Comparison of length and dynamics of wood pieces in streams covered with coniferous and broadleaf forests mapped using orthophotos acquired by an unmanned aerial vehicle

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Abstract

As wood pieces supplied by landslides and debris flows are one of the main components of ecological and geomorphic systems, the importance of quantifying the dimensions of the wood pieces is evident. However, the low accessibility of disturbed channels after landslides and debris flows generally impedes accurate and quick wood-piece investigations. Recent advances in photogrammetry techniques may overcome such issues. In this study, we used orthophotos acquired using a small unmanned aerial vehicle (UAV) to measure the lengths of wood pieces (> 0.2-m long and > 0.03-m diameter) entrapped mainly by check-dams. We focused on channels that are located in coniferous and broadleaf forests and affected by two different landslide events. The measurement accuracy was analyzed by comparing the lengths derived from the UAV method with direct measurements. When the both ends of a wood piece are satisfactorily extracted from an orthophoto acquired via the UAV, the wood-piece lengths of coniferous trees can be measured with an accuracy of approximately ±0.5 m. For broadleaf trees, most of the extracted lengths were shorter than the directly measured lengths, probably due to the low visibility arising from the complex structures of the root wad and tree crown. Most wood pieces were discharged from landslide scars in the broadleaf forest, whereas approximately 750 wood pieces were left in the landslide scars of the coniferous forest. The number of wood pieces in the landslide scars increased with the increase in the landslide area, suggesting that some wood pieces can be left even if large landslides occur. There were no significant changes in the lengths or locations of the entrapped wood pieces, at either site seven months after the first UAV flight. In the coniferous forests, the rainfall that triggered landslides in 2017 exceeded the 100-year return level, which was an abnormally intense rainfall. Although the 2019 rainfall event that occurred between UAV flights did not provide enough rainfall to trigger landslides, rainfall intensities with different durations reached the second-highest value from 1976 to 2019, exceeding the 30-year return period. This suggests that most of the entrapped wood pieces rarely migrate even under extreme rainfall.

Introduction

Debris flow causes the entrainment of stand-woods located in initiation and riparian zones, and consequently it may include ~10%–60% of fluvial wood pieces by volume (Johnson et al., 2000; May and Gresswell, 2003a; Lancaster et al., 2003). In addition to its destructive impact on life and infrastructure (e.g., Ruiz-Villanueva et al., 2013), wood pieces in a debris flow can alter the flow regime because of their irregular shapes, which can be entrapped around obstacles and lead to anomalous deposition of sediment and inundations (e.g., May, 2002; Lancaster et al., 2003; Tang et al., 2018; Booth et al., 2020). The accumulation of wood pieces results in structural peculiarities around channel networks (e.g., Keller and Swanson, 1979; Woodsmith and Buffington, 1996; Montgomery et al., 1996; Nakamura and Swanson, 2003). This contributes to changes in the ecosystem, the channel morphology, and the sediment flux through logjam formation and the decay of wood pieces (e.g., Wallace and Benke, 1984; Lisle, 1995; Montgomery et al., 1995; Gurnell et al., 2001; Comiti et al., 2006; Ruiz-Villanueva et al., 2016). Hence, the river form and function are determined by the interaction between water, sediment, and wood
Therefore, quantifying wood pieces is important for assessing their impacts on ecological, geomorphological, and fluvial conditions.

Many previous studies focusing on wood pieces in streams have contributed to unraveling the role of wood pieces in various spatiotemporal-scales and environmental settings, but most of these approaches required direct field measurements, such as local monitoring (e.g., Manners et al., 2007), the tracking of wood pieces (e.g., Ravazzolo et al., 2015; Wyżga et al., 2017), and field experiments using artificial wood pieces (e.g., Haga et al., 2002). Taking into account the diversity of forests around channels (e.g., age, species, and density of trees), the monitoring and field survey of wood pieces is evidently an effective approach. However, the necessity of human effort in the field hinders data acquisition in inaccessible areas (e.g., headwater channels and disturbed areas immediately after landslides and debris flows). In practice, field-data acquisition is difficult over large-scale areas exceeding the size of a sub-basin. The improvement of field-measurement techniques for wood pieces thus remains a critical issue.

