases and transmit nematodes to attack weakened forest species (Gebhardt et al. 2004; Dajoz 2007; Eckhardt et al. 2007; Jacobi et al. 2007; Lieutier 2007; M’hirit 2008; Togashi et al., 2008; Wermelinger et al. 2008; Nageleisen et al. 2010; Edburg et al. 2012; Sallé et al. 2014; Raffa et al. 2016).

Besides, data collected on the ecology of xylophagous insects (lato sensu) indicate selective trophic specificity toward the different tissues of their hosts, inducing a spatio-temporal distribution characteristic of each insect over the attacked species (Lieutier 2007; Paine and Lieutier 2016). Even though the majority of these taxa develop on host tissues of dead or recently wounded trees that exhibit low moisture content, some taxa regularly kill heavily defended healthy trees by means of mass attack (Wood 1982; Paine et al., 1997).

The irreversible damages caused by these insects are more intense on forest ecosystems that are weakened by the combined actions of abiotic factors (intense and prolonged episodic droughts and skeletal soils), and biotic parameters like the defoliator attacks—such as processionary caterpillar—or the actions of anthropozoogenic agents (Lieutier 2007; M’hirit 2008; Gandh and Herms 2010; Sallé et al. 2014).

Some early research has been devoted to the inventory of bark beetles and woodborer insects in association with the Atlas cedar population in the northern cedar forests of Algeria (De Peyerimhoff 1915, 1919, 1930; Villiers 1946; Balachowsky 1963, 1969; Chararas et al. 1968; Khemici 2001).

However, no studies have previously been carried out in the southern cedar forests of Algeria, thus several questions remain unanswered. In this context, the scientific community would search for wood-boring taxa that are closely associated with the Atlas cedar in Aures forest, in order to know how these taxa are involved on the decline process. The degree of the pathological impairment would to be quantified and the logical attack suction according to the relationship between the density of each wood-boring taxa with the prevalence of cedar trees explained.

In this regard, the present study aims to highlight the main xylophagous taxa associated with cedar dieback, in order to understand their importance and indicate the dynamics of their infestation on Atlas cedars. The study was out in 2010–2013 and 2016. In addition, we have also tried to identify any affinities occurring with regards to sampling stations, seasonal activity, height distribution, and wood moisture. Finally, we investigated attacks rate and emergence densities of key bark and wood-boring species in the cedar forest region of Aures.

**Materials and methods**

**Study area**

The present study was carried out on two cedars areas (Chelia and Ouled Yagoub mounts, 7,000 ha and 3,000 ha respectively) in the Aures forest -eastern Algeria- (Supplemental Figure S1). The cedar trees have almost the same age (55 years in the Chelia mounts and 65 years in the Ouled Yagoub mounts), grew on lower cretaceous sandstones associated with dolomites (Abdessemed 1981).

In these areas, we have selected eight plots of one hectare (Martikainen et al. 1999; Gering and Crist 2000). Four plots were exposed north (two ones in Chelia and Ouled Yagoub mounts), the rest of the plots were exposed south (south-facing) (three in the Chelia mounts and one plot in the Ouled Yagoub mounts), all plots are characterized by a subhumid climate (Figure 1; Table 1).

Although, observation prevalence of trees shows different dieback degrees that are clearly pronounced on Ouled Yagoub mounts.

The chosen plots, host pure cedars in association with *Rananculetum spicatii* (*Cedro atlanticae* – *Rananculetum spicatii*) (Abdessemed 1981), to provide accurate results on xylophagous entomofauna of Atlas cedar.

**Sampling logs**

To study the incidence of the xylophagous insects in the decline of Atlas cedar forests, three classes of trees representing three categories of dieback were chosen according to needle-drying degrees (Benhalima 2004; Rouault et al. 2006; Samalens 2009; Beghami 2010).
Healthy trees (D_0) are related to subjects that show a good physiological state with normal foliage, the dying subjects (D_100) shows 50% needle loss from the crown. Last, dead trees (D_200) presents individuals with 100% dry leaves.

The choice of the latter classes is justified by the absence of a significant difference between the emerging entomofauna in classes that vary between 50 and 80% needle loss (Benhalima 2006; Wermelinger et al. 2008; Beghami 2010; Talbi and Bouhraoua 2015).

In each station, a tree was removed from each dieback blocks, in sum, 24 trees were sampled at all eight stations for each decline level over each year.

The trees were split into three blocks of 5 meters long: top, mid, crown, and branches (Kelsey and Joseph 2001; Johansson et al. 2007). On each high class, two sections of trunks of an overall lateral area of 42 dm² (corresponding to logs that of an average of 0.45 m × 0.3 m) have been collected and placed in hatchers (Leather 2005; Manly 2015).

