https://doi.org/10.31298/sl.149.9-10.5

Izvorni znanstveni članci – Original scientific papers
Šumarski list, 9-10 (2025): 457-465

ASSESSMENT OF TETHERED HARVESTER PRODUCTIVITY: A CASE STUDY IN WESTERN OREGON, USA

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SUMMARY

The use of winch-assisted (tethered) mechanized harvesting systems has recently increased on steep terrain in the Pacific Northwest, USA. Tethered systems are used to support and stabilize the operation of production machines such as harvesters, feller bunchers, forwarders, and grapple skidders on steep slopes. Studies on the environmental impacts, productivity, and costs of these systems should be in focus due to the rapid use of winch-assisted systems in forestry. In this study, a tethered harvester operation working was evaluated using time and motion study analysis. The study was conducted in a clear-cutting area within a Douglas-fir stand in the Oregon Coast Range near Corvallis, Oregon, United States. The production activities were evaluated in stages, including the tethered harvester moving to the tree, preparing for cutting, cutting, and processing. The most time-consuming work stage in the study was determined to be the processing time of the tree. The average delay-free efficiency of the tethered harvester was determined as 40.16 m^3/h, while the minimum efficiency was 16 m^3/h and the maximum efficiency was 75.02 m^3/h. Production efficiency was mostly affected by tree size, with productivity increasing as tree size increased. Statistical analysis showed that there was a significant relationship between tree height, tree diameter, tree volume, and productivity.

KEY WORDS: winch-assisted harvesting systems, steep terrain, tethered harvester, time and motion study, productivity, Pacific Northwest, USA

INTRODUCTION

Mechanized timber harvesting operations are conducted in most forested regions (Long et al. 2002, Wang et al. 2004, Visser and Spinelli 2012, Hiesl and Benjamin 2013, Chung et al. 2022). Mechanized harvesting vehicles, such as harvesters and feller bunchers, are used during the cutting stage, while skidders, forwarders, and skylines are utilized for timber extraction (Gülci et al. 2021). However, since mechanical harvesting vehicles are efficient in areas where the terrain slope is less than 30%, their safe use in mountainous regions with steeper slopes has been limited (Gülci et al. 2021, Pokharel et al. 2023). All known mobility criteria and restrictions for forest vehicles are mainly concerned with their ability to move uphill (Poršinsky et al. 2023). For this reason, innovative mechanical harvesting systems integrated with cable winches have been increasingly used in the mountainous terrain of the United States in recent years (Acuna et al. 2011, Holzfeind et al. 2020, Green et al. 2020, Chung et al. 2022, Pokharel et al. 2023).

Winch-assisted harvesting is called tethered or cable-assisted. Tethered harvesting systems use cable winch systems on harvesters, feller bunchers, forwarders, loaders, and skidders to stabilize and support equipment operations on steep slopes. Harvesting machines are secured with cable connections, ensuring safe operation on steep terrain (Sessions et al. 2017, Pokharel et al. 2023). The system is specifically designed to increase machine mobility and reduce wheel or track slippage (Holzfeind et al. 2020, Chung et al. 2022). In this system, the machine

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can go up and down a steep slope with the help of a winch (Sessions et al. 2017, Pokharel et al. 2023). This winch system is either mounted directly on the working equipment or placed on another piece of equipment to serve as a fixed base (Holzfeind et al. 2020, Pokharel et al. 2023).

Tethered harvesting systems provide significant advantages such as enhancing operator safety, replacing dangerous manual felling, reducing negative impacts on the soil, and improving productivity for forwarding, skidding, or yarding operations (Green et al. 2020, Holzfeind et al. 2020). The cable system enables equipment to operate on slopes that would typically be considered hazardous for the equipment or harmful to the soil. Thus, the cable system enhances the stability of equipment on steep or unstable terrain and improves traction on gentler slopes (USDA 2024).

