Thinning of cypress forest increases subsurface runoff but reduces peak storm-runoff: a lysimeter observation

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Abstract:
Changes in runoff caused by forest management practices such as thinning need to be better understood for effective water resource management. We established matched (20° slope) 62%-thinning treatment and grassland control lysimeter plots in a 22-year-old cypress plantation in the Inuyama Research Forest of the Ecohydrology Research Institute, Japan. Runoff (surface and subsurface) was directed into a collection tank with a 90° v-notch weir outlet. Measurements were made before and after the thinning treatment and were compared with grassland control. Monthly manual measurements of subsurface runoff (March 2011–December 2014) performed via a measuring cylinder and stopwatch yielded 18 pre-thinning and 24 post-thinning observations. In addition, 26 pre-thinning and 24 post-thinning sets of storm-event measurements were continuously recorded via a water level data logger. Following thinning, subsurface runoff and peak storm-runoff changed by up to +133% and –80% respectively. By controlling the geology, soil characteristics and hydrological pathways, we were able to attribute these outcomes to reduced transpiration and increased ground resistance from felled logs respectively, suggesting that well-managed high-intensity thinning may be beneficial for increasing water supply and controlling floods. However, this is only achievable if felled logs are aligned along contour lines on the hillslopes.

KEYWORDS forest management; hydrology; cypress; thinning; forestry; runoff

INTRODUCTION
Approximately 65% of Japan is forested, with 40% of these forests being plantation forests, and Japanese cypress being the most commonly planted trees (Forestry Agency, 2017). Without forest management practices such as thinning, the extensive canopy coverage of these trees prevents sunlight from reaching forest floors thus preventing growth of understorey vegetation. This in turn causes increased soil erosion during rain events through three mechanisms: (i) high kinetic energy and erosive power of crown drips falling from high canopies; (ii) water drops hitting the bare soil without first being intercepted by understorey vegetation; (iii) absence of overland flow attenuation due to lack of ground resistance (Onda, 2008). Whilst forest thinning can help to prevent these undesirable processes and therefore the rates of soil erosion, it can also modify the water balance and flowpath, which in turn affect water availability, quality and supply rate to downstream users. In addition, different thinning practices such as whether felled logs are removed or retained, may significantly impact runoff processes. Therefore, a number of studies (Onda, 2008; Dung et al., 2012; Gomi et al., 2013; Sun et al., 2015b, 2016) have been carried out to understand the characteristics of each flow component (from rainfall to streamflow) in plantation forests, and how best to manage these competing effects.

Previous studies concluded that forest clearing and thinning reduce evapotranspiration and increase runoff (Dung et al., 2011; Sun et al., 2014). Dung et al. (2012) observed significant increases in delayed flow and flow-duration of ephemeral streams but quick flow remained unchanged from the pre-thinning phase. In a 46-year-old Japanese cypress and cedar stand, Sun et al. (2017a) observed higher flashiness (higher peak flows, steeper rising and falling limbs) after 50% thinning – indicating increased flood risk and soil erosion. However, Tateishi et al. (2014) found the opposite effect where post-thinning runoff was reduced due to increased surface evaporation that exceeded the effects of reduced transpiration. In other studies, similar levels of thinning of Japanese cypress led to slightly increased mean annual runoff (maximum increase of 147 mm in second year post-thinning) without affecting peak runoff characteristics (Kubota et al., 2013, 2018).

Besides runoff, Sun et al. (2017b) found insignificant changes in the relative contribution of each evapotranspiration component (canopy interception, tree transpiration, and floor evaporation) but significant overall decrease in evapotranspiration (~21.4 and ~10.4% in the growing and dormant season respectively), which translates to increased water availability. On the other hand, throughfall increased from 64.3 to 76.2% following 50% thinning of Japanese cypress (Sun et al., 2015a). In general, forest thinning increases water availability, although the opposite effect.

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may sometimes occur in cases where felled logs were removed from the catchment (Tateishi et al., 2014).

This spectrum of results suggests that a variety of factors such as climate, soil type, geology and management practices influence the hydrological impacts of forest thinning. While such catchment-scale studies are important because they assess real-world conditions, it is impossible to fully control environmental factors such as geology, groundwater dynamics and inflow of runoff water therefore making it difficult to draw universal conclusions. Carrying out land-treatment experiments in a lysimeter is one of the ways in which these factors can be controlled. A lysimeter compartment is made from impermeable materials (usually concrete) that isolates external hydrological pathways. This compartment is then installed into the ground and filled with soil to simulate natural environmental conditions whilst preventing the inflow and outflow of runoff water. Using a non-weighing type slope lysimeter (Yamaguchi et al., 1987; Shibano et al., 1988; Kuraji and Shibano, 1991; Shiraki, 1999; Nagai et al., 2000), this study aims to investigate the effects of high-intensity thinning on subsurface runoff and peak storm-runoff in Japanese cypress plantation forests. This research design has the advantage of controlling external hydrological pathways, hence controlling the factors that influence interception, evaporation and transpiration. This experiment tests the effects exerted by land-treatment and management practices on runoff and tree responses, with the aim of addressing some of the uncertainties that existed in past catchment-scale studies and providing novel insights on tree-water interaction for future catchment-scale experiments.