This operation has been performed over three periods: End of January, May, and September, during three sampling years (2010, 2013, and 2016), in order to follow the seasonal infestations process of the BWB species (Okland 1996; Kelsey and Joseph 2001; Benhalima 2004; Johansson et al. 2007). These sampling periods were defined according to preliminary investigations (Beghami 2010) that were carried out by the monitoring of the emergence of the principal wood-boring species by the means of a multidirectional window and yellow traps.

**Monitoring of diachronic emergences**

1,728 roundwood logs are sampled throughout three tree sampling campaign 2010–2013 and 2016. These campaigns were carried out in order to monitor the bioecology of the main BWB species, and observe the influence of biotic and/or abiotic stationary conditions on the BWB insects infestation process overtime (incoming studies), succession of the main beetles attacks, and unreeing the pattern of the prevalence of healthy, dead and dying trees according to the density of insect attacks.

The sampled logs were then put into hatchers bearing similarity to the “cylinder extraction and photo-eclectors” (Okland 1996) or “totholz eklektor” (Albrecht 1990; Schmitt 1992). The harvesting principle is based on the attraction that insects have for light (Speight 2005; Wermelinger et al. 2008; Shimoda and Honda 2013), the hatchers are cardboard boxes lined inside with a dark plastic film with a collection device annexed to the outside.

In order to follow the emergence chronology of the main xylophagous species, daily monitoring of the collected insects is carried out during one year after each campaign, since the sampling of the logs until the cessation of insects’ emergence.

The logs were then husked after a period of immersion in water to soften tree bark so as to study the frequency and density of infestation in relation with the bark thickness.

The gathered insects were identified and inventoried according to their taxonomic characteristics. Eight major species whose biological cycle had been controlled were set aside to study their contribution to the Atlas cedar decline phenomenon and thus became the key species of interest in this study.

The infestation frequency (FA%) of different wood-boring taxa is calculated according to the formula: FA % = Ni/Nt. Where Ni is the number of attacked logs by each specific species and Nt is the total number of logs observed in each station (Benhalima 2004; Starzyk et al. 2008).

The average emergence of the most frequent wood-boring species is explained by both dieback and height classes. Furthermore, the seasonal activity of these insects is noted and averaged over the three sampling campaigns.

In the aftermath, the average infestation density (Id) of the three major BWB insects was expressed as the number of average mating chambers per 1 dm² for all stations per year. (Grodzki et al. 2004). Finally, the infestation rate of the most forgotten insects is calculated according to the formula: Ta (%) = (Sai × St) / 100. Where Sai = (Lgm × lgm) + (Lgl × lgl) × Ngl and Ta (%) is the infestation rate; S_ai is the attacked surface that is associated with each species; Lgm: is the length of the maternal galleries, lgm: is the width of the maternal galleries, Llg: is the length of larval galleries, llg: is the width of larval galleries and Ngl: is the number of larval galleries (Benhalima 2004). These parameters are measured by image tool—annexed to SmartRoot plugin—software after picture calibration.

**Statistical analyses**

In the present study, we have performed a $\chi^2$ test to highlight the effect of height and dieback classes on the cumulative emergence of the main adult wood-boring species followed by Cramer’s Phi in order to evaluate the strength of the association. In addition, a correlation study based on the calculation of Spearman’s $\rho$ coefficient was carried out in order to assess the relationship between bark thickness and attacks intensity, expressed in terms of the number of total maternal galleries associated with the principal bark and wood-boring species.

Furthermore, an ANOVA analysis ($\rho < 0.05$) followed by a Student Newman, Keuls Post-Hoc test, was
performed in order to study the variation between the attacked area and the infestation density of the three main species over the three sampling campaigns.

Finally, potential links between the main woodborers species and the prevalence of different tree health classes at different sampling sites are established by means of factorial correspondence analysis (FCA). Agglomerative hierarchical clustering has been generated to distinguish similarities between stations.

Statistical tests were performed using SPSS Version 22.0 (IBM® Corp., USA) software after testing for homoscedasticity and normality of the residual.

Results

During the 3 sampling instances, 23,879 specimens were identified and grouped into 23 xylophagous species belonging to 2 systematic orders. Beetles represent nearly 99% of the emerging species that are classified to two systematic orders. Beetles were identified and grouped into 23 xylophagous species and the prevalence of different tree health classes at different sampling sites are established by means of factorial correspondence analysis (FCA). Agglomerative hierarchical clustering has been generated to distinguish similarities between stations.

Statistical tests were performed using SPSS Version 22.0 (IBM®, Corp, USA) software after testing for homoscedasticity and normality of the residual.

