論　文

Productivity of forwarding operation for long logs with side-loaded forwarder
横積式フォワーダによる長尺材集材作業の生産性

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Abstract: For developing an efficient logging system for forest biomass, we generally consider the “Integrated Wood Logging System” that conducts logging without separating butt logs from stem butts. Since integrated wood logs have a greater log length compared to that of normal logs, there is a concern that the operating efficiency would drop if it was conducted using a general forwarder with a rear-mounted loading platform. This is why a prototype forwarder with a side-loading platform was developed. In this study, an on-site forwarding operation test was conducted to compare this side-loaded forwarder with a rear-loaded forwarder in the same class for evaluating the operating efficiency of the prototype. The results showed that the operating efficiency for loading varied depending on the length of the logs used, and although no significant differences in load volume, loading speed, unloading speed, and driving speed favoring the rear-loaded type were identified with 4-m logs, these values were higher for the side-loaded type for 6-m logs. Although productivity with a forwarding distance of 200 m was 10% higher with the rear-loaded type for 4-m logs, it was 46% higher with the side-loaded type for 6-m logs, calculated as 20.7 m^3/h. These results suggest that a side-loaded forwarder is more effective for loading long logs.
Key-words: side-loaded forwarder, productivity of forwarding operation, long log, integrated wood log

要旨：森林バイオマスの効率的な搬出方法を開発するため，端材を用材と切り離さずに搬出する一体材方式を検討している。一体材は用材に比べ材長が長いことから，荷台が後方にある従来のフォワーダへ積載する場合，作業効率の低下が懸念される。そこで，荷台が車体の側方にある横積式フォワーダを試作した。本研究は，試作した横積式フォワーダの作業性能を評価することを目的に，試作機と同クラスの後積式フォワーダとの比較による集材作業の現地試験を行い，積載量や作業時間等を分析するとともに生産性を算出した。その結果，積載する丸太の材長によって作業効率は異なり，積載量，荷積速度，荷降速度，走行速度のいずれも 4m 材では後積式の方が高いが有意差は認められず，6m 材では横積式の方が高くなった。集材距離 200m の生産性は，4m 材では後積式の方が 10%高いが，6m 材では横積式の方が 46%高く 20.7m^3/h と試算された。長尺材集材における横積式フォワーダの有効性が示唆された。
キーワード：横積式フォワーダ，集材生産性，長尺材，一体材

I Introduction

For developing an efficient logging system for forest biomass, we generally consider the “Integrated Wood Logging System” that performs logging without cutting off the stem butts and butt logs during the log bucking operations (*3*). Since the integrated logs are longer than the normal logs due to the stem butt length, there is a concern that loading them on a general forwarder with a rear-mounted loading platform could decrease the loading efficiency and the operation safety due to the restrictions on the length of the loading platform. Therefore, a prototype side-loaded forwarder with the loading platform positioned to the side of the machine body was developed to load long length

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logs (*4*). The prototype machine was designed to load long logs, and some of the characteristic features that differ from those of existing side-loaded mini forwarders (working cars in forest) are as follows: maximum loading capacity, dumping functions both forward and to the side, and camera setup for handling blind spots. Previous studies on the mini forwarders have included aspects on safety (*1*) and productivity (*2*). However, these studies have been intended for comparatively small models for loading normal length logs, suggesting that these studies have not clarified the adaptability of side-loaded forwarders for loading long length logs.

In this study, an on-site forwarding operation test was conducted with the goal of evaluating the operating efficiency of the prototype side-loaded forwarder, and the productivity was calculated for different log lengths and forwarder types along with an analysis of differences in loading volume, operation time, and other factors.

II Methods

1. Test Site The test was carried out in Himi City, Toyama Prefecture, with a 54-year-old sugi (*Cryptomeria japonica*) planted forest. The diameter at breast height (DBH) was 49.2 ± 9.2 cm (mean ± SD, same below), the tree height was 30.4 ± 4.4 m, and the standing tree volume was 2.49 ± 0.92 m^3. The spur road used for the test had an average road width of 4.0 m, an average longitudinal gradient of 7.0 degrees, and a maximum longitudinal gradient of 14.5 degrees downhill. The loading area was a distance of 165–255 m from the landing.