The productivity of harvesting increases with the tethered system because trees are cut, bucked, and bunched in a short time with mechanical harvesting systems (Green et al. 2020). These systems reduce costs from the first stage of production to loading onto the truck (Chung et al. 2022). Studies conducted in both the US and worldwide indicate that salvage logging has lower productivity and higher costs than harvesting undamaged stands (Conrad and Joseph 2023). Tethered systems can be more efficient compared to traditional methods, such as chainsaws used on steep slopes (Gülci et al. 2016, Chung et al. 2022).

The tethered harvesting system was first developed in Europe in the early 2000s and then began to be extensively developed in New Zealand in the mid-2000s, after which Chile began to adopt this technology (Belart et al. 2019, Holzfeind et al. 2020). Subsequently, in the early 2010s, it was adopted by the forestry industry in the Pacific Northwest of the United States (Acuna et al. 2011, Green et al. 2020, Holzfeind et al. 2020, Chung et al. 2022, Pokharel et al. 2023). Today, in Central Europe, Canada, and the Pacific Northwest of the United States, cable-assisted systems are widely used due to steep terrain and low environmental impact (Garren et al. 2019). However, only a few studies have been conducted on the productivity of these new harvesting systems. In this study, time study techniques were applied to estimate the productivity of harvesting with a tethered harvester.

MATERIALS AND METHODS

Study area

The study was carried out in the Oregon Coast Range of western Oregon, United States (123.605833 W, 44.320278 N), where the average terrain slope is 60% (Figure 1). The study was carried out in a Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) stand damaged by the ice storm that occurred in mid-January 2024. The operation was done to recover value from the damaged trees and to permit prompt reforestation.

Field study

In this study, measurements were carried out with a tethered harvester. The field study was conducted using a 2021 model 260 kW Ponsse Bear harvester. Harvesting operations were observed from the operator's cabin

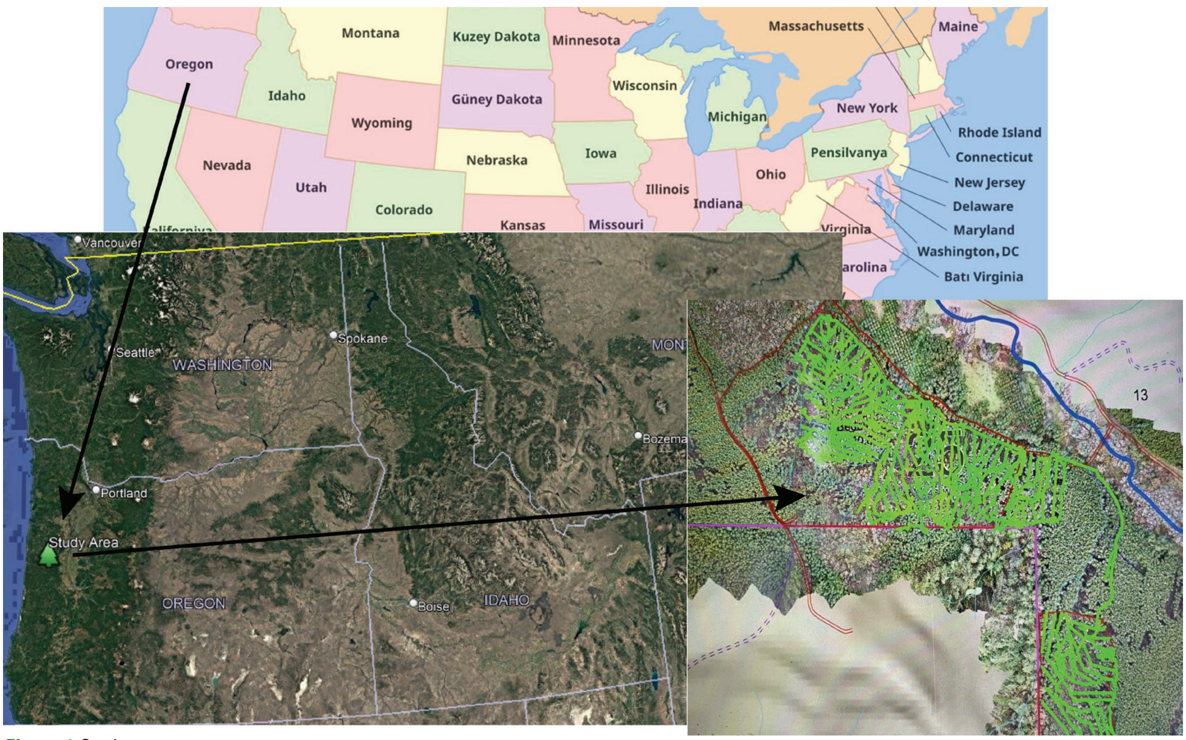

Figure 1 Study area.