Table 2. Attacks frequency of Cedrus atlantica log by the main bark beetle and other wood-boring species.

| Species                          | ST1 | ST2 | ST3 | ST4 | ST5 | ST6 | ST7 | ST8 | Mean |
|----------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Coleoptera                       |     |     |     |     |     |     |     |     |      |
| Curculionidae                    |     |     |     |     |     |     |     |     |      |
| Scolytinae                       |     |     |     |     |     |     |     |     |      |
| Hylastes batptinus batptinus Brousson, 1833 | 14.07 | 13.89 | 16.02 | 11.76 | 18.52 | 11.65 | 12.50 | 12.22 | 13.83 |
| Cryptopus numidicus Eichhoff, 1878 | 62.96 | 55.56 | 57.87 | 54.63 | 51.85 | 52.78 | 54.17 | 51.39 | 55.15 |
| Scolytus numidicus Brousson, 1883 | 52.31 | 47.22 | 51.39 | 42.59 | 50.46 | 46.30 | 50.46 | 50.00 | 48.84 |
| Cryptopus cedri Eichhoff, 1868  | 25.93 | 30.09 | 28.70 | 32.87 | 24.07 | 27.78 | 28.70 | 25.93 | 28.01 |
| Xyletusus dryographus Ratzen, 1837 | 17.13 | 16.20 | 18.06 | 19.44 | 17.13 | 19.44 | 16.67 | 19.91 | 18.00 |
| Orthotoxemia eosus Wollaston, 1857 | 16.20 | 12.04 | 18.06 | 14.81 | 16.67 | 15.74 | 16.67 | 15.74 | 15.74 |
| Phloeosinus cedri Brousson, 1883 | 23.15 | 16.67 | 21.76 | 16.20 | 14.81 | 14.35 | 22.69 | 15.74 | 18.17 |
| Hylurgops bonvoluoini Wood & Bright, 1992 | 16.20 | 15.28 | 15.28 | 13.43 | 14.35 | 15.28 | 17.13 | 14.35 | 15.16 |
| Ciidae                           |     |     |     |     |     |     |     |     |      |
| Brachyderes pubescens Boheman, 1833 | 14.35 | 13.43 | 17.13 | 13.43 | 11.11 | 11.57 | 18.52 | 12.04 | 13.95 |
| Pachyphorus raffrayi Desbrochers, 1871 | 15.28 | 16.20 | 16.67 | 15.74 | 12.96 | 9.26 | 19.44 | 15.74 | 15.16 |
| Buprestidae                      |     |     |     |     |     |     |     |     |      |
| Melanophila marmottani Feinmaire, 1868 | 32.41 | 29.63 | 36.11 | 35.65 | 31.94 | 49.07 | 53.24 | 48.61 | 39.58 |
| Chrysobothroa soleri Laporte et Gory, 1839 | 16.67 | 16.67 | 20.37 | 15.79 | 15.28 | 18.06 | 17.13 | 23.61 | 18.17 |
| Acmaeodera degener Scopoli, 1763  | 19.91 | 18.06 | 20.37 | 15.79 | 15.28 | 18.06 | 17.13 | 23.61 | 18.17 |
| Acmaeodera bipunctata Olivier, 1790 | 15.28 | 15.28 | 22.69 | 17.59 | 15.28 | 18.06 | 17.13 | 23.61 | 18.17 |
| Anthaxia martini Brousson, 1883  | 14.81 | 14.35 | 17.13 | 24.54 | 12.96 | 25.00 | 31.48 | 28.70 | 21.12 |
| Anthaxia umbellatorum Fabricius, 1787 | 33.33 | 30.09 | 34.72 | 26.85 | 29.17 | 22.69 | 31.48 | 33.80 | 30.96 |
| Cerambycidae                     |     |     |     |     |     |     |     |     |      |
| Tachinoides griseus Frivaldsky, 1838 | 16.20 | 23.61 | 15.28 | 15.74 | 18.98 | 18.98 | 18.52 | 15.74 | 17.88 |
| Brachyderes pubescens Boheman, 1833 | 14.35 | 11.57 | 12.50 | 12.04 | 12.04 | 15.74 | 16.20 | 13.43 | 13.48 |
| Alocerus moesiacus Frivaldsky, 1838 | 16.04 | 18.98 | 13.89 | 14.35 | 12.96 | 12.96 | 12.04 | 13.89 | 13.89 |
| Callidium cedri Eichhoff, 1868  | 9.26 | 16.20 | 15.74 | 14.35 | 12.96 | 15.74 | 20.37 | 18.52 | 15.39 |
| Ciidae                           |     |     |     |     |     |     |     |     |      |
| Cis (Cisodyga) corioli Peyerimhoff, 1915 | 33.80 | 39.81 | 38.43 | 38.43 | 37.04 | 39.35 | 43.06 | 37.04 | 38.37 |
| Zopheridae                       |     |     |     |     |     |     |     |     |      |
| Endophloeus marcowichianus Piller, 1783 | 10.65 | 11.57 | 8.80 | 9.26 | 11.11 | 9.26 | 11.57 | 10.19 | 10.30 |

Chelia Highlands and 5.09% in the 8th station in Ouled Yagoub mountains.

