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Diurnal changes in embolism and sap flow in living tree trunks

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Abstract

In living tree trunks, cavitation occurs in the water-conducting tissue, leading to embolism. The occurrence of embolism can be evaluated using the acoustic emission (AE) method, which detects and monitors ultrasonic stress waves released when cavitation occurs. However, long-term measurements have rarely been conducted to understand the factors and patterns of embolism. As tree sap is essential for the transport of nutrients and phytohormones within the tree, elucidating its variation is fundamental to understanding the physiological survival strategies of trees. The aim of this study is to examine the variation of sap flow and embolism in a sapling. We used an olive sapling in our experiment, which was conducted at Kobe University, Japan from May to December 2021. The number of AE events was recorded at 10-minute intervals, and the sap flow velocity was measured using a heat flux sensor. Both AE and heat flux sensors are non-destructive measurement methods. In the olive sapling, few AE events were observed after the first irrigation, and the number of AE events gradually increased after 27 days. When irrigation was applied during this period of AE generations, AE events decreased temporarily, but then reoccurred soon after. As described above, we confirmed that the number of AE events in an olive sapling changes in response to irrigation.

Keywords: embolism, cavitation, sap flow, field measurement, broad-leaved tree

INTRODUCTION

In living tree trunks, cavitation occurs in the water-conducting tissue, leading to embolism. Embolism progresses due to increasing tension on the sap caused by diurnal water stress and inhibit sap transport (Tyree and Zimmermann 2002, Fukuda et al., 2015). As tree sap is essential for the transport of nutrients and phytohormones within the tree, elucidating variation in embolism is fundamental to understanding the physiological survival strategies of trees. Nondestructive measurement is essential to evaluate the long-term variation of embolism. The occurrence of embolism can be evaluated by detecting acoustic emission (AE), which is emitted when cavitation occurs (Tyree 1986, Tyree and Sperry 1989). Here, we investigated diurnal variation of sap flow and embolism in a sapling.

MATERIALS AND METHODS

The study was conducted from May to December 2021 at the balcony of Science and Technology Research Building 2, Kobe University in Hyogo Prefecture, Japan (34°73'N, 135°23'E, 132.3 m above sea level) where the annual mean air temperature and precipitation in 2021 were 17.5 °C and 1637.0 mm, respectively (data from Japan Meteorological agency) (Figure 1(a)). For our experiments, we used a *Olea europaea* sapling, known as olive. The sapling with a height of 0.6 m and a trunk diameter of 0.8 cm (diameter was measured 10 cm from the ground, where the sensors were placed) (Figure 1(b)). We investigated the changes in embolism caused by irrigation conditions in olive trees.

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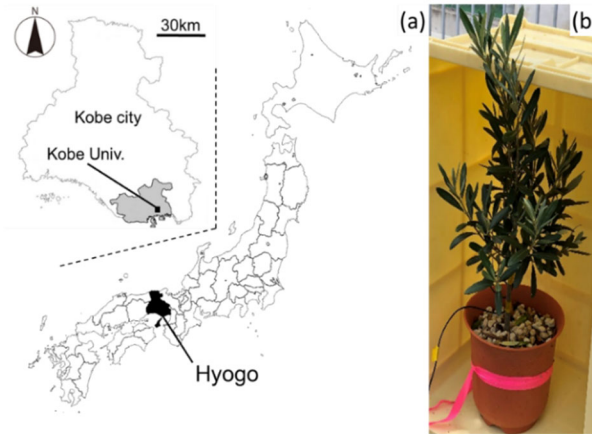


Figure1. (a) The study site, Kobe University in Hyogo Prefecture, Japan, (b) the appearance of the experimental sapling tree, *Olea Europaea* with the windbreak container.

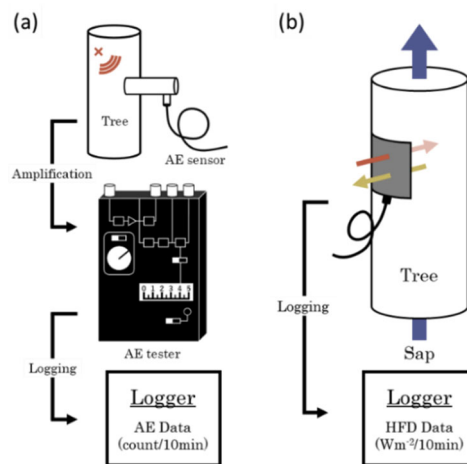


Figure2. (a) The schematic view of experimental system for AE measurement. AE generated in the tree is detected by an AE sensor and amplified by an AE tester. Finally, it is recorded in the logger as the number of events. (b) The schematic view of experimental system for HFD measurement. The instantaneous value of HFD is recorded in the logger.