Figure 2 Tethered harvester (up), observation from inside the operator cabin (down).

Table 1 Technical specifications of tethered harvester.

Dimensions	
Minimum weight (kg)	23800
Typical weight (kg)	24500
Length (m)	8.99
Width (m)	2.9-3.1
Ground clearance (m)	0.7
Transportation height (m)	3.88
Crane	
Tilt angle	±20°
Turning angle	250°
Crane reach (m)	8.6-10
Engine	
Engine power	260 kW
Tractive force	230 kN
Hydraulic system	
Control system	Ponsse OptiControl
Hydraulic circuits	Separate
Crane pump (cm^3)	190
Harvester head pump (cm^3)	190
Harvester heads	
Minimum weight (kg)	1450
Feed system	3 feed rollers
Feed force (kN)	36
Maximum opening (cm)	74
Feeding speed (m/s)	4.5

(Figure 2). The technical specifications of the harvester are given in Table 1.

All work stages of harvesting were recorded with a mobile phone camera. After the field studies, the time data were transferred to Excel. All information was automatically recorded in the on-board computer during the operator's working time. Certain information (tree diameter, tree height and volume) about this harvesting was obtained from the vehicle records.

The work cycle of a tethered harvester includes move (movement between trees), cut preparation (started when the boom started moving), fell and process (started with cutting for felling), and bunch (sorting felled and processed trees into decks) (Figure 3). In this study, a direct observation was conducted solely for the measurement of efficient basic working time. No delays were experienced due to vehicle breakdowns or other reasons. Therefore, delay time has not been considered. The trees that were cut and processed with a tethered harvester were removed from the field using a forwarder.

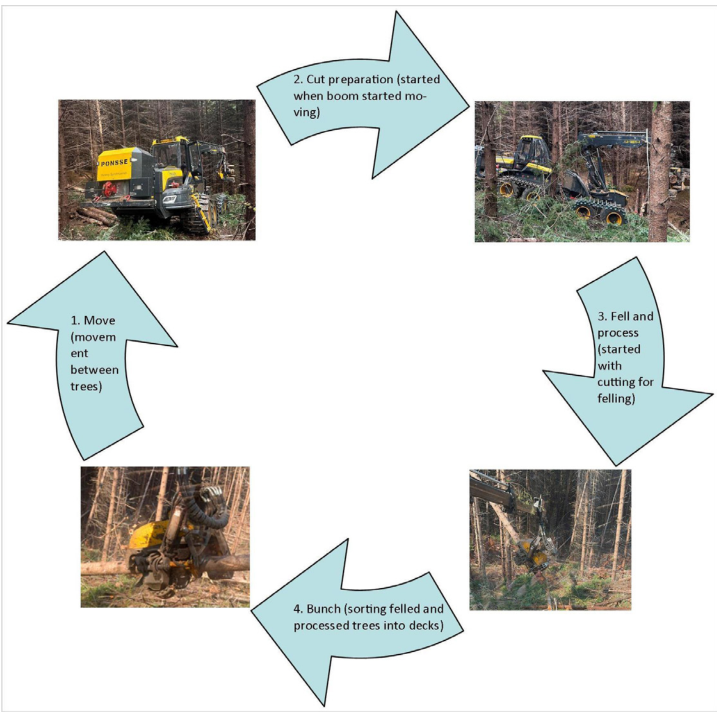

Figure 3 Tethered harvester work cycle.

Table 2 Descriptive statistics for field measurement and productivity.