METHODS

Study area

The study was conducted in the Inuyama Research Forest, within the University of Tokyo Forests in Aichi Prefecture, central Japan. The lysimeter is nested within a catchment of cypress plantation, was constructed in 1985, and is managed by the Ecohydrology Research Institute (Yamaguchi et al., 1987). Prior to the establishment of the experimental area/university forest in 1922, the area was completely denuded and bare. Between 1922 and 1942, restoration initiatives began with the planting of Black Pine (Pinus thunbergii) and Alder (Alnus japonica) with the aim of reducing soil erosion. Construction of check-dams for slope-protection took place between 1950 and 1952. Starting in the 1980s, Japanese cypress (Chamaecyparis obtusa) were planted in small patches and managed as plantation forests. Today, this experimental forest has a total area of 443 hectares and comprises secondary mixed-broadleaf forest and patches of cypress plantation (The University of Tokyo Forests, 2019). Mean annual rainfall (2008–2016) measured by a tipping bucket rain gauge 250 m south of the lysimeter is 1916 mm. Daily maximum and minimum temperatures (2013–2016) are 38°C and –4°C in summer and winter respectively with an annual mean of 14–16°C. The geology is tertiary sediment from the Neogene period. Lysimeter design and treatment

Six sections/plots make up the lysimeter, each of which measures 3 m (width) × 6.2 m (length) × 2.5 m (depth) with a slope of 20 degrees (Figure 1). Walls and floors of each plot were made from concrete, forming an impermeable boundary. Soils were dug up during construction and filled back into the lysimeter compartments upon completion resulting in the plots having the same soil type as the rest of the area (unconsolidated freshwater sediment from the Neogene period), but with a simplified and homogeneous soil structure between all plots.

Observations from two lysimeter sections were compared and discussed in this article. The first section (plot T) was planted with cypress trees at a density of 7,389 trees/ha. Just prior to thinning, the stand was 22 years of age with an average basal area of 50 m²/ha. Thinning (treatment) was applied on 20th December 2012 resulting in 2,463 trees/ha (67% reduction in stand density) and 19 m²/ha (62% reduction in basal area). Trunks and branches of felled trees were left on the ground in plot T (Figure 2) following the common forestry practice in the region. The ground cover afforded by felled-trees being placed on the slopes exceeded the felled basal area (31 m²/ha) because the felled-trunks were laid-down horizontally. In addition, foliage attached to the branches provided an extensive ground cover (Figure 2). Another section, plot C of the lysimeter is a grassland control without forest cover.

Data collection and analysis

In each lysimeter plot, runoff (both surface and subsurface) were channelled into a container with a 90° sharp-crested v-notch outlet. Although there were separate outlets

Figure 1. a) Perspective; and b) side cross-sectional view of the slope lysimeter. Subsurface flow from each level are collected and recorded as total subsurface flow
for surface runoff and subsurface runoff at differing soil depths, runoff from all soil depths were channelled into one collector/container and treated as total runoff in this study (Figure 1). Runoff data during no-rain periods (hereafter referred to as subsurface runoff) were recorded during monthly site visits by means of a measuring cylinder and stopwatch. In addition, water levels in the containers were continuously recorded by “Odyssey Capacitance” water level data loggers (manufactured by: Dataflow Systems Ltd.) at 5-minute intervals to be used for storm event runoff analyses. These water level readings were then converted to runoff rate via monthly calibration exercise by means of a measuring cylinder and stopwatch. Site visits and data collection were performed at least once a month from March 2011 to December 2014. Continuously-recorded water level data were only used in storm event runoff (peak storm-runoff) analyses because subsurface runoff during no-rain days is below the reliable detection range of the data logger. All rain events that resulted in at least 0.01 m rise in water level in plot C were used for storm event analyses. Peak storm-runoff for each storm event is defined as the instantaneous runoff rate at the highest point on the hydrograph. A period of at least 30 minutes without rainfall was used as a criterion to separate between one storm event and the next. Only the first hydrograph peak of each storm event was analysed because the second peak was not interflow, but rather the channelling of accumulated water at the impermeable concrete base (shown in Figure 5 in a later section) (Nagai et al., 2000).