To address the measurement issues for wood pieces, remote sensing approaches using three-dimensional data have been applied. The use of LiDAR (light detection and ranging) data clearly reduces the processing time required for mapping logjams and individual wood pieces (Kasprak et al., 2012; Abalharth et al., 2015; Atha and Dietrich, 2016). However, this technology is expensive and is therefore available only in some regions. Alternatively, photogrammetry based on structure-from-motion multi-view stereo (SfM-MVS) using a UAV (unmanned aerial vehicle) can produce three-dimensional data (e.g., digital-surface-models and point-clouds), which has been proven to be time-efficient compared to classical field surveys (Sanhueza et al., 2019). This approach overcomes data-availability issues and is relatively low cost. Nevertheless, most tests have been conducted in lowlands and flood plains rather than in low-accessibility areas such as steep channels (e.g., Sanhueza et al., 2019). As the accuracy of three-dimensional data acquired by SfM-MVS is greatly influenced by complex surfaces and obstacles—such as steep slopes, large reliefs, and vegetation coverage (e.g., Fonstad et al., 2013; James and Robson, 2014)—many unresolved uncertainties remain over the application of the SfM-MVS approach using three-dimensional data for wood-piece measurements in steep and complex areas such as channels impacted by landslides and debris flows.

Aerial photography is a traditional source of two-dimensional data that may provide more-or-less meaningful information about wood pieces. Even satellite images from Google Earth are being used for accurate wood-piece mapping (Atha, 2013; Ulloa et al., 2015). Hence, the efficacy of aerial photography is evident, but the accuracy and effort of mapping depend on the image quality. In this respect, it is expected that small UAVs may allow the acquisition of high-resolution aerial photographs at low cost because of the lower flight altitudes and higher portability of UAVs compared to conventional manned aerial vehicles. Moreover, because flights of small UAVs can overcome inaccessibility issues and cover several kilometers, depending on the flight design, a UAV is a fairly attractive tool for obtaining wood-piece measurements in low-accessibility areas.
In addition, wood pieces are often quickly removed by river administrators to avoid unexpected damages in the downstream area resulting from its transport by streamflow after being supplied and entrapped in streams (hereinafter this is referred to as secondary transport). The risk arising from the secondary transport of wood pieces (e.g., damages on facilities in residential regions) has not been evaluated properly so far, because it has been difficult to conduct field surveys of the wood-piece supply immediately after intense rainfall. In contrast, UAV flights can be conducted immediately after rainfall events that result in a large number of wood pieces, which can potentially contribute to unraveling wood-piece dynamics after their supply and entrapment. Therefore, an efficient mapping method of wood pieces enables the investigations of wood-piece transport due to subsequent rainfall, even if it is carried out with a simple method using aerial photography. Nevertheless, the potential to measure wood pieces based on aerial photographs acquired using UAV has not been thoroughly examined due to lack of sample cases.

In this study, we analyze the accuracy of UAV-based measurements for wood-piece lengths. Two regions are selected representing two forest types, coniferous and broadleaf forests. In both regions, large numbers of wood pieces were supplied to streams through landslides and debris flows triggered by a single rainfall event. This research has two main objectives: (1) to analyze the capability of orthophotos acquired via UAVs to measure the lengths of wood pieces, and (2) to investigate whether entrapped wood pieces move again due to intense rainfall. Based on the results, we discuss the effectiveness of UAV measurements and how wood pieces behave after their entrapment.

**Study sites**

To examine the influence of tree type on the accuracy of wood-piece measurements obtained using the orthophotos acquired by the UAV, we selected two different sites covered by coniferous or broadleaf forests (Figure 1a). Hereafter, the former site is referred to as the CF (coniferous forest) site (Figure 1b), while the latter site is referred to as the BF (broadleaf forest) site (Figure 1c). In this study, we use the term “tree type” to indicate either coniferous or broadleaf trees rather than the detailed tree species.

**Coniferous forest site**

The CF site is a sub-watershed of the Otoishi watershed located in the northern part of Kyusyu Island, Japan (Figure 1a, b). Its highest point is approximately 385 m above sea level (a.s.l.), and its lowest point is approximately 225 m a.s.l. The total length of the main channel is approximately 760 m with an average slope of approximately 12° (before the debris-flow occurrence), and the drainage area is approximately 0.15 km$^2$. To prevent the destabilization of hillslopes and banks, five closed-type check-
dams (check-dams without slit and steel lattice structures for trapping wood pieces and boulders; e.g., Piton and Recking, 2016) were constructed before the debris flow occurred in 2017 (Figure 2a). Most hillslopes are covered with artificial coniferous forests that consist mainly of Cryptomeria japonica and Chamaecyparis obtusa. The tree heights range from approximately 15 to 25 m.

In the region around the CF site, an intense rainfall on July 5, 2017, triggered more than 2,000 landslides, which resulted in debris-flow propagations and therefore a large number of wood pieces (Chigira et al., 2018). The sliding sediment layers were mainly granodiorite and pelitic schist (Chigira et al., 2018). The intense rainfall in July 2017 triggered six landslides at the CF site (Figure 2a), but the existing check-dams effectively prevented the descent of sediment and wood pieces. Hence, most of the wood pieces were trapped around the check-dams and along the channel, thereby preventing damage in the downstream residential areas. Because of this low impact on the residences, the wood pieces were not removed and were left in-situ until the time we carried out observations.