	Height (m)	DBH (cm)	Volume (m^3)	Moving (s)	Preparing (s)	Cutting (s)	Processing (s)	Total (s)	Productivity (m^3/h)
N	60	60	60	60	60	60	60	60	60
Mean	17.98	18.78	0.29	3.90	2.72	1.43	16.05	24.10	40.16
STD.	3.67	4.53	0.16	1.09	0.80	0.50	4.06	4.54	16.87
Min.	10.00	12.00	0.08	2.00	1.00	1.00	9.00	17.00	16.00
Max.	25.00	26.00	0.65	6.00	5.00	2.00	25.00	31.00	75.02

Statistics

Initially, basic mean and standard deviation values were calculated and visualized using SPSS and the Rstudio (R Core Team 2018). The Pearson correlation test was then applied to examine the relationships between specific factors—tree height (X_1), DBH (X_2), and volume (X_3)—and the productivity (Y) of the tethered harvesting operation.

In this study, multiple linear regression analysis was used to develop mathematical models for predicting tethered harvester productivity in cut-to-length harvesting. Initially, a multiple linear regression model was applied to assess the relationships between tree height, DBH, volume, and productivity. Diagnostic plots were used to evaluate model fit. The residuals vs. fitted plot, Q-Q plot, and scale-location plot were considered for models, while Cook's distance was analyzed to detect influential observations that could potentially affect the model's performance.

Initially, we applied a log-transformed polynomial regression model to improve consistency and predictive accuracy. Due to preliminary diagnostic assessments, which indicated possible non-linearity and heteroscedasticity (non-constant variance) in the residuals, this transformation was applied for further analysis. The polynomial transformation helped us to understand the relationships between the predictors and productivity. Logarithmic transformation by skewed data into a more normal distribution stabilized the variance and improved model interpretability.

Outliers and disturbance points, which could have adversely affected model accuracy, were detected. Outliers were removed from the model. The prediction model was re-established to ensure reliability of the model. Metrics such as R2, adjusted R2, root mean square error (RMSE) and mean absolute error (MAE) were used as the success indicator of both the linear and polynomial models. Besides, Variance Inflation Factor (VIF) values were used to assess multicollinearity. In this study, R packages, including "psych", "broom", "tidyverse", "mass" and "ggplot2" (Venables and Ripley 2002, Wickham 2009, Van den Boogaart and Tolosana-Delgado 2013, Revelle 2017, Wickham et al. 2019, Robinson et al. 2024) were used in RStudio environment.

RESULTS

In this study, data from 60 trees was collected. The average tree height, diameter and volume were 17.98 m, 18.78 cm and 0.29 m^3, respectively. During harvesting, the time values of the work stages (moving towards the tree, preparing to cut, cutting, and processing) were calculated for the 260 kW Ponsse Bear model tethered harvester. According to the descriptive statistics results, the work stages that took the most time were processing,

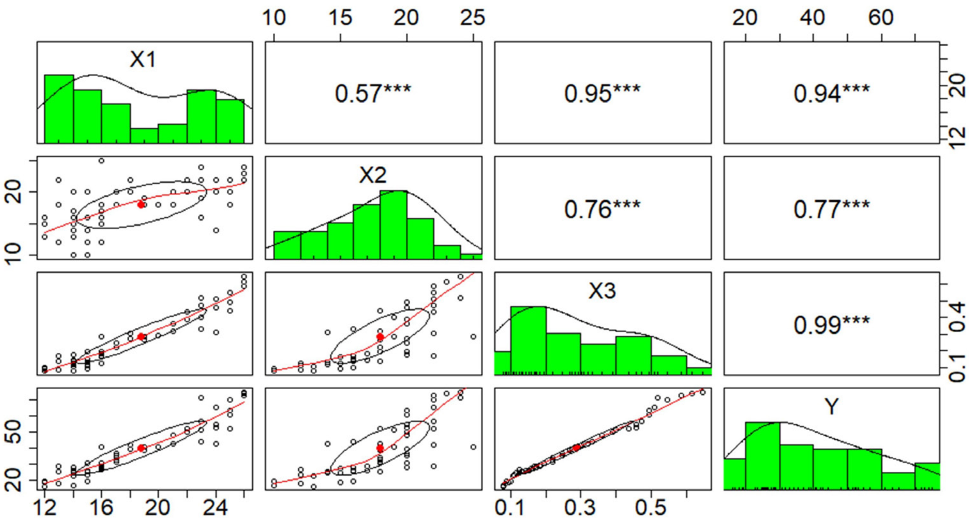

Figure 4 The Pearson r correlations (significance levels are *: 0.05 and ***: 0.001).

averaging 16.05 seconds, followed by the moving stage with an average of 3.90 seconds. The phase that took the least time was cutting, with an average of 1.43 seconds (Table 2).