In addition to comparing peak storm-runoff, analysis of storm runoff coefficient ($f_p$), defined as the ratio of the highest 10-minute runoff against its corresponding 10-minute rainfall, was also performed on plot T. The $f_p$ is a stricter measure of peak runoff and when the effects of rainfall are controlled for, may show peak runoff response (Gomyo and Kuraji, 2013). Instead of regressing against total event rainfall, $f_p$ was regressed against $P_i$. The $P_i$ is defined as the total precipitation from the start of a rain event to its peak intensity. Significance of differences in runoff components (subsurface runoff, peak storm-runoff, and storm runoff coefficient) between pre- and post-thinning periods was tested using analysis of covariance (ANCOVA) and Mann-Whitney U test.

RESULTS

Changes in subsurface runoff

Comparison of runoff during non-rain periods (subsurface runoff) before and after thinning is shown in Figure 3. Strong positive relationships were found between plot C and T for both before ($r^2 = 0.98$) and after ($r^2 = 0.99$) thinning.

An analysis of covariance (ANCOVA) between the two regression lines resulted in statistically significant differences in both coefficients of slope (0.519 before thinning, 0.749 after thinning) and intercept (−0.0027 before thinning, −0.0201 after thinning) at a significance level of $p < 0.05$. These differences translate to an increase in runoff in the thinned plot relative to pre-thinning of 133% (from 0.03 to 0.07 mm/h) when runoff in the control plot is at 0.1 mm/h (typical regular runoff rate), and an increase of 50% (from 0.5 to 0.75 mm/h) when runoff in the control is 1.0 mm/h (typical high runoff rate). In summary, thinning

Figure 3. Subsurface runoff for the thinning treatment (T) in comparison to grassland control (C) before and after conducting thinning. Minimum limit for regression equation: $y = 0$
increases subsurface runoff, but the degree of increase is less in higher moisture conditions.

**Changes in peak storm-runoff**

Figure 4 shows the comparison of peak storm-runoff before and after applying the thinning treatment. Moderate-strong positive relationships were found in peak storm-runoff for periods before \((r^2 = 0.69)\) and after \((r^2 = 0.76)\) thinning.

Although the slopes do not differ significantly from one another, significant differences were found in the intercepts \((2.448 \text{ before thinning, } -0.0015 \text{ after thinning})\) via ANCOVA at \(p < 0.05\). This translates to a reduction in peak storm-runoff from 3.74 to 0.74 mm/h (80% reduction) when peak storm-runoff in the control plot is at 1.0 mm/h (typical minimum), and from 28.29 to 14.88 mm/h (47% reduction) when peak storm-runoff in the control plot is 20.0 mm/h (typical maximum). An example of differences in hydrograph characteristics (especially peak runoff) at the event scale between periods of before and after logging is shown in Figure 5. Although differing slightly in total rainfall, peak intensity and duration of rainfall (Figure 5 a & b), these storms are of the same order of magnitude and make an appropriate paired-storm comparison (note the change in peak runoff in plot T whereas that of plot C remain unchanged).

Post-thinning storm runoff coefficient \((f_p)\) values were significantly lower compared to that of pre-thinning (Mann-Whitney U test, \(p < 0.05\)). Although coefficients of determination for \(f_p - P_i\) relationships are moderate (0.49 and 0.38 for before and after thinning respectively), the slopes of the regression lines shown in Figure 6 (0.0103 before thinning, 0.0017 after thinning) were statistically significantly different (ANOVA, \(p < 0.05\)). These results translate to a significant reduction in flashiness after thinning, and this reduction is greater during events of higher intensity.

**DISCUSSION**

High-intensity thinning of Japanese cypress forest increases subsurface runoff by up to 133%, but the degree of increase diminishes with increasing soil moisture. This can be attributed to an increase in net precipitation caused by decreases in canopy interception and/or an increase in soil moisture due to reduced evapotranspiration. Similar observations were noted by Dung et al. (2012) in a catchment-scale study in Mie prefecture, south-central Japan under similar climate conditions where high-intensity thinning (58.3% by stem count, 43.2% by basal area) increased annual catchment runoff by 240.7 mm. Flow-duration of ephemeral channels also increased from 56.9% to 73.3%. Kubota et al. (2018) also recorded a mean annual increase in runoff by 54 mm after 50% removal of stems (22.5% removal of basal area) in Ibaraki prefecture, though
Figure 6. Storm runoff coefficient ($f_p$) against total precipitation from start to peak precipitation intensity ($P_i$). Note that when computing $P_i$, the start of a rain event was defined as when cumulative precipitation reached 1.0 mm

this increase is not significant. Compared to Kubota et al. (2018), the higher increase in runoff in this study as well as that of Dung et al. (2012) may be linked to the larger tree size as indicated by the higher basal area despite a similar percentage of stems removed. In addition, the mean annual temperature that is 2°C lower in Ibaraki prefecture (Kanto region, mid-northeast Japan) may have resulted in decreased evapotranspiration despite similar rainfall amount.

