For. Sci. 63(2):192–200
http://dx.doi.org/10.5849/forsci.16-069

harvesting & operations

Theoretical Stability and Traction of Steep Slope Tethered Feller-Bunchers

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Manual felling in afforested land is a productivity constraint and, more importantly, a safety concern. This has prompted the development of innovative mechanized harvesting systems to overcome the constraint, particularly on steeper slopes. The primary technique that has been developed and employed consists of cable-assisted, or "tethered," feller-bunchers, which use tension in a wire rope anchored upslope to assist with traction and gradeability. However, despite their deployment internationally, there is little quantitative framework with which to evaluate the relationship between tether tension, stability, ground pressures, and slip, especially in the context of machine specifications and site operative conditions. This study presents a theoretical framework that uses a moment equilibrium approach to evaluate the relationship between equipment dimensions and specifications and soil and site conditions to identify allowable slopes of operation and associated ground pressures. This quantitative framework highlights the facts that deeper grousers, higher cable tensions, wider tracks, and uphill boom orientation all increase gradeability and stability during operation. Inversely, effective track length (hence, increased soil pressures) and stability are decreased from grappling of heavier trees, operation on weaker soils, fully extended boom operation in the downhill direction, and increasing slope. Increasing soil pressure, increasing slope, and decreasing stability may increase soil disturbance but needs to be corroborated with future, planned field tests.

Keywords: tethered assist, cable assist, steep slope harvest, stability, soil impacts

Safety of timber fallers and choker setters on steep slopes and the potential for increased productivity for felling and yarding have prompted interest in New Zealand, Europe, Canada, and the Pacific Northwest of the United States in the use of cable-assisted, or "tethered," feller-bunchers (Figure 1).

Tethered feller-bunchers use one of two potential winching mechanisms. Winch systems are either installed on the feller-buncher (called an integral winch system) or on a separate winch carrier placed at a landing or clearing at the top of the harvest unit. For integral winch systems, the tether line is usually attached to a stump, deadman, or mechanical anchor. When a separate carrier is used, the carrier equipment may serve as sufficient anchoring when equipment weight, soil strength, embedment, and configuration conditions are appropriate (Leshchinsky et al. 2015). Both systems control the winching operation by limiting cable tensions to levels that are considered operationally acceptable.

Untethered feller-bunchers have been used on progressively steeper slopes in the Pacific Northwest of the United States for the past 30 years to improve worker productivity. Whereas untethered feller-bunchers normally cut on the upslope, tethered feller-bunchers cut on the downslope. Untethered systems adhere to cutting upslope to keep the machine center of gravity forward and, with a leveling cab, enable longer uphill reach, easier positioning of the cutting head, and reduced swing torque. For tethered feller-buncher systems, cutting on the downslope prevents interference with the tether line and, on steeper slopes, facilitates tree placement for uphill extraction. However, there is little quantitative context regarding the soil response during either uphill or downhill operation.

An early feasibility study of a self-contained cable tether system dates from work done by the US Department of Agriculture Forest Service (McKenzie and Richardson 1978) for evaluating options for extending mechanized equipment operations to steep terrain. Although tethered machinery for forest operations has been available in Europe for at least 15 years, primarily with wheeled machines (Bombosch et al. 2003, Visser and Stampfer 2015), experiments with tethered feller-bunchers began to appear recently (Amishev and Evanson 2010).

Manuscript received August 25, 2016; accepted September 20, 2016; published online January 19, 2017.

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Acknowledgments: *This research was supported by the National Institute of Occupational Safety and Health under Grant U01 OH010978-02. We gratefully acknowledge the constructive commentary and assistance of three anonymous reviewers, whose feedback greatly helped improve this article.*

This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft.

Figure 1. Tethered feller-bunchers working in western Washington: Krume Logging (A); C&C Logging (B).

Challenges with use of tethered feller-bunchers on steep slopes include stability, traction, and anchoring (Stampfer 1999, Visser and Stampfer 2015). Visser (2013) showed the effect of tether tension on extending the operating range for feller-bunchers for various traction coefficients. Visser and Stampfer (2015) suggested that overturning of untethered machinery on steep slopes is probably preceded by loss of traction that prompts sliding, followed by rapid deceleration and potentially dangerous conditions. Horn et al. (2007) and Visser and Berkett (2015) suggested that steep slope operations can increase soil disturbance and Visser and Stampfer (2015) state that it can be assumed that a tethered assist system will reduce soil disturbance through reduced slippage of the tracks compared with that for untethered vehicles. However, tethered machines are likely to be able to negotiate steeper terrain, potentially increasing soil disturbance in comparison with conventional falling methods. One metric that leads to soil disturbance is increased ground pressure; yet, there is little quantitative framework for evaluating the relationship between tether tension, equipment stability, track slip, and ground pressure.

In this article, a theoretical model for stability and traction for tethered feller-bunchers is presented, based on the theory of locomotion (Bekker 1956), particularly in the context of future field experiments intended for model validation. Important equipment and operational parameters are considered, including mass locations, track lengths, soil characteristics, grouser heights, direction of operation, hitch height, and disturbance constraints to identify maximum operating conditions. This analysis is limited to operating conditions where tracks are parallel to the slope and both tracks are equally loaded.