The correlation between height, DBH, and volume with productivity was determined using the Pearson correlation test. A strong positive relationship was found between productivity and tree height (X_1) (r = 0.76), DBH (X_2) (r = 0.94), and volume (X_3) (r = 0.99) (Figure 4).

The analysis involved comparing a multiple linear regression model and a log-transformed polynomial regression model to evaluate their effectiveness in predicting the dependent variable (productivity) based on predictors X_1, X_2, and X_3. Both models showed high R^2 values, indicating that a substantial amount of variance in the dependent variable was explained by the predictors. However, the models differed in terms of fit quality, residual distribution, coefficient significance, and multicollinearity concerns, providing insights into which approach might be more suitable for capturing the underlying relationships in the data.

The multiple linear regression model exhibited a high R^2 value of 0.986, with an adjusted R^2 of 0.985, suggesting that it captures most of the variation in the dependent variable. The residual standard error was 2.061, and the performance metrics were acceptable. However, the vresiduals displayed considerable spread, with a minimum of -4.43 m^3/h and a maximum of 7.44 m^3/h. This range indicates potential variability in how well the model fits different data points, especially outliers or observations with higher leverage.

The calculation of MSE, RMSE, and MAE resulted in acceptable range values. However, in terms of the significance of coefficients, only X_3 was statistically significant ($p < 0.001$), while X_1 and X_2 had high *p*-values, indicating non-significant effects. This lack of significance could be due to multicollinearity, as evidenced by the high Variance Inflation Factor (VIF) values, particularly for X_1 and X_3, suggesting severe multicollinearity, which can inflate standard errors and obscure the true relationship between predictors and the dependent variable. The presence of multicollinearity could also be responsible for the high standard error associated with the estimates, reducing the interpretability of the coefficients (Table 3).

Table 3 Parameters of multiple linear regression model for productivity.

	Model 1	Performance and VIF* values	
Intercept	10.229	R^2	0.986
Height (X_1)	-0.086	AdjR^2	0.985
Height^2 (X_1^2)		RMSE	1.990
DBH (X_2)	0.085	MAE	1.426
DBH^2 (X_2^2)		MSE	3.964
Volume (X_3)	104.215	Height*	21.746
Volume^2 (X_3^2)		DBH*	5.149
		Volume*	34.796

* Variance Inflation Factor (VIF)

The residual plots for the linear model indicated some heteroscedasticity, with a pattern in the residuals vs. fitted plot suggesting that residuals might increase with fitted values. Additionally, the normal Q-Q plot showed deviations from normality in the tails, suggesting the presence of outliers or influential points. These issues imply that the linear model might not fully satisfy the assumptions required for a reliable linear regression model, particularly in terms of homoscedasticity and