However, Cis corioli, Cryptalus numidicus, Cryptopus cedri, and Melanophila marmottani record the highest average (FA%) with 43.06, 43.86%, 55.15% and 39.58% respectively.

Data analysis of key BWB insects obtained after χ² test (Table 3) on contingency table regarding the emergence of adults of the main woodborers species according to height and decline classes indicates that C. numidicus and S. numidicus attacks all parts of C. atlantica trees in D 50 class with a value of Cramer’s Phi between 0.40 and 0.50. While C. cedri settles on dead trees in D 100 class with Cramer’s Phi between 0.41 and 0.53. Phloeosinus cedri infects the branches and top parts of trees of D 0 class with Cramer’s Phi from 0.43 to 0.55, although it’s noted on the middle parts and the branches of D 50 trees class.

Buprestidae, M. marmottani and A. martini reported significantly on subjects in class D 25 on all prospected parts (Cramer’s Phi between 0.42 and 0.61). The longhorn beetle C. cedri was found on trees of class D 50 with a clear preference for tops and branches. Whereas, the Ciidae Cis corioli is clearly noticed on dead trees where it settles on all parts of the tree.

Seasonal activity of main species (Figure 2) indicates that C. numidicus, S. numidicus, M. martini and Ciidae Cis corioli are active from spring to early autumn. On the other hand, P. cedri was observed during late summer and early autumn. C. cedri has been noticed at late spring to early summer; M. martini
and *Cis corioli* emerge in spring and their spreads are in early summer (maximum activity).

*Cryphalus numidicus* is the most active species over all seasons with a maximum of 5.97, 15.33, and 6.5 adults/log that were respectively obtained in spring; summer and autumn on the medium and basal strata ridges.

In addition, *Scolytus numidicus* and *Crypturgus cedri* have shown a maximum activity in summer with an estimated abundance of 5.55 and 2.36 adults/logs. Whereas, *Phloeosinus cedri* was found to be active in late summer-early Autumn with 2.4 adults/logs. Whereas, *Melanophila marmottani* was found on summer and autumn on the medium and basal strata ridges.

*Melanophila marmottani* is active on summer with maximum mean emergence of 3.93 adults/logs. However, *Anthaxia martini* occurs in earlier spring, with intense activity on the ridges of the middle stratum.

The Cerambycidae, *Callidium cedri*, was found on summer with 1.55 adults/log. The Ciidae, *Cisdygma corioli* mainly occurs in summer where we record a mean of 4.77 adults in the log bases and 4.16 adults in branches of D<sub>100</sub>.

Correlation analysis between bark thickness and adult emergence of the main woodboring species (Figure 3) indicates that the activity of *C. numidicus*, *P. cedri*, *Callidium cedri*, *M. marmottani*, and *A. Martini* is positively correlated with bark thickness with coefficients values equal to 0.68, 0.15, 0.74, 0.63, and 0.69 respectively; *C. cedri* and *C. corioli* seem to be indifferent to bark thickness; while bark thickness seems to be negatively correlated with *S. numidicus* attacks.

An evaluation of the infestation rate and infestation density on the three most forgotten BWB species (Table 4) indicates the presence of a significant difference between *C. numidicus* that are most active species with infestation rates from 30.71% to 47.56%, and 1d between 10.83 and 11.19 compared to, *S. numidicus* and *M. marmottani* who showed respectively an infestation rates from 1.90% to 2.05% and 1.11% to 3.38% and an infestation density from 2.14 to 6.21 from *S. numidicus* and between 2.17 and 4.2 for *M. marmottani*.

In the analytical part of this study, we have performed a factorial correspondence analysis (Figure 4) that showed a prominent dominance of the Scolytidae (bark beetle) in the Chelia massifs. On the other hand, the Buprestidae species (jewel beetles) were more abundant and associated with the Ouled Yagoub Massifs where the cedar wood seems to be more painful. The agglomerative hierarchical clustering study has confirmed this trend by showing similarity of abundances between the 2nd and the 5th station; the 3rd and 4th station along with the 1st one and finally the 6th and the 8th station along with the 7th plot (Figure 5).

### Discussion

Bark and wood-boring insects are one of the most dangerous pests in forest ecosystems. Indeed, some species can kill huge numbers of trees over large areas during intermittent outbreaks (Wargo 1995; Johnson and Miyanihasi 2007; Raffa et al. 2008).

Xylophagous insects that infest conifers in the Mediterranean basin show a high level of endemism since it has been shown that most of the wood-boring insects are secondary species that attack those subjects who exhibit physiological weakness and ailing health because of constraining ecosystems.