To evaluate embolism, we measured it using an AE sensor (AE901U, NF Circuit Design Block Co., Ltd., Japan). It is known that ultrasound (acoustic emission, AE) is generated in response to the occurrence of cavitation or embolism inside trees. The frequency of this sensor was calibrated using the contact method and had a resonance frequency of 140 kHz. This frequency was targeted in accordance with research that indicates that the effective frequency band for capturing AE caused by embolism was 100-200 kHz (Vergeynst et al., 2016). When installing the sensor, the outer bark surface of the trunk was peeled off in 1.5 cm² area and smoothed with a cutter. After applying grease to prevent water, the sensor was attached to the trunk using a vinyl tape. The signal output from the AE sensor was amplified by an AE tester (AE9501A, NF Circuit Design Block Co., Ltd., Japan), and the integrated value of the number of AE events per 10 minutes (count/10 min) was recorded by a logger (UX120-017xM, Onset Corp., USA). When adjusting the sensitivity of the AE tester, the AE detection sensitivity was set to 0.5 mV and the rate full scale was set to 50 counts/sec. Power was supplied to the AE tester using rechargeable AA nickel metal hydride batteries, which were

replaced as needed to maintain the battery level above the measurable threshold. Data were downloaded from the logger using a dedicated application (HOBOWare, Onset Corp., USA). Data from June 19th to November 28th was used for the analysis. The sensor was covered with aluminum to protect it from direct sunlight.

To evaluate the sap flow velocity, we measured it using a heat flux sensor. Because the temperature of the water in the soil that tree suck up from their root is lower than the air temperature, the amount of heat transfers from the outside to the inside of the trunk increases as the sap flow velocity increases. Thus, the change in sap flow velocity can be indirectly evaluated by measuring the heat flux density (HFD) in the radial direction. In this study, a HFD sensor (S11, Eto Co., Ltd., Japan) was set using a masking tape from July 30th. The HFD was recorded as instantaneous values (W/m^2) every 10 minutes on a logger (LR5041, HIOKI Co., Ltd., Japan). Data was acquired from the logger using a dedicated application (LR5000 Utility, HIOKI Co., Ltd., Japan). The sensor was covered with aluminum to protect it from direct sunlight.

Olive saplings were small, and there was a possibility that wind could affect the AE events. Therefore, we installed windbreak containers from June 23rd, which at the same time prevented irrigation by natural rainfall. After one-time irrigation by natural rainfall at the beginning of the experiment on 19th June, no irrigation was carried out except for one artificial irrigation on July 25th. AE and HFD data were plotted together with precipitation data (Japan Meteorological Agency) as time-series data. Data affected by artificial noise from mechanical adjustments or malfunction of the Japan Meteorological Agency's observation equipment were removed.

RESULTS AND DISCUSSION

AE occurrence remained low until 27 days after irrigation was stopped (July 16th), which was considered to be the normal pattern of AE occurrence (Figure 3a). Olives have stomatal control against drying to prevent water loss (Fernández et al., 1997). This result suggested that adaptation against drought such as the decrease in transpiration may reduce embolisms. From the 28th day after irrigation was stopped (July 17th), daily cyclic AE events were routinely observed (Figure 3b). This indicated that water stress progressed and embolism occurred gradually during this period, and periodic occurrence of AE has also been confirmed in previous studies (Jackson and Grace 1996). On July 25th, 36 days after the irrigation was stopped, sufficient irrigation was done at 1:00 pm. As a result, AE events was temporarily suppressed, but then reappeared (Figure 3c). This indicates that irrigation reduced the embolism corresponding to a temporary mitigation of tension on the sap. Finally, Figure 3(d) shows the variation in AE until olive died. During this period, the overall number of AEs increased (note the change in the scale of AE events). AE and HFD values became unstable and AE events occurred even at night. Subsequently, the daily cyclic of AE and sap flow was no longer observed, and on August 31st, yellowing of the leaves was observed and the saplings died. This suggested that water stress reached insufficient levels to refill the vessels.

CONCLUSIONS

In conclusion, variations in embolism in response to changes from increased drought stress to temporary mitigation and eventually mortality could be monitored by nondestructive measurements with AE sensors. Olive trees showed drought tolerance, but embolism became a routine occurrence after approximately one month of irrigation stop. Although the trees were subsequently re-irrigated once, the embolism just prior to mortality not only increased rapidly, but also showed an unusual pattern with a loss of the daily cycle pattern. To understand the water transport function of trees, embolism in trunk needs to be quantified, measured over time, and continuously compared to environmental data.