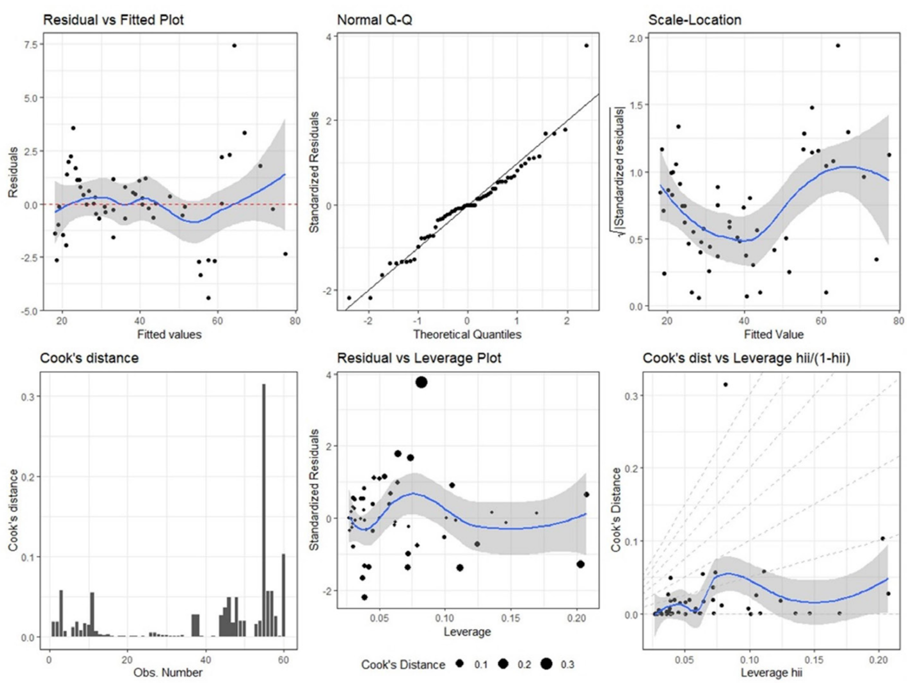

Figure 5 Diagnostic plots of the linear model.

normality of residuals. The lack of fit indicated in Figure 5 is because the linear model cannot adequately explain the intricacies of the given data.

A log-transformed polynomial regression model produced more successful and reliable results. Polynomial terms were suitable for non-linear relationships between the predictors and the dependent variable. The log transformation reduced heteroscedasticity, while the polynomial terms allowed for a more flexible fit. The resulting model showed a slight improvement in R^2 and adjusted R^2, suggesting that the polynomial transformation provided a marginally better fit than the linear model. The residuals had a tighter distribution, ranging from -0.107 m^3/h to 0.125 m^3/h, indicating a more consistent fit across observations. The smaller residual range and improved residual metrics suggest that the polynomial model captures the data points more accurately, reducing the influence of outliers and high-leverage points compared to the linear model.

Considering the linear regression model, the residual standard error for the polynomial model decreased to 0.0516, and the performance metrics showed slight improvements with MSE, RMSE, and MAE. The log-transformed polynomial model shows a significant reduction in VIF values compared to the linear model, especially for X_1 and X_3. In the linear model, X_1 and X_3 have high VIFs of 21.746 and 34.796, respectively (Table 3), indicating strong multicollinearity. In contrast, after transforming to a polynomial form and using log-transformation, poly(X_1^2) and poly(X_2^2) have much lower adjusted VIF values (2.724 and 1.879), suggesting reduced multicollinearity in the polynomial model. For X_3, the VIF also decreases to 9.269, though it remains relatively high compared to the other predictors in the polynomial model (Table 4).

Table 4 Parameters of the log-transformed polynomial regression model for productivity.

	Model 2	Performance and VIF* values	
Intercept	3.431	R^2	0.986
Height (X_1)	1.820	AdjR^2	0.985
Height^2 (X_1^2)	-0.216	RMSE	1.976
DBH (X_2)	1.051	MAE	1.456
DBH^2 (X_2^2)	-0.08	MSE	3.904
Volume (X_3)	0.594	Height*	2.724
Volume^2 (X_3^2)		DBH*	1.879
		Volume*	9.269

* Variance Inflation Factor (VIF)

The residuals appear more randomly scattered around the horizontal line with minimal patterns, indicating an improved fit compared to the linear model. Diagnostic plots were implemented to explain and compare the results in the linear model (Figure 6).