From 23 wood-boring species that have been inventoried in this study, The Scolytidae species, are the most prominent with 8 numbered species. Among these species, three were found to be the most important according to their endemism characteristics, specificity, and virulence of attack (Supplemental Figures S2).

*Cryphalus numidicus* is an endemic species to the Mediterranean region, reported on *Abies numidica* de Lannoy ex Carrière, *Abies pinsapo* Boissier, *Pinus halepensis* Miller and *Cedrus atlantica* Endlicher in northern Europe and northern Africa (De Peyerimhoff 1919; Barbey 1925; Chararas 1963, 1974; Mouna 1994; Knizêk, 1994; Paine and Lieutier 2016).

On the other hand, *Scolytus numidicus* and *Crypturgus cedri* are oligophagous and endemic species to Algeria and Morocco forests, these two species are exclusively reported on *Cedrus atlantica* (De Peyerimhoff 1919; Mouna and Graf 1994; Fabre et al. 1999; Paine and Lieutier 2016).

*Phloeosinus cedri*, is also an endemic and oligophagous species of *Cedrus atlantica* (De Peyerimhoff 1919; Paine and Lieutier 2016).

### Table 3

|              | Base | Mid | Crown | Branches | p-Value (bilateral) |
|--------------|------|-----|-------|----------|---------------------|
| *C. numidicus* |      |     |       |          |                     |
| D0           | 0.2502 | 0.2519 | 0.2283 | 0.1925 | <0.0001            |
| D50          | 0.4239 | 0.4572 | 0.5064 | 0.4983 |                     |
| D100         | 0.3259 | 0.2909 | 0.2653 | 0.3092 |                     |
| *S. numidicus* |      |     |       |          |                     |
| D0           | 0.1331 | 0.2212 | 0.0913 | 0.2469 | <0.0001            |
| D50          | 0.4886 | 0.4712 | 0.4544 | 0.4002 |                     |
| D100         | 0.3783 | 0.3075 | 0.4544 | 0.3529 |                     |
| *C. cedri*   |      |     |       |          |                     |
| D0           | 0.1652 | 0.1743 | 0.1156 | 0.1736 | <0.0001            |
| D50          | 0.4152 | 0.3914 | 0.3467 | 0.3388 |                     |
| D100         | 0.4196 | 0.4342 | 0.5377 | 0.4876 |                     |
| *P. Cedri*   |      |     |       |          |                     |
| D0           | 0.2469 | 0.3828 | 0.5593 | 0.4783 | <0.0001            |
| D50          | 0.3333 | 0.4570 | 0.2881 | 0.4348 |                     |
| D100         | 0.4198 | 0.1602 | 0.1525 | 0.0870 |                     |
| *M. marmottani* |     |     |       |          |                     |
| D0           | 0.1637 | 0.2370 | 0.0580 | 0.1583 | <0.0001            |
| D50          | 0.4720 | 0.4351 | 0.4106 | 0.4222 |                     |
| D100         | 0.3643 | 0.3279 | 0.5314 | 0.4195 |                     |
| *A. Martini* |      |     |       |          |                     |
| D0           | 0.2394 | 0.2744 | 0.1625 | 0.1975 | 0.0444             |
| D50          | 0.4970 | 0.4543 | 0.6125 | 0.5987 |                     |
| D100         | 0.2636 | 0.2713 | 0.2250 | 0.2038 |                     |
| *Callidium cedri* |    |     |       |          |                     |
| D0           | 0.1227 | 0.1948 | 0.0000 | 0.0000 | <0.0001            |
| D50          | 0.4356 | 0.4610 | 1.0000 | 0.9231 |                     |
| D100         | 0.4417 | 0.3442 | 0.0000 | 0.0769 |                     |
| *C. corioli* |      |     |       |          |                     |
| D0           | 0.0477 | 0.0501 | 0.0938 | 0.0478 | <0.0001            |
| D50          | 0.3196 | 0.3630 | 0.4188 | 0.4071 |                     |
| D100         | 0.6328 | 0.5869 | 0.4875 | 0.5451 |                     |
Melanophila (Phaenops) marmottani and Anthaxia martini are the main species of the Buprestidae family which originated from Atlantic-Mediterranean area, these species are found on several Abies, Cedrus and Cupressus forests (Théry 1928; Kocher 1969; Fabre et al. 1999; Benhalima 2004; Mouna 2009; Ilmen and Benjelloun 2013; Nichane and Khelil 2017).

The Cerambycidae, Callidium cedri is recorded only in North Africa on cedar forest (Villiers 1946; Benhalima 2006).

At last, Cis corioli is the unique Ciidae that found to be an endemic species from Algeria, and was observed for the first time by De Peyerimhoff on cedar trees (De Peyerimhoff 1915; Jelinek 2008; Beghami 2010).