Broadleaf forest site

The BF site is located in the Hiroshima prefecture in the western part of Japan (Figure 1c). Here, two channels are confluent at an irrigation pond that is located at the lower ends of channels (~305 m a.s.l., Figure 2b). The highest points of channels A and B are ~410 and ~480 m a.s.l., respectively. Their total lengths are ~880 and ~466 m, respectively. The average slopes of the two channels are similar, at ~11°–12° (before the debris-flow occurrence). The drainage areas of channels A and B are ~0.07 and ~0.13 km², respectively. Similar to the case of the CF site, four closed-type check-dams were constructed before the debris flow occurred in 2018 (Figure 2b). The forest type is completely different from the CF site, and most of the hillslopes are covered by broadleaf forests with various tree types. The tree heights range from approximately 10 to 20 m.

In the Hiroshima prefecture, a stationary front affected by Typhoon Prapiroon caused heavy rainfall on July 5–7, 2018 (Tsuguti et al., 2019) and triggered approximately 8,000 landslides due to the vulnerable geological setting, which is mainly dominated by weathered granite (Kaibori et al., 2018). Five landslides occurred at the BF site, but the check-dams and the pond effectively prevented the descent of sediment and wood pieces. Similar to the situation at the CF site after the disaster, the wood pieces produced in the BF site were left in-situ until we carried out the observations.

Methods

This study consists of two parts: (1) an assessment of the accuracy of the wood-piece measurements obtained from ortho-photography acquired via the UAV, and (2) a rainfall analysis to investigate the possible transport of entrapped wood pieces.
**UAV flights and aerial-photograph processing**

A small consumer-grade UAV (DJI Mavic 2 pro; Table 1) was used for the flights covering the channels and landslides (Figure 2). Two UAV flights were conducted at each of the respective study sites (Table 2): (1) February 14 and September 26, 2019, at the CF site, and (2) November 16, 2018, and December 25, 2019, at the BF site. The flights were conducted manually at heights above ground between approximately 50 and 150 m, and most of the photographs were taken in the nadir direction. The flight path provided at least 70% overlaps in the forward and side directions of the aerial photographs. To reduce the differences in shade and brightness among the acquired aerial photographs, the flights were operated avoiding strong sunlight.

Table 1. Properties of the UAV and the installed camera.

| UAV              |                  |
|------------------|------------------|
| Model            | DJI Mavic 2 pro  |
| Weight           | 907 g            |
| Diagonal size    | 354 mm           |
| Max. duration of flight | 31 min          |
| Camera           |                  |
| Number of pixels | 20 M             |
| Sensor size      | 13.2 × 8.8 mm    |
| Focal length     | ∞                |

Table 2. Dates of UAV flights and number of aerial images used to provide orthophotos.

| Site   | Date                  | Number of aerial images |
|--------|-----------------------|-------------------------|
| CF site| First flight          | February 14, 2019       |
|        |                       | 159                     |
|        | Second flight         | September 26, 2019      |
|        |                       | 284                     |
| BF site| First flight          | November 16, 2018       |
|        |                       | 315                     |
|        | Second flight         | December 25, 2019       |
|        |                       | 141                     |

The acquired images were processed using SfM-MVS photogrammetry software (Agisoft, Metashape Professional version 1.5.1). Usually, artificial reference markers are established, and their absolute coordinates are measured with a GNSS (global navigation satellite system), providing ground-control
points (GCPs) for geo-referencing the SfM-MVS photogrammetry (e.g., Barnhart et al., 2019; Tsunetaka et al., 2020). However, immediately after a debris-flow disaster, the establishment of artificial reference markers is impeded by wood pieces, which behave as obstacles. The recently developed, high-accuracy, RTK (real time kinematic) GNSS-based direct geo-referencing system built into a UAV for SfM-MVS photogrammetry processing makes it possible to obtain accurate absolute coordinates without GCPs (e.g., Carbonneau and Dietrich, 2017). However, it is an expensive technology and the consumer-grade UAV that we used does not include such an RTK-GNSS system. Because of these operational limitations, we focused on the ability to make wood-piece measurements using relatively low-cost UAV-based processing. Our intention was thus to assess the accuracy of measurements using only UAV flights without any other field operations (e.g., setting artificial reference markers) or RTK-GNSS systems.