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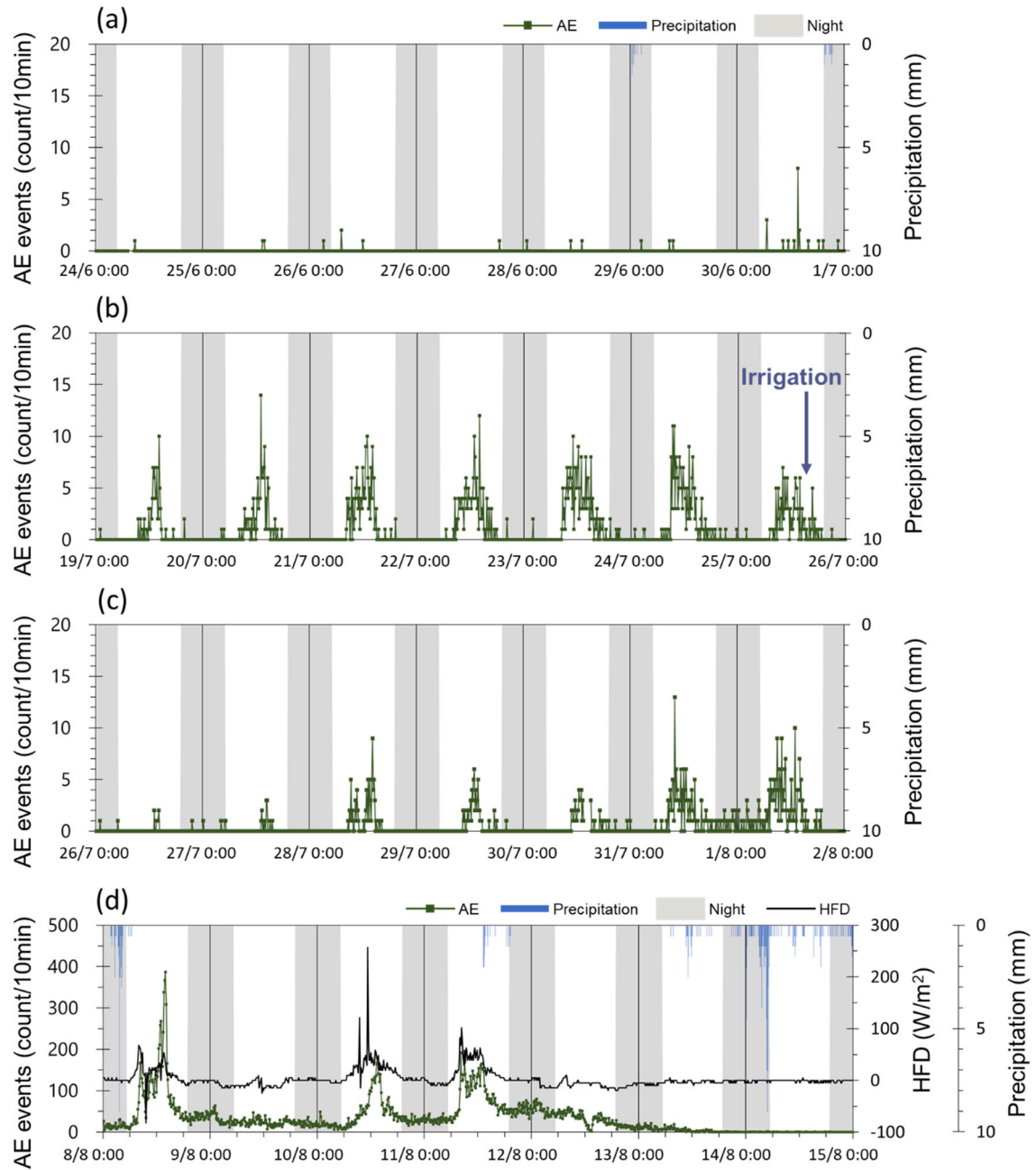


Figure 3. Relation between AE and water stress in *Olea europaea*: (a) normal AE occurrence patterns in *O. europaea* (b), occurrence patterns of AE under water stress in *O. europaea*, (c) temporary decrease in AE immediately after irrigation and reoccurrence in *O. europaea*, and (d) occurrence pattern of AE before the death in *O. europaea*. The left axis indicates the number of AE (green line), and the gray area indicates the nighttime. The right axis shows the amount of rainfall (blue bar) and heat flux density (HFD; black line).

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