2. Machine Used The prototype side-loaded forwarder is based on MST-650VDL made by the M Company (loading platform capacity: 6.1 m^3), which has been remodeled. The loading capacity is 5.3 m^3, the maximum load volume is 4,000 kg, and the maximum driving speed is 10 km/h. For the performance test, the prototype side-loaded forwarder (below, side-loaded type) and MST-650VDL (below, rear-loaded type) were the two machines used.

3. Test Method The test operations consisted of using a grapple excavator to load the forwarders with logs on the spur road and then forwarding them to the landing. There were four types of logs loaded with log lengths of 2, 4, 6, and 8 m, and the tests of the forwarding operations with the side-loaded type and those with the rear-loaded type were tried three times each. The primary measurements were operation time of work elements, load volume, driving speed, and others. In addition, Tukey–Kramer's multiple comparison test was used to determine the significant differences between the various elements.

4. Productivity Calculation Using the measured operation time and the operation speed values, the cycle time for forwarding operation was calculated using equation (1), and the productivity was calculated using equation (2).

$$T = d\,(1 / v_1 + 1/v_2) + w\,(1 / v_3 + 1 / v_4) + t \qquad (1)$$

$$P = 3600\, w / T \qquad (2)$$

where T: cycle time (s), d: forwarding distance (m), w: loaded volume (m^3), v_1: driving speed loaded (m/s), v_2: driving speed unloaded (m/s), v_3: loading speed (m^3/s), v_4: unloading speed (m^3/s), t: other times (s), and P: productivity (m^3/h).

III Results and Discussion

1. Work Elements Figure 1 shows the operation times for each work element carried out with the side-loaded type and the rear-loaded type. However, as there was a danger of load collapse when using 2-m logs with the side-loaded type, and safe driving was difficult for 8-m log loading with the rear-loaded type, these testing were stopped. In the results, for the side-loaded type, seven cycles (three cycles for 4-m and 6-m respectively, and one cycle for 8-m) were conducted, and for the rear-loaded type, nine cycles (three cycles for 4-m, 6-m and 8-m, respectively) were conducted. The average cycle time for the rear-loaded type was 1,311 s, and that for the side-loaded type was 1,305 s. The average forwarding distance was about 200 m. Since the forwarding distance and the loading volume differed for each cycle, simple comparisons were impossible. However, the times for each work element tended to be shorter for both driving unloaded and driving loaded with the rear-loaded type. Similarly, the times for both loading and unloading tended to be shorter for the side-loaded type as well.

2. Loading Volume Figure 2 shows the average loading volume for each log length for the rear-loaded type and the side-loaded type. In addition, 8-m log operations were conducted

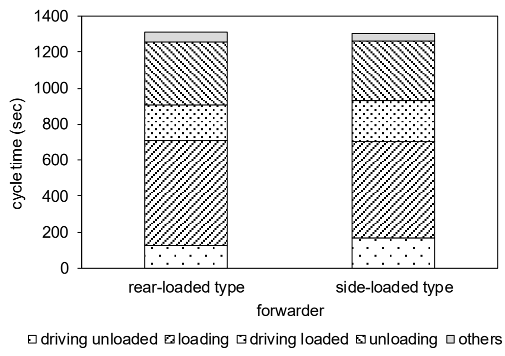

Fig. 1. Cycle time of forwarding operations

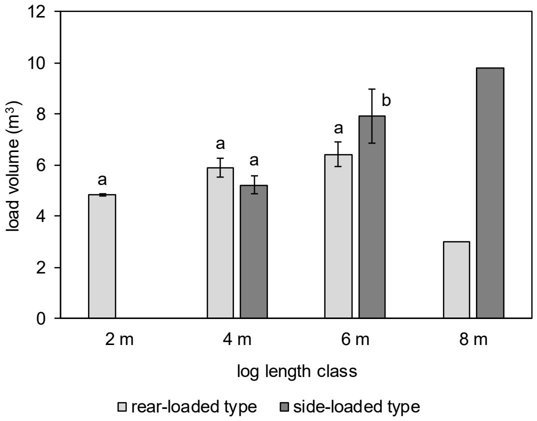

Fig. 2.　Average loaded volume for each log length class
Error bars represent standard deviation. Different letters indicate significant differences. (Tukey–Kramer test, $P < 0.05$)