The position data from the built-in GNSS that controlled the flight position were contained in exchangeable image file format data for each photograph. Using these data, we preliminarily collected the coordinates of the processed orthophotos. Following standard SfM-MVS photogrammetry workflow, the orthophotos were produced with a spatial resolution of 0.03–0.05 m. Because the measurements were performed without establishing artificial reference markers, the coordinates of the resulting orthophotos taken during the different flight dates did not overlap accurately. As the principal aim of using sequential orthophotos was to investigate the transport of the wood pieces, it is necessary only to have relative coordinate system overlap (i.e., absolute coordinate system overlap is not required). Thus, we manually adjusted two sequential orthophotos using the crests of the check-dams as GCPs for which the coordinates were taken from the older orthophoto. Using the extracted coordinates, the orthophoto acquired on the later date was transformed to fit the first one. The differences in the lengths of selected immobilized objects (e.g., large boulders and the crests of check-dams) were less than approximately 0.2 m. Therefore, we considered the horizontal accuracy of the orthophotos to be less than 0.2 m.

### Accuracy assessment

Because we used orthophotos (i.e., two-dimensional data) to quantify the wood pieces, the dimension of wood pieces measured by the UAV is its length. First, we extracted the length of the wood pieces, both as a single piece and as an element of a jam-forming log as line data from the acquired orthophotos. Note that invisible wood pieces below a jam-forming log are out of the measurement target. All visible wood pieces were extracted at the CF site (the area surrounded by the dotted white line in Figure 2a), whereas only wood pieces around the check-dams A and B were investigated at the BF site because of the low visibility of wood pieces originating from broadleaf trees (Figure 2b). Accordingly, the measurement range differed from a reach scale at the BF site to a sub-watershed scale at the CF site.

The measurement accuracy of the extracted length is presumably affected by visibility, which is related to the types and sizes of the trees. Moreover, because wood pieces are often inclined and broadleaf trees have a curved shape, orthogonal projection to obtain the extracted length may cause a measurement
error (Figure 3). Hence, we focused on the differences among the tree types (i.e., coniferous or broadleaf trees), diameters, and entrapment inclinations of the wood pieces.

To compare with the extracted lengths of the wood pieces, we directly measured wood pieces at the study sites (Figure 3). Based on the orthophotos from the first flight, the visible wood pieces were labeled. When we conducted the second flight, we found and directly measured some of the labeled wood pieces (50 wood pieces at the CF site and 131 wood pieces at the BF site). In the found wood pieces, we measured the lengths—excluding the root-wads and twigs—directly using a tape (estimated precision < 0.05 m), similar to the approach of Sanhueza et al. (2019) and compared those measurements with the lengths extracted from the orthophotos from the first UAV flight (Figure 3). Using the same tape, we measured the circumferences of the found wood pieces at approximately 1.0 to 1.5 m height from the root wad. For wood pieces less than approximately 1.5 m in length, because there were only slight differences in the thickness of a single fragment, we measured the circumference at an arbitrary location. From the measured circumferences, we calculated the diameters of the found wood pieces. Note that, because the minimum measurable circumference was approximately 0.1 m, some of the calculated diameters of the wood pieces were smaller than the estimated precision of the tape measurement (0.05 m). At the CF site, as the wood pieces retained relatively straight shapes, the entrapment inclination was measured directly using an angle meter (estimated precision < ±1°, Figure 3a).

The extraction of wood pieces depends on its visibility in the orthophotos, and thus the identification of its origin as well as the detection of small wood pieces of less than the minimum resolution of the orthophotos (i.e., 0.03 m in diameter) were beyond the measurement purpose. In addition, the successful extraction of wood pieces from the orthophotos was constrained by the visibility of the wood-piece length, not by the visibility of the wood-piece width (diameter). Considering the horizontal accuracy of the orthophotos (< 0.2 m), the minimum length of the extracted wood pieces was set to 0.2 m. Although wood piece called “large wood” is typically defined as a wood piece > 0.1 m in diameter and > 1 m in length (e.g., Jackson and Sturm, 2002; Tang et al., 2018), our dataset included further small wood pieces (a wood piece > 0.03 m in diameter and > 0.2 m in length), following the minimum measured diameters and the lengths of the wood pieces. Moreover, the extracted wood pieces may contain multiple pieces that originated from a single tree. Note that, as a single stand-wood may result in several wood pieces, counting the extracted wood pieces involves uncertainty.

Analysis to determine the transport of wood pieces

To analyze whether or not wood pieces migrated through time, we created the quantile–quantile (Q–Q) plots of the probability density of the extracted length. The CF site was divided into seven zones: six landslide scars and the riparian zone with a channel approximately 760 m in length (Figure 2a). Changes in the probability density of the wood-piece length were visually tested using the Q–Q plots. Similarly, Q–Q plots were made for channels A and B at the BF site (Figure 2b). For each zone, to investigate the
coincidence of the probability density of the extracted length between the two flight dates (Table 2)—(1) February and September, 2019 (i.e., approximately seven months), at the CF site, and (2) November, 2018, and December, 2019 (i.e., approximately eleven months), at the BF site—we conducted a goodness-of-fit test using the Kolmogorov–Smirnov test.