Methodology: Model for Stability and Traction

To analyze traction and cable tension in a tethered system in the context of ground conditions, soil properties, and machine configuration, a moment equilibrium analysis is performed. In this approach, the tethered feller-buncher undercarriage is assumed to be a "rigid" suspension tracked vehicle operating on a soil that compresses in proportion to a given normal force (e.g., soil exponent $n =$ 1, Bernstein equation [Wong 2008]), supporting the assumption of a linear pressure distribution under the tracks (Figure 2). Fiske (1973) suggested that $n = 1$ is reasonable for many soils encountered in agriculture and forestry. Nonlinearly elastic soils can also be modeled, but closed form solutions are often not readily available and require numerical techniques to solve. See Wong (2008) for typical soil parameters including soil exponents.

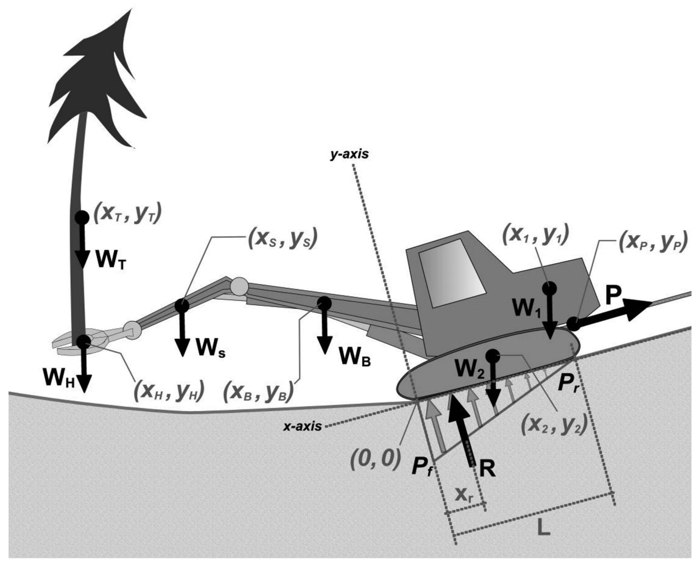

Figure 2. Free body diagram of a tethered feller-buncher with a directional felling head on a rigid suspension tracked undercarriage with boom downhill. P_f is the pressure at the leading edge of track. For downhill travel, P_f is at the lower end of the track; for uphill travel P_f is at the upper end of the track. Nomenclature is defined in Table 1.

Stability: Overturning

Stability of the feller-buncher can be defined as a function of the ratio x_r/L, where R is the resultant force of the reaction pressure distribution from soil acting on the bottom of track with length L and x_r is the distance from the pivot point to the resultant of the y components of the equipment pieces (Figure 2). The equipment force components are defined as cab/engine (weight, W_1; coordinates, x_1, y_1), undercarriage (weight, W_2; coordinates, x_2, y_2), boom (weight, W_B; coordinates, x_B, y_B), stick (weight, W_s; coordinates, x_s, y_s), cutting head (weight, W_H; coordinates, x_H, y_H), a grappled tree (weight, W_T; coordinates, x_T, y_T), and the tether tension (force, P; coordinates, x_P, y_P) on a slope of angle θ . When x_r/L is negative, the feller-buncher has overturned. Alternatively, the machine is stable (i.e., the cusp of failure) when x_r/L is positive, but to provide a margin of safety and to prevent soil disturbance from excessive compaction or slip, some minimum value of $x_r/L > 0$, such as $x_r/L > 0.333$ to maintain full track contact might be desirable. The resultant normal reaction force acting underneath the tracks, R, can be calculated by summing the normal forces on tracks.

$$R = (W_1 + W_2 + W_B + W_S + W_H + W_T)\cos\theta \quad (1)$$

R acts at a distance X_r calculated by summing the moments about the ground contact point of the centerline through the leading (downhill) sprocket of the undercarriage. X_r is defined as

$$X_r = (\text{SumRestore} - \text{SumOver}_1 - \text{SumOver}_2)/R \quad (2)$$

where

$$\text{SumRestore} = (W_1 \cdot x_1 + W_2 \cdot x_2)\cos\theta + \text{P}\cdot\text{y}_\text{p} \quad (3)$$

$$\text{SumOver}_1 = (W_1 \cdot y_1 + W_2 \cdot y_2 + W_B \cdot y_B + W_T \cdot y_T + W_s \cdot y_s + W_H \cdot y_H)\sin\theta \quad (4)$$

$$\text{SumOver}_2 = (-1)(W_B \cdot x_b + W_s \cdot x_s + W_H \cdot x_H + W_T \cdot x_T)\cos\theta \quad (5)$$

In Equation 5, the multiplier (-1) is used because of sign convention of (0, 0) representing the centerline of downhill sprocket (where x values are negative). For downhill travel, the sum of the resistances is defined as

$$\text{R}_\text{SUM} = (W_1 + W_2 + W_B + W_S + W_H + W_T)\sin\theta - (R \cdot MR) \quad (6)$$

and for uphill travel as

$$\text{R}_\text{SUM} = (W_1 + W_2 + W_B + W_S + W_H + W_T)\sin\theta + (R \cdot MR) \quad (7)$$

where MR is the motion resistance coefficient of the tracked vehicle on a given soil. To ensure feasible operation, the combined cable tension and the thrust must be greater than the downslope driving component, R_SUM, i.e.,

$$Thrust + P \geq \text{R}_\text{SUM} \quad (8)$$

where *Thrust* is calculated based on soil properties, track engagement, and bearing pressures of the undercarriage discussed in the following sections.