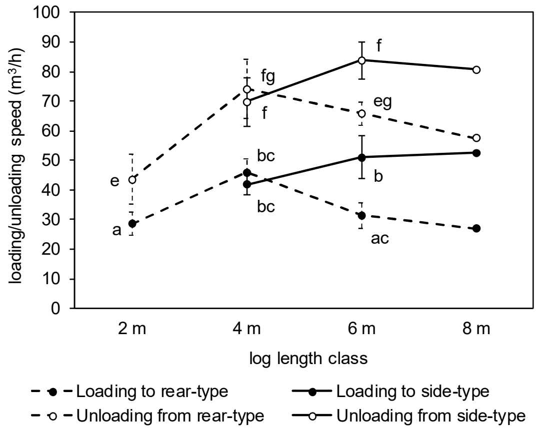

Fig. 3.　Loading and unloading speed
Error bars represent standard deviation. Different letters indicate significant differences. (Tukey–Kramer test, $P < 0.05$)

two times with the side-loaded type, and one time with the rear-loaded type. Although the loading volume for 4-m logs was higher with the rear-loaded type, no significant difference was found ($P > 0.05$).　However, for 6-m logs, the loading volume was 23% higher with the side-loaded type, with a significant difference ($P < 0.05$). In addition, although the loading volume with the side-loaded type was significantly higher as the log lengths increased from 4 to 8 m ($P < 0.05$), with the rear-loaded type, the loading volume was not significantly different for logs in the length range of 2–6 m ($P > 0.05$) and decreased considerably for the 8-m logs. Compared with the side-loaded type with no walls at the front and back of the loading platform, the rear-loaded type with a barrier at the front had difficulty maintaining balance when loading long length logs, which probably led to the decrease in the loading volume.

As mentioned above, the loading volume of the side-loaded type was not significantly higher for normal use of 4-m logs compared to that with the rear-loaded type, and regarding the possibility of loading approximately the same volume of these logs, the side-loaded type tended to achieve greater loading volume for long length logs of 6 m or more.

3. Loading Speed　Figure 3 shows the loading speed and unloading speed of volume over time. Regarding the loading speed of 4-m logs, no significant difference was observed between the side-loaded type and the rear-loaded type ($P > 0.05$); however, the side-loaded type was 1.6 times faster than the rear-loaded type for logs of 6 m ($P < 0.05$). In addition, when loading 8-m logs, although no significant difference was noted between the side-loaded type's speed for loading 6-m logs, the rear-loaded type was slower than with 6-m logs. These results suggest that the volume per log increases with log length, which led to the increased loading speed with the side-loaded type. However, the rear-loaded type required increased operation time due to the need to maintain balance during loading, which could have probably caused the decrease in the loading speed. In addition, these trends were observed for unloading speed as for the loading speed.

4. Driving Speed　Figure 4 shows the driving speed for the two machines with different log lengths. In addition, 8-m log operations were conducted two times with the side-loaded type, and those were stopped with the rear-loaded type. When the driving speed for the two machines was compared, although no significant difference was found, the driving speed was faster with the rear-loaded type for unloading and 4-m log loading operations ($P > 0.05$). For 6-m log loading operation, the side-loaded type was 52% faster than the rear-loaded type ($P < 0.05$). In addition, the driving speed tended to decline with increase in log length for the rear-loaded type; in particular, the speed with