In addition, we investigated whether specific rainfall characteristics triggered the secondary transport of wood pieces. For this reason, we used the hourly rainfall records from 1976 to 2019 obtained at the closest rain-gauges installed by the Japan Meteorological Agency, the Asakura station (for the CF site, Figure 1b) and the Higashihiroshima station (for the BF site, Figure 1c). The annual maxima of rainfall intensity of various durations (1, 2, 3, 6, 12, 24, 48, and 72 hours) were investigated from 1976 to 2019 and compared with the intensity of the rainfall that triggered the debris flows. In addition, we examined the records of rainfall maxima after the debris-flow occurrence. The return periods were calculated based on the probability density of each rainfall intensity fitted by a Gumbel distribution based on the annual maxima (e.g., Koutsoyiannis et al., 1998; Sane et al., 2018). For this fitting process, the goodness-of-fit test (Kolmogorov–Smirnov test) resulted in $p$-values exceeding 0.1, suggesting that the applied Gumbel-distribution models well fitted the probability density of the observed rainfall.

Results

Lengths of the entrapped wood pieces

As expected, a comparison of the extracted and measured wood-piece lengths indicates that the measurement accuracy depends on the visibility of the wood pieces. Fifty wood pieces were directly measured at the CF site (Figure 4a). Fourteen of them were trapped by stand-woods located in the riparian zone, and they were partially invisible from the sky due to the coverage by the tree crowns. This low visibility caused underestimates of the extracted lengths, with errors in length being a maximum at ~10 m. In contrast, 36 other pieces were fully visible, and their lengths ranged between about 3 and 22 m. Despite this wide range, most measurements coincided well with the extracted lengths. This clear dependence on the visibility of the wood pieces is reflected in the boxplot (Figure 5), indicating that the interquartile ranges obviously differed between the visible and covered wood pieces; the differences ranged from −0.4 to 0.5 m and from 1.6 to 4.3 m, respectively (Figure 5).

The lengths of 130 wood pieces without crown coverage were directly measured at the BF site, but they rarely coincided with the extracted lengths, which were usually underestimates (Figure 4b). Moreover, the differences between the lengths varied. The related interquartile range varied between approximately 0.3 and 2.1 m, reflecting the lower accuracy and higher uncertainty when measuring broadleaf trees than when measuring coniferous trees (Figure 5).

Strictly speaking, the extracted length was the orthogonally projected length, and we therefore calculated the slope distance of the measured wood pieces from the extracted length using the measured slope. However, this correction did not significantly improve the measurement accuracy because differences in
the visibility of the wood pieces depending on the difference in the tree types overwhelmed the influence arising from the approximation by the orthogonal projection (Figures 4a and 6). The differences in the wood-piece diameters indicate that the extracted lengths of relatively narrow pieces (<~0.2–0.3 m in diameter) at the BF site tend to be underestimated (Figure 7), despite the absence of crown and logjam coverages. Note that, especially for wood pieces with diameters less than 0.1 m, direct measurements (estimated precision < 0.05 m) and orthophotos (estimated precision < 0.2 m) can contain significant measurement error independent of the differences in tree types. However, even for wood pieces with diameters between 0.1 and 0.2 m, the measurement errors were higher at the BF site than at the CF site (without coverage, see Figure 7). This suggests that the decrease in the visibility of small-diameter pieces was responsible for the decreased measurement accuracy at the BF site.

Most wood pieces were discharged from landslide scars at the BF site, whereas a total of approximately 750 wood pieces (exceeding 50% of the total of ~1,370 wood pieces) were left in the landslide scars at the CF site. At the CF site, the interquartile of the wood-piece length differed slightly among the landslide scars, but they were similar between the riparian zone and the average of all landslides: 2.5 to 7.7 m and 2.6 to 8.3 m, respectively (Figure 8a). The median length of the wood pieces ranged from 3.4 m (in landslide 4) to 7.8 m (in landslide 1). At the BF site, the interquartile of the wood-piece length at check-dams A and B were 1.1 to 3.1 m and 0.8 to 2.6 m, respectively (Figure 8b). The median lengths of the wood pieces at check-dams A and B were similar: 1.8 m and 1.5 m, respectively. The median wood-piece length at the CF site was ~4.5 m, which is evidently greater than that at the BF site (Figure 8c).