Pressure Distribution

For an assumed linear pressure distribution underneath the tracks, as described in Lysne and Burditt (1983), a pressure distribution depends on the eccentricity of the system it suspends (e.g., deviation of the center of gravity location from the centerline). Specifically, using downhill travel as the vehicle direction of motion, whether x_r is located within the first third of the tracks ($x_r/L < ⅓$), the middle third of the tracks ($⅓ < x_r/L < ⅔$), or the rear third of the tracks ($x_r/L > ⅔$). If $x_r/L < ⅓$, then the pressure in the front of the tracks, P_f is defined as

$$P_f = \frac{R}{3(w_t)(x_r)} \quad (9)$$

where the pressure at the rear of the tracks, P_r, is 0 at a point equal to $3x_r$. When $⅓ < x_r/L < ⅔$, the pressure under the tracks is defined as

$$P_f = \left[\frac{3R}{(TW)(L)}\right]\left[\frac{2}{3} - \frac{x_r}{L}\right] \quad (10)$$

$$P_r = \left[\frac{3R}{(TW)(L)}\right]\left[\frac{x_r}{L} - \frac{1}{3}\right] \quad (11)$$

Finally, when $x_r/L > ⅔$, the pressure under the front of the tracks begins at distance x_o from the centerline of the leading sprocket, defined as

$$x_o = [3L]\left[\frac{x_r}{L} - \frac{2}{3}\right] \quad (12)$$

where the pressure at the rear of the tracks is defined as

$$P_r = \frac{R}{3(TW)(L)\left(1 - \frac{x_r}{L}\right)} \quad (13)$$

We do not expect that x_r will be in the upper third of the tracks for steep slope applications. For uphill travel, the pressure distribution is the same, but the definitions of P_r and P_f are reversed in Equation 20.

Traction

Formulations of thrust for tracked vehicles vary from simple traction coefficients (Visser 2013, Caterpillar 2014) to empirical and semiempirical methods drawing from terramechanics (Bekker 1956, Le et al. 1997, Book and Goering 2000, Wong 2008). In this analysis, traction developed by the tethered machine is dependent on soil properties, track dimensions, grouser height, the pressure distribution underneath the tracks, and the amount of slip that the tracks develop to produce the necessary thrust to travel with a given tether line tension. Depending on vehicle direction of motion, track skid or track slip can cause ground disturbance.

For steep downhill vehicle motion, Wong (2008) defines track skid, S, as

$$S = 1 - \frac{\text{theoretical vehicle velocity}}{\text{actual vehicle velocity}} \quad (14a)$$

For steep uphill vehicle motion, Wong (2008) defines track slip, S, as

$$S = 1 - \frac{\text{actual vehicle velocity}}{\text{theoretical vehicle velocity}} \quad (14b)$$

According to Wong (2008), the thrust under a tracked system can be calculated by summing the shear stresses, τ, along the track engaged within the surface of soil. Defining the gross tractor pull as *Thrust*, then the pull contribution at any point x along the two tracks is defined as

$$Thrust(x) = 2TW\,\tau\,dx \quad (15)$$

$$Thrust = 2TW\int_0^{LE} \tau \, dx \quad (16)$$

where *dx* is a differential length along the track and *TW* is the width of one track. These stresses exist only under the effective length of the track, *LE*, that mobilizes normal pressures (i.e., in "contact" with the ground surface: if $x_r/L < ⅓$, then $LE = 3x_r$; if x_r/L is in the middle third of the tracks, then $LE = L$). Substituting the relationship for shear stress as a function of the soil shear strength properties, defined as cohesion, c, and the angle of internal friction, ϕ, in addition to the soil modulus, K, and slip, S, yields the following definition for thrust:

$$Thrust = 2TW\int_0^{LE} [a\ c + b\ p(x)\ \tan\phi][1 - e^{-Sx/K}]\, dx \quad (17)$$

where a is a multiplier that represents the influence of the grouser height/track width ratio due the cohesive soil properties and b is a multiplier that represents the influence of the grouser height/track width ratio due to the frictional soil properties (Bekker 1956), where

$$a = 1 + 2(HG/TW) \quad (18)$$

$$b = 1 + 0.64(HG/TW)\cot^{-1}(HG/TW) \quad (19)$$

By using the assumed pressure distributions discussed in Equations 9–13, the pressure distribution can be defined as

$$p(x) = P_f + (P_r - P_f)\left(\frac{x}{LE}\right) \quad (20)$$

With this function defined, the total gross thrust provided by the tracks can now be integrated over the length of track in contact with the ground. For a linear pressure distribution