While some past studies have linked increases in runoff to reduction in interception and transpiration following conventional theory, others have observed the opposite (Tateishi et al., 2014), reasoning that increased ground evaporation may offset the increased net rainfall (Tateishi et al., 2014; Sun et al., 2016, 2017b). Catchment-scale studies such as these have had the challenge of being unable to control for confounding variables such as soil type, soil structure, geology and hydrological pathways. Through a lysimeter-based experimental approach, this study has controlled these variables, and results support the hypothesis that increases in runoff are linked to vegetation. Furthermore, the effects of reduced canopy interception are offset by the practice of leaving felled logs (with branches and foliage, Figure 2) on the hillslope. Drawing upon results from current and previous studies as well as knowledge on the mechanism of a lysimeter, we can therefore suggest with greater confidence that increases in subsurface runoff result from decreases in tree water use (transpiration).

The reduction in peak storm-runoff by up to 80% post thinning is attributed to the practice of leaving felled logs parallel to slope contours. These logs act as barriers that impede overland flow causing longer downslope travel time, hence promoting infiltration. At the same time, the lush foliage placed on the hillslope (Figure 2) may make up for the effects of lost canopy interception. Despite the reduction in magnitude, the similar relationship between peak storm-runoff and rainfall intensity reflects similar hydrological dynamics. Such consistent characteristics before and after thinning were also observed by Dung et al. (2012) and were linked to similar quickflow patterns in pre- and post-thinning phases. Sun et al. (2017a) however found increased hydrograph flashiness with rapid rising and falling limbs that resulted in no net change in peak flow volume. They attributed this phenomenon to shallower flow paths during heavy rainfall after thinning, although the reason for changes in flow paths remain unexplained. This is most likely linked to management practices that differed from this present study in that felled logs were removed from the catchment, resulting in unbuffered rain input and increased net rainfall.

While observed changes agree with previous studies that applied the same treatment (Dung et al., 2012; Tateishi et al., 2014; Sun et al., 2017a; Kubota et al., 2018), direct comparison of absolute values are difficult because of three methodological differences: (i) while other catchment-scale studies measured streamflow (surface and subsurface) during non-rain days, this study measured slope runoff which is predominantly subsurface flow; (ii) while continuous monitoring of streamflow has been possible for catchment-scale observations, the low levels of subsurface flow requires manual periodical spot-measurement; and (iii) while runoff responses in hillslope plots are almost immediate, runoffs at the catchment-scale are subjected to hydrological storage, sinks and preferential flows. For this reason, increases in subsurface runoff may be lower at the catchment scale because felled logs left on catchment slopes will not provide ground cover as extensive as that in a lysimeter plot, thereby subjecting the bare areas to increased evaporation losses (Tateishi et al., 2014) prior to understorey growth. This lower coverage of leftover felled logs may also subject the catchment to lower rainfall interception and surface runoff attenuation, resulting in a higher peak storm-runoff when compared to a lysimeter study.

CONCLUSION

Through this experiment, we were able to observe changes in runoff characteristics from conducting high-intensity (62%) thinning on Japanese cypress plantation forests while physically controlling for the effects of soil characteristics, geology, water table and hydrological pathways that remained unaccounted for in catchment-scale studies. The increase (50–133%) in subsurface flow is likely to increase stream baseflow whereas the reduction (47–80%) in peak storm-runoff afforded by the increased ground resistance may be beneficial for flood regulation. Results from this study reinforce findings of past catchment-scale studies that link increases in baseflow runoff to reduced transpiration; and decreases in stormflow to leaving felled logs in place. However, outcomes similar to this study are only achievable with sound forestry management practices such as the proper placement of logs along contour lines on hillslopes. It should, however, be noted that at the catchment scale, various environmental and scale factors may affect the magnitude of changes in runoff char-
characteristics.

Although we have successfully utilised the lysimeter to investigate runoff while controlling for externalities, this experiment is limited in terms of the number of treatments. Suggestions for future studies include conducting similar investigations on (i) stands of different age and species, and (ii) the hydrological impacts over the longer-term (post-thinning recovery phase).

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