The areas of the landslide scars at the CF site ranged widely, from ~800 to 5,400 m² (Figure 9). The number of entrapped wood pieces tended to increase with the increase in the area of the landslide scars (Figure 9). Landslide 2 (~5,400 m²) accounted for approximately 40% of the total area of the landslide scars (i.e., the total landslide area at the CF site is ~14,000 m²), and thus this landslide was the predominant sediment source at the CF site. Despite this huge sediment discharge, the number of entrapped wood pieces was highest among the landslide scars, at approximately 350 wood pieces.

**Transport of entrapped wood pieces**

At both sites, there were only slight visible changes in the spatial distribution of the wood pieces between the two orthophotos (Figures 10 and 11). The wood pieces were trapped in various areas—for instance, as stand-woods in the riparian zone, the check-dams, and the landslide areas. Despite these differences in the entrapment zones, it seems that most of the wood pieces did not move even after about 7 months (at the CF site, Figure 10) and over one year (at the BF site, Figure 11). The Q–Q plots indicate that the probability density of the extracted wood-piece length coincided well with the measured length, regardless of the division of the entrapment zones (Figure 12). Thus, the *p*-values with respect to the goodness-of-fit test exceeded 0.05, suggesting that the changes were statistically insignificant.
The rainfall anomalies that triggered debris flows were revealed by comparing the annual maxima of the rainfall intensity in each case. At the CF site, the rainfall that triggered the debris flow in 2017 was obviously excessive rainfall, as the rainfall intensity was the highest compared with the annual maxima of other years, regardless of the rainfall duration (Figure 13a). This suggests that the highly intense and continuous rainfall resulted in the large number of wood pieces. At the BF site, for the rainfall that triggered debris flows in 2018, rainfall intensities with 1–6 hour durations were not higher than the other annual maxima since 1976, but those with 12–72 hour durations were the most intense since 1976 (Figure 13b). This suggests that a high rainfall intensity continuing over 12 hours resulted in landslides and debris flow accompanied by the propagation of wood pieces. Both rainfall events that triggered debris flows at the CF and BF sites reached levels exceeding the 100-year return period (Tables 3 and 4).

Table 3. Return period ($RP$) for the annual maxima of rainfall intensities at the CF site.

| Year | $RP_{1h}$ | $RP_{2h}$ | $RP_{3h}$ | $RP_{6h}$ | $RP_{12h}$ | $RP_{24h}$ | $RP_{48h}$ | $RP_{72h}$ |
|------|-----------|-----------|-----------|-----------|------------|------------|------------|-----------|
| 2017 | > 100     | > 100     | > 100     | > 100     | > 100      | > 100      | > 100      | > 100     |
| 2018 | 1.66      | 2.68      | 3.47      | 10.84     | 17.60      | 20.70      | 33.67      | 17.05     |
| 2019 | 10.32     | 11.98     | 14.18     | 33.46     | 32.22      | 15.86      | 11.17      | 11.31     |

Table 4. Return period ($RP$) for the annual maxima of rainfall intensities at the BF site.

| Year | $RP_{1h}$ | $RP_{2h}$ | $RP_{3h}$ | $RP_{6h}$ | $RP_{12h}$ | $RP_{24h}$ | $RP_{48h}$ | $RP_{72h}$ |
|------|-----------|-----------|-----------|-----------|------------|------------|------------|-----------|
| 2018 | 15.60     | 14.67     | 11.88     | 13.70     | > 100      | > 100      | > 100      | > 100     |
| 2019 | 3.77      | 2.76      | 1.90      | 2.36      | 2.13       | 2.00       | 1.77       | 1.67      |

At the BF site, after the landslides and debris flows in 2018, the maximum annual rainfall intensity in 2019 was not remarkable (Figure 13b, Table 4). Thus, although most wood pieces remained in place, it is difficult to analyze the potential of secondary transport of entrapped wood pieces via intense rainfall. In contrast, at the CF site, after the landslides and debris flows in 2017, the annual rainfall intensity maxima in 2018 and 2019 were the second or third highest values since 1976 (Figure 13a). Although the intensity of the triggering rainfall in 2017 significantly exceeded the annual maxima in 2018 and 2019 in terms of the return period, some rainfall intensities in 2018 and 2019 exceeded the level of the 30-year return period (Table 3). Such a heavy rainfall event occurred on July 21, 2019 (in between the UAV flights at the CF site; Table 2).