The polynomial terms seem to address some of the non-linearity observed in the linear model. According to normal Q-Q plots, the residuals for the polynomial model align more closely with the 45-degree line,

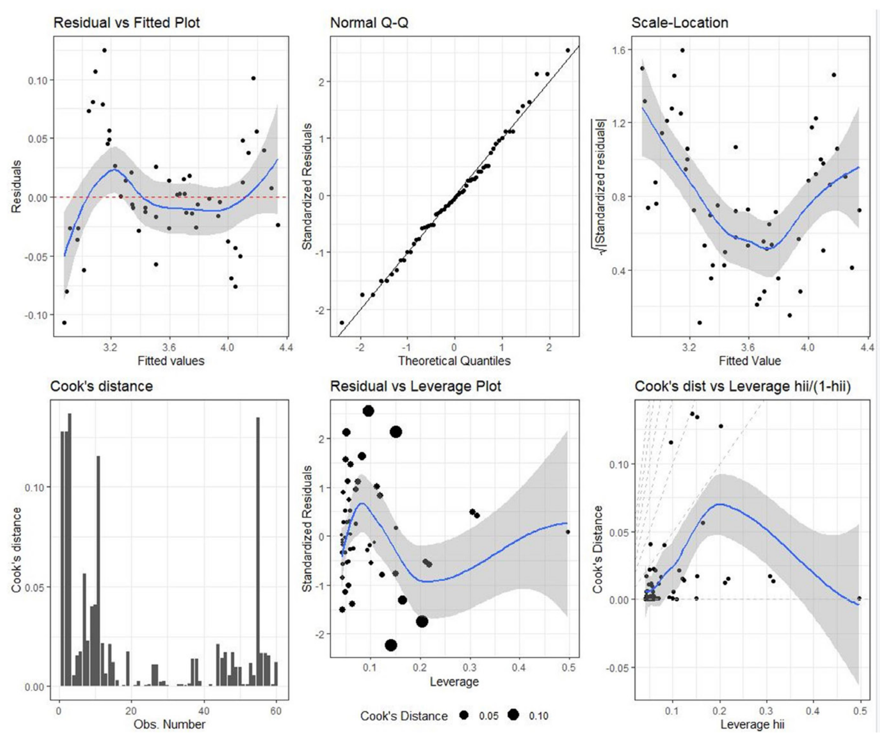

Figure 6 Diagnostic plot of the polynomial model.

though slight deviations may still occur at the tails. This alignment suggests an improvement in the normality of residuals, despite some deviations indicating minor issues with normality. The blue line in the polynomial model scale-location plot is relatively horizontal, with a more consistent spread of residuals along the fitted values. This suggests that heteroscedasticity has been reduced, meaning that the polynomial transformation helped to stabilize the variance. In this plot, there are fewer points with high Cook's distances compared to the linear model. Observations previously identified as influential have reduced impact, showing that the polynomial model is less sensitive to these points. The polynomial model shows fewer points with both high leverage and large residuals, reducing the overall influence of outliers. Observation 55, flagged in the linear model, appears less problematic here, showing that the polynomial model accommodates these data points better. Similar to the residuals vs leverage plot, fewer points have both high leverage and Cook's distance, indicating that influential observations exert less control over the model's results.

DISCUSSION

In this study, our results indicated that the average operation productivity of the tethered harvester was calculated as 40.16 m^3/h, while the minimum efficiency was 16 m^3/h and the maximum efficiency was 75.02 m^3/h. This variation is related to tree dimensions, including diameter, height, and volume. In general, our results showed slight difference considering previous studies on tethered harvesting productivity. This case study showed higher productivity than the untethered harvesting studies. For example, Tufts (1997) calculated productivity by using untethered Ponsse HS-15 harvester, which ranged from 8.8 to 65.2 m^3 per productive machine hour (PMH). Jiroušek et al. (2007) conducted a study where productivity of a harvester ranged from 13.5 m^3/h to 60.5 m^3/h with a fairly large stem size (0.1 m^3 to 1.0 m^3). Bilici and Abbas (2018) conducted a study on the productivity of untethered harvesting in a clear-cutting operation by using single-grip harvester in Brutian pine stands. Productivity of the harvesting operation was found to be 24 m^3/h, ranging between 6 m^3/h and 57 m^3/h. Baek (2018) calculated productivity for harvesting ranging from 28.8 to 35.6 m^3 per productive machine hour (PMH). Apafaian et al. (2017) observed 26.5 m^3/PMH for 0.36 m^3 per stem in a Norway spruce clear-cutting. Ghaffariyan et al. (2013) observed that the productivity of the harvester was 56.7 m^3/h. However, Green et al. (2020), whose study showed higher productivity than our study, found machine productivity which ranged from 28.75 to 92.36 m^3 per scheduled machine hour. Differences between previous studies may include variations between operators, differences in silvicultural prescriptions, and more advanced technologies in newer equipment.