In this paper, the taxa inventoried show a high frequency of attacks on all sampling stations that can probably be attributed to the fact that weakened trees release more allelochemical substances (e.g. α-pinene, δ-3-carene) that attract xylophagous taxa. In this context, several physicochemical processes that belong to the natural defenses process of the host trees (active and/or passive) are weakened and consequently, trees lose its ability of repelling woodborer infestations (Wood 1982; Byers 2007; Lieutier et al. 2004; Vega and Hofstetter 2015; Paine and Lieutier 2016).

The study of the BWB activity according to height and decline classes demonstrated that the attacks of C. numidicus depend on wood moisture content, where it

Figure 2. Seasonal average emergence of the main BWB of Atlas cedar during the three sampling campaigns.
was recorded frequently on all parts of weakened trees (class D50). *S. numidicus* attacks all parts of the cedars that belong to D50 class; Whereas, *P. cedri* seems to be the only Scolytidae species able to attack all parts of healthy cedar in D5 class.

*Melanophila (Phaenops) marmottani* and *Anthaxia martini* attack trees of D50 and D100 class. *A. martini* operates on well-heated parts of the hosts, as well as C. *cedri* that operate on physiologically weakened (D50, D100).

**Figure 3.** Correlation between bark thickness and attacks intensity of main BWB of Atlas cedar.
At last, *C. Corioli* is significantly associated with all parts of D100 class of cedar.

The present study showed a positive correlation between the thickness of the trunk bark and attacks of *S. numidicus*, *C. cedri*, and *A. martini*. A negative correlation is recorded between *S. numidicus* activity and the thickness of Atlas cedar bark, while *P. cedri*, *Crypturgus cedri*, and *C. corioli* attacks seem to be indifferent to the thickness of the bark.

Data of seasonal monitoring of BWBs assigned to the atlas cedar indicates that *C. numidicus* have massive and intense attacks that can reach 3 generations per year (two sister broods in early spring and summer and the 2nd generation in mid-September, early November in the case of favorable weather conditions). *Scolytus numidicus* and *Crypturgus cedri* appear to be univoltine, adults are active in late spring/early summer where we have exceptionally observed 2nd flight
in 2010 and 2016 when we had mild winters. Crypturgus cedri is univoltine too and attack cedars that are in the situation of advanced decline in late spring and during summer.

Phloeosinus cedri has only one generation per year and exhibits intense activity in late summer and early fall.

The Buprestidae species M. marmottani and A. martini are univoltine, the first species are active from late spring to early fall, the second one has an intense activity in spring. Whereas, the Cerambycidae Callidium cedri seems to have one generation that operates in summer time.

Finally, C. coriolii seems to be univoltine xylomycophagous species who operate from late spring to late summer.

A temporal succession of bark beetle and wood insect infestation has also been observed (Paine and Lieutier 2016) witnessing that BWB insect can be grouped according to their affinities to wood moisture (De Peyerimhoff 1919; Rungs 1940; Balachowsky 1969; Chararas 1963, 1974; Fabre et al. 1999; Benhalima 2004).

Cryphalus numidicus and P. cedri are “pioneer” species that established themselves on relatively healthy cedar after 4 months cutting (spring activity). Benhalima (2004), Beghami (2010), and Talbi and Bouhraoua (2015) have shown that the two previously cited species are the first one to notice in the fresh wood and prefers middle and top parts of trees as well as the branches of small diameters.

Scolytus numidicus, C. cedri, M. marmottani, A. martini, and Callidium cedri are “weakness inducing” species that have a pronounced preference for drying or dry wood. This colonization pattern follows a dispersion gradient that depends on the size of the woodworm and the thickness of the bark. These findings are supported Fabre et al. (1999), Benhalima (2004), Mouna (2009), Vega and Hofstetter (2015), and Paine and Lieutier (2016) who converge to the same findings in Morocco.

Analysis of infestation activity indicates that the cambiophagous species: C. numidicus; causes the most serious harm on D50 logs followed by S. numidicus and M. marmottani on weakened trees.

Since the insects studied are normally secondary, their attacks can directly succeed only in the case of large outbreaks, where they usually cause important damages on healthy trees, or when the damaged trees have physiological deficiencies (Vega and Hofstetter 2015; Paine and Lieutier 2016).

The correspondence factor analysis followed by the CAH analysis clearly indicates that the stations in the Chelia series are attacked by bark beetle species, particularly C. numidicus, P. Cedri, and S. numidicus; these data suggest a recent outbreak of these cedar forests. This hypothesis is consolidated by the good valence of healthy trees and an acceptable phytosanitary state compared to the Ouled Yagoub forest where Buprestidae and Cerambycidae species—known as dieback completion agents—are the most found, and where decline patterns range from 60% to 70%.