**Discussion**

**Implications for UAV-based wood-piece mapping**

Our results demonstrate that the visibility and tree types of the wood pieces determine the ability to measure their lengths accurately using orthophotos acquired via UAVs. The lengths of most of the wood
pieces originating from coniferous trees were measured with better than ±0.5 m accuracy using the orthophotos acquired by the UAV, but for the broadleaf trees, the lengths were underestimated systematically despite the absence of tree-crown coverage reducing the visibility (Figures 4b and 5). Considering the complex structures of both ends of the broadleaf trees (i.e., wide and rounded crowns and root-wads; Figure 3b), these underestimates may be attributed to missing extractions due to the low visibility of the broadleaf trees arising from the complex structures at the ends. In addition, the lengths of the entrapped wood pieces at the BF site was less than that at the CF site (Figure 8), implying the fragmentation of broadleaf trees during the debris flow. Although the characteristics of the debris flow also probably influence the magnitude of wood-piece fragmentation (e.g., Johnson et al., 2000; Lancaster et al., 2003), the fragility of broadleaf trees may reduce the measurement accuracy based on the orthophoto at the BF site by decreasing the visibility of the wood pieces.

Hence, most of the factors that decrease the measurement accuracy of wood pieces depend on visibility. Based on this interpretation, wood-piece measurements via UAV have both positive and negative aspects. Several components that affect the quality of the aerial photographs (e.g., black shadows, brightness involving overexposure, and insufficient overlap ratios among the aerial photographs) depend on the weather conditions and the flight plan (e.g., the path, height, and direction of shooting). For example, it is expected that low flight altitudes and flights under cloudy conditions can avoid block-out shadows and blown-out highlights in the acquired UAV images, resulting in an increase in the visibility of wood pieces in the processed orthophotos. Thus, an adequate flight plan may significantly improve the accuracy of UAV-based wood-piece measurements, without additional processing in the SfM-MVS photogrammetry.

Conversely, our results reveal an obvious limitation of orthophoto-based measurements. In general, wood pieces are not only dispersed along a channel but also result in logjam due to stacking and accumulation (e.g., Manners et al., 2007; Abalharth et al., 2015). However, the correlation between measurement accuracy and visibility from the sky demonstrates that the length measurements of wood pieces covered by a logjam are beyond the scope of orthophoto-based measurements. Sanhueza et al (2019) pointed out that vegetation in streams also may cover wood pieces and thus decrease the measurement accuracy of wood pieces based on images acquired by UAV. Indeed, the tree-crown coverage decreased the measurement accuracy of wood-piece length (Figure 4a). Given these measurement limitations, it is especially difficult to measure jam-forming wood pieces in streams deeply covered by vegetation (e.g., riparian trees) using the approach employing images acquired by a UAV.

In other words, the total number of wood pieces is probably underestimated in all UAV-based measurements. In this respect, the entrapment of wood pieces in landslide scars at the CF site may also have been underestimated, suggesting that high-ratio wood pieces were left even in slipped hillslopes. In some sub-watersheds with coniferous forests located around the CF site, no wood pieces were left in the landslide scars (Marutani et al., 2017). Thus, the difference in tree type (i.e., coniferous or broadleaf trees) cannot account for the high-ratio of wood-piece entrapments in the landslide scars at the CF site compared with that at the BF site. The median length of wood pieces varied among landslide scars (Figure 8a), probably depending on differences in runout processes and sediment volume among
landslides. Considering this, the increase in the number of entrapped wood pieces with the increase in the landslide area (Figure 9) indicates that wood pieces may remain in landslide scars regardless of differences in size and the dynamics of landslides. It seems that the outlets of landslide scars at the CF site are relatively narrow (like bottle-necked shapes) compared with those at the BF site (Figure 2), which may lead to high-ratio wood-piece entrapments.

Possibility of the transport of the entrapped wood pieces

The slight changes in the lengths and spatial distributions of the wood pieces suggest that the wood pieces that were entrapped by the check-dams did not move after the debris-flow disaster (Figures 10, 11, and 12). The elapsed time from the first flight was about seven months for the CF site and over a year for the BF site (Table 2), which may be insufficient to cause significant visible decay. This means that intact wood pieces still remain in the upper reaches of the channels. However, considering the slight differences in the spatial distribution and the Q–Q plot of the wood pieces at the CF site (Figures 10 and 12), the extremely high rainfall intensities in 2019 (Figure 13a and Table 3) suggest that most of the entrapped wood pieces remain in place and rarely migrates, even when intense rainfall exceeding the level of the 30-year return period occurs. This implies that most rainfall events that do not cause debris flows and landslides cannot trigger secondary transport of entrapped wood pieces.