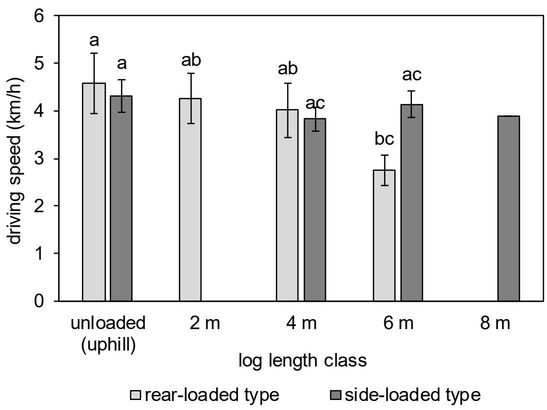

Fig. 4.　Average driving speed for each loading log length
Error bars represent standard deviation. Different letters indicate significant differences. (Tukey–Kramer test, $P < 0.05$)

6-m logs was 32% slower than that with 4-m logs. On the other hand, there was no clear trend for the different log lengths with the side-loaded type.

Since the driving speed can be influenced by multiple factors such as road shape, road surface, and loading volume, no significant difference was found for loaded log length on its own. However, compared with the rear-loaded type, driving speed for the side-loaded type was less affected by changes in the log length. For this reason, the side-loaded type could be more effective for loading long length logs than the rear-loaded type.

5. Productivity Using the analyzed operating time and speed, the cycle times of the forwarders were calculated from equation (1), and the productivities were calculated from equation (2). Figure 5 shows the productivities for each forwarding distance. As we could not collect sufficient data using 8-m log operations with the rear-loaded type and 2-m log operations with the side-loaded type, these entries were deleted. Productivity for the average forward distance of 200 m was as follows. For the rear-loaded type, 2-m logs: 12.1 m^3/h, *4*-m logs: 17.8 m^3/h, and 6-m logs: 14.1 m^3/h. For the side-loaded type, 4-m logs: 16.0 m^3/h, 6-m logs: 20.7 m^3/h, and 8-m logs: 22.7 m^3/h. Although the productivity for the rear-loaded type was higher with 4-m logs than that with 6-m logs, the productivity for the side-loaded type increased with an increase in log length. In addition, when the productivity of the two machines for the same log length was compared, we observed that although it was 10% higher for 4-m logs with the rear-loaded type, it was 46% higher for 6-m logs with the side-loaded type. When loading the normal length logs (4-m logs), although the rear-loaded type showed higher productivity than that of the side-loaded type, the difference was small. However, with long length logs (6 m and above), the side-loaded type showed higher productivity. This result suggests that the side-loaded type could be effective for loading long length logs.

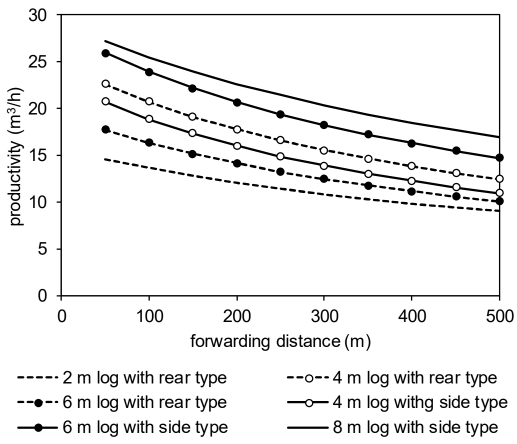

Fig. 5. Productivity of forwarding operation with rear-/side-loaded types

IV Conclusion

The results of the comparative analysis of forwarding operations using the prototype side-loaded forwarder and a rear-loaded forwarder of the same class did not show any significant differences between the two machines in terms of loading volume, loading speed, and driving speed for 4-m logs. For 6-m logs, the side-loaded type demonstrated higher operating efficiencies. Based on the results of the calculated productivity, the rear-loaded type's productivity was higher for 4-m logs, but the side-loaded type's productivity was higher when loading 6-m logs. This result suggests that for loading long length logs, the side-loaded forwarder is a more efficient loading platform configuration. However, the analysis described above is based on results from one test site; therefore, further data accumulation and consideration will be required in the future.

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