Stationary variations in infestation can be attributed to in situ conditions. This would include bark thickness, soil quality and nutrient availability that determine the physiology of the host tree, as well as the microclimates of each station, especially in summer when dry winds increase evapotranspiration and consequently disrupt the cedar water balance. The above factors are involved in the dispersion, selection, concentration, and woodborers taxa establishment (Wood 1982; Vega and Hofstetter 2015; Paine and Lieutier 2016).

The threat posed by BWB insects in all stations is not restricted to the damage inflicted to sap conducting channels. Indeed, the noxiousness of these insects extends to a set of other infestations such as the inoculation of ophiostomatoïd fungi (such as Ceratocystis, Ophiostoma, Thielaviopsis …) (Upcoming publications) and nematodes (Bursaphelenchus …) during their epidemic attacks.

Conclusion

Nearly 350 woodboring species are reported in Western Europe and North Africa, however, the main species living in Mediterranean conifers amount to only 42, which corresponds to about 11% of the western Palearctic fauna (Lieutier et al. 2007; Paine and Lieutier 2016).

Bark beetle and woodborer insects play an important part in the process of Atlas cedar decline in Aures forests. These areas trees, that are already submitted to stress, are prone to be more receptive to infestations from a wide range of cambiophagous taxa.

In this original study, we provided for the first time a list of BWB species associated with Atlas cedar in the forests of Chelia and Ouled Yagoub.

The gathered data showed that C. numidicus, S. numidicus and M. marmottani are the most active species in the eighth prospected stations.

The monitoring of seasonal activity and the distribution of BWBs by height and decline class as well as the dynamics of attacks by the bark thickness allowed us to explain the process of cedars colonization.

The Attacks are initiated by both C. numidicus and P. cedri, the latter is considered to be the only species able to attack the crow and the mid of healthy cedars. Afterwards, C. numidicus impaired cedar defenses through massive attacks.

The remaining species attacks cedars of the D50 and D100 classes, increasing the decline of already weakened species.

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References
Abdessemed K. 1981. Le cèdre de l’Atlas (Cedrus atlantica Manetti) dans le massif des Aurès et de Belezma: étude phytosociologique, problème de conservation et d’aménagement [Doct. Ing. thesis]. Faculty St Jerome, Marseille, France, p. 199.

Albercht L. 1990. Grundlagen, Ziele und Methodik der Waldkologologischen Forschung in Naturwaldreservaten. Naturwaldreservate in Bayern. Schriftenreihe. 1:1–220.

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell L, Vennetier M, Kitzberger T, Rigling A, Breshears DD, Hogg EHT, et al. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For Ecol Manage. 259(4):660–684.

Balachowsky AS. 1963. Entomologie appliquée à l’agriculture. Vol. 2. Paris (France): Masson, 1391 p.

Balachowsky AS. 1969. Les scolytes du cèdre dans le nord de l’Afrique. Ann Entomol Soc France. 5:647–655.

Barbey A. 1925. Traité d’entomologie forestière à l’usage des sylviculteurs, des reboiseurs, des propriétaires de bois et des biologistes. Paris (France): Paris Berger-Levrault, 749 p.

Beghami R. 2010. Contribution à l’étude des insectes associés au dépérissement du cèdre de l’Atlas (Cedrus atlantica) dans la région des Aurès: cas de la cédraie de Cheila [Magister thesis]. University Hadj Lakhdar, Batna, Algeria, 132 p.

Beghami Y. 2012. Ecologie et dynamique de la végétation de l’Aurès: analyse spatio-temporelle et étude de la flore forestière et montagnarde [PhD thesis]. Biskra (Algeria): University Mohamed Khider, 193 p.

Benhalima S. 2004. Les insectes xylophages et leur rôle dans la transmission des maladies des conifères. PhD thesis. University of Masson, 107 p.

Bentouati A. 2008. La situation du cèdre de l’Atlas dans les Aurès (Algérie). Forêt Médiiterranéenne. 28:203–208.

Bentouati A, Barrat M, 2006. Réflexions sur le dépérissement du Cèdre de l’Atlas des Aurès (Algérie). Forét Médiiterranéenne. 27:317–322.

Boudy P. 1950. Economie forestière nord-africaine: Monographie et traitements des essences forestières. France: Larousse, p. 878.

Byers JA. 2007. Chemical ecology of bark beetles in a complex ollary landscape. In: Leustier F, Battisti A, Grégoire JC, Evans H, editors. Bark and wood boring insects in living trees in Europe, a synthesis. Netherlands: Springer, p. 89–134.

Chararas C. 1963. Scolytides des Conifères. Encyclopédie Entomologique. Société Linnéenne de Lyon. 32:181–183.

Chararas C. 1974. Recherches écophysiologiques sur certains Scolytidae spécifiques de Cedrus atlantica du Moyen Atlas. Travaux de la RCP, CNRS. 249:231–255.