Because the pre-existing check-dams trapped wood pieces at both sites, differences in the trend between such artificial trapping and natural entrapment of wood pieces should be noted. Even so, the low transportability of the entrapped wood pieces provides insight into the role of the wood pieces and sediment deposited in the upstream channel after debris flows and landslides. The efficacy of wood-piece trapping by closed-type check-dams (check-dams without slit and steel lattice structures) is generally considered relatively low compared with that of open-type check-dams (e.g., Piton and Recking, 2016). Nevertheless, the entrapment of wood pieces by closed-type check-dams continued in the long term, due to the low possibility of secondary transport at our study sites. May and Gresswell (2003b) argued that wood pieces in streams can facilitate sediment deposition, thereby resulting in an increase in sediment storage. Indeed, the low transportability of the entrapped wood pieces in the CF and BF sites indirectly indicates low erosion and discharge rates of the sediment stored after a landslide occurrence, suggesting that the entrapped wood pieces can impede subsequent sediment transport. For this reason, the trapping of wood pieces in low-order streams during and immediately after a landslide occurrence is notably important in mitigating subsequent impacts on facilities in residential regions due to the wood pieces and sediment supplied.

Conclusions

We mapped wood pieces using orthophotos acquired using a UAV in two headwater channels covered by coniferous or broadleaf forests (the CF and BF sites, respectively): (1) to determine whether or not ortho-
photography acquired via UAV allows measurements of the wood-piece lengths, and (2) to investigate the possibility of the transport of entrapped wood pieces by intense rainfall.

At the CF site, comparing the directly measured lengths with the lengths extracted by UAV mapping indicates that aerial-photography measurements had approximately ±0.5 m accuracy when the both ends of the wood pieces were satisfactorily visible. In contrast, some wood pieces were trapped by standwoods in the riparian zone, which were invisible underneath the tree crowns, and this led to underestimation of the extracted lengths. At the BF site, most of the extracted length values were shorter than the lengths measured directly, probably due to low visibility of the ends of the wood pieces due to complex tree structures in the root-wads and tree crowns. Hence, these results suggest that the measurement accuracy of wood pieces via UAV strongly depends on the visibility of the wood pieces arising from tree types. In other words, although flight operations that adequately increase the visibility of wood pieces in UAV images may improve the accuracy of wood-piece length measurements, the UAV-image-based approach is fundamentally inadequate for measuring jam-forming wood pieces, especially in streams covered by riparian trees.

Most wood pieces did not remain in the landslide scars at the BF site, whereas approximately 750 wood pieces were left in the landslide scars at the CF site. The number of wood pieces in the landslide scar tended to increase, depending on the increase in the landslide area. Therefore, even large landslides cannot transport all wood pieces from their slip hillslopes in some cases, suggesting that wood pieces may remain in landslide scars regardless of the landslide area.

At both sites, changes in the frequency distribution of the lengths and the locations with respect to entrapped wood pieces were slight even over seven months had passed since the first mapping. Nevertheless, at the CF site, some rainfall intensities between the two flights reached the second-highest values since 1976. Although the rainfall intensity that triggered the landslides in 2017 was higher than the annual maxima in 2019, some intensity values in 2019 exceeded the 30-year return period. This suggests that most of the entrapped wood pieces remains and rarely migrates again, even under intense rainfall.

**Abbreviations**

BF: Broadleaf forest; CF: Coniferous forest; GCP: Ground-control point; GNSS: Global navigation satellite system; LiDAR: Light detection and ranging; SfM-MVS: Structure-from-motion multi-view stereo; UAV: Unmanned aerial vehicle

**Declarations**

**Availability of data and material**

The data used in this paper are available from the authors upon request.
Competing interests

The authors declare that they have no competing interest.

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Authors’ contributions

HT conducted field measurements using a UAV and data analysis, and drafted this manuscript. SM conducted field measurements and rainfall processing. SA, TO, and UK carried out field measurements. All authors read and approved the final manuscript.

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Figure 3

Schematic representation of the components for the direct measurement of wood pieces: (a) the coniferous tree and (b) broadleaf tree. The left side indicates the top of each type of tree (the side of the tree crown). The right side depicts the root-wad.
Figure 9

Comparison between landslide area and the number of remaining wood pieces. The black line is the linear regression line.
Figure 10

Comparison between landslide area and the number of remaining wood pieces. The black line is the linear regression line.
Figure 11

Spatial distribution of extracted wood pieces at the broadleaf forest (BF) site: (a) check-dam A on November 16, 2018, (b) check-dam A on December 25, 2019, (c) check-dam B on November 16, 2018, and (d) check-dam B on December 25, 2019.
Figure 12

Q–Q plots for the lengths of the extracted wood pieces: (a–g) the coniferous forest (CF) site and (h–i) the broadleaf forest (BF) site. The p-value indicates the result of the goodness-of-fit test (the Kolmogorov–Smirnov test).
Figure 13

Q–Q plots for the lengths of the extracted wood pieces: (a–g) the coniferous forest (CF) site and (h–i) the broadleaf forest (BF) site. The p-value indicates the result of the goodness-of-fit test (the Kolmogorov–Smirnov test).