In this study, statistical analyses revealed that the productivity of the tethered harvester varied according to tree height, DBH, and volume. According to the results, as tree size increased, productivity also increased. Similar studies have shown that productivity increases with the increase in tree size (Kellogg and Bettinger 1994, Tufts 1997, Wang et al. 2004, Nurminen et al. 2006, Bilici and Abbas 2018, Gülci et al. 2021, Pokharel et al. 2023).

The work stage that took the most time in this study was the processing stage (Table 2). Comparing our results with previous studies on tethered or untethered harvesting, the processing stage consumes more time than the other work stages (Kellogg and Bettinger 1994, Tufts 1997, Nurminen et al. 2006, Bilici and Abbas 2018). The size of felled trees directly affected the stage of processing (Suadicani and Fjeld 2001, Wang and Haarlaa 2002, Bilici and Abbas 2018).

The polynomial model proved to be more effective for non-linear patterns. In other words, polynomial model presented a better choice when the relationship between variables is not purely linear. In forestry operations, factors like DBH and height can have a non-linear effect on productivity (Ackerman et al. 2024). Normality of data, which is essential for a valid parametric analysis, can be provided by performing polynomial models (Gülci et al. 2021). As a result, the log-transformed polynomial regression model provided a better fit to the data rather than the multiple linear regression model. On the other hand, the log transformation reduced heteroscedasticity, and showed that the residuals are more consistent. Additionally, the log-transformed polynomial model appears to address multicollinearity issues better, especially for X_1 and X_3, making it a potentially more reliable model for interpreting the effects of these predictors on productivity (Tables 3 and 4). Polynomial terms allow an improved capture of the nonlinear relationship between the two variables and a better fulfillment of certain parametric assumptions such as normality, homoscedasticity, and insensitivity to influential points (Gülci et al. 2021). Both these models, however, appear to show minor deviations from normality; hence, further transformations may be considered if strict normality is required.

The polynomial model satisfies the homoscedasticity assumption and it is more acceptable and much more effective for reliable parametric regression analysis in this study. The reduced heteroscedasticity indicates that the polynomial model error terms have more constant variance, improving model efficiency. The polynomial model's reduced sensitivity to influential points makes it a more robust choice for parametric analysis, where outlier influence can skew results. Also, the polynomial model better handles leverage and influential points, making it a more effective choice in parametric modeling by providing a fit less susceptible to skewing by outliers.

CONCLUSIONS

In this case study, production operations with a tethered harvester were examined in terms of productivity in a Douglas-fir stand damaged by just one ice storm in western Oregon. The results showed that the average productivity of the tethered harvester operating were 40 m^3/h. The results also indicated that tree dimensions (diameter, height, and volume) affected the productivity of the tethered harvester.

The productivity of the tethered harvester's harvesting equipment can be analyzed using polynomial regression, because the polynomial regression model provided a more effective fit than the linear model for analyzing productivity in tethered harvester operations. Considering metrics and ability to handle non-linear patterns, the log-transformed polynomial regression model was chosen as the suitable approach for this data set. In the future, concentration on the model should be made with regard to the problem of multicollinearity. For example, when considering advanced techniques of data standardization or further exploration of other variable transformation methods, reliability could be further improved. Additionally, robust regression methods could be considered to further mitigate the impact of influential points and enhance model stability. In summary, the log-transformed polynomial model provides a more accurate and nuanced fit, but multicollinearity remains a key area for improvement.

ACKNOWLEDGMENT

This study was conducted with support from TÜBİTAK BİDEB 2219 as part of the visiting scholar program, under grant number 1059B192301745. No financial assistance was provided for research materials, equipment, or publication.

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