Chararas C, Juster M, Balmain N. 1968. Recherches sur le stimulus attractif de Cedrus libani barr. vis-à-vis de Philocosmus codri Schedli. (Coléoptère: Scolytidae). Bull Soc Zool. 93:309–316.

Dajoz R. 2007. Les insectes et la forêt: rôle et diversité des insectes dans le milieu forestier. Paris: TEC & DOC, p. 648.

De Peyerimhoff P. 1915. Notes sur la biologie de quelques coléoptères phytophages du nord-africain. Ann Soc entomol. Fr. 84:19–61.

De Peyerimhoff P. 1919. Notes sur la biologie de quelques coléoptères phytophages du nord-africain. Ann Soc entomol. Fr. 88:169–258.

De Peyerimhoff P. 1930. Les Coleoptères attachés aux Conifères dans le nord de l’Afrique. Ann Soc entomol Fr. 102:359–412.

Eckhardt LG, Weber AM, Menard RD, Jones JP, Hess NJ. 2007. Insect-fungal complex associated with loblolly pine decline in central Alabama. For. Sci. 53:84–92.

Edburg SL, Hicke JA, Brooks PD, Pendall EG, Ewers BE, Norton U, Gochis D, Gutmann ED, Meddens AJ. 2012. Cascading impacts of bark beetle-caused tree mortality on coupled biogeochemical and biogeographical processes. Ecol Soc Am10(8): 416–424.

Fabre JP, Mouna M, Merle PD, Benhalima S. 1999. Le point sur certains ravageurs du cèdre de l’Atlas en Afrique du nord en France et en Europe. Forêt Méditerranéenne. 20:203–218.

Gandh KJK, Herms DA. 2010. Direct and indirect effects of alien insect herbivores on ecological processes and interactions in forests of eastern North America. Biol Invasions. 12(2):389–405.

Gebrandt H, Begerow D, Oberwinkler F. 2004. Identification of the ambrosia fungus of Xyleborus monographus and X. drygaphus (Coleoptera: Curculionidae, Scolytinae). Mycol Progress. 3(2):95–102.

Gering JC, Crist TO. 2000. Patterns of beetle (Coleoptera) diversity in crowns of representative tree species in an old-growth temperate deciduous forest. Selbyana. 21:38–47.

Grodzki W, McManus M, Knizk M, Meshkova V, Mihalicu V, Novotny J, Turciani M, Slobodyan Y. 2004. Occurrence of spruce bark beetles in forest stands at different levels of air pollution stress. Environ Pollut. 130(1):73–83.

Hamm S, Simonneau V, Allifriqui M, Auclair L, Montes N. 2007. Évolution des recouvrements forestiers et de l’occupation des sols entre 1964 et 2002 dans la haute vallée des Ait Bouguemaz (Haut Atlas central, Maroc), Impact des modes de gestion. Sécheresse. 18:1–7.

Harfouche A, Nedjah A. 2003. Prospections écologiques et sylvicoles dans les cédraies du Bélezma et de l’Aurès à la recherche de peuplements semenciers et d’arbres plus. Rev For Fr. 55:113–122.

Ilmen R, Benjelloun H. 2013. Les écosystèmes forestiers marocains à l’épreuve des changements climatiques. Forêt Méditerranéenne. 34:195–208.

Jacobi WR, Koski RD, Harrington TC, Witsosky JJ. 2007. Association of Ophiostoma novo-ulmi with Scolytus scolyrevrei (Scolytidae) in Colorado. Plant Dis. 91(3):245–247.

Jelínek J. 2008. Family Cididae. In: Löbl I, Smetana A, editors. Catalogue of Palaearctic Coleoptera. 5. Apollo Books; p. 55–62.

Johansson T, Hjältén J, Gibb H, Hilaczszanski J, Stenlid J, Ball JP, Alinvi O, Danell K. 2007. Variable response of different functional groups of saproxylic beetles to substrate manipulation and forest management: Implications for conservation strategies. For Ecol Manage. 242(2–3):496–510.

Johnson EA, Miyashiki K. 2007. Plant disturbance ecology the process and the response. London (UK); Heveiber Inc., 720 p.

Kelsey RG, Joseph G. 2001. Attraction of Ophiostoma novo-ulmi to ethanol in water-stressed Douglas-fir branches. For Ecol Manage. 238(3):229–238.

Khemici M. 2001. Protection des cédraies de l’Algérie: inventaire des insectes ravageurs et réseaux d’avertissement et de lutte. In: Workshop on assessment of the scale of insect infestation in cedar forest in Lebanon and the Mediterranean region. Lebanon: American University of Bayreuth, p. 10–18.

Knizk M. 1994. New species of Philocosmus (Chapuis) from Cyprus (Coleoptera, Scolytidae). Folia Heyrovskyana. 2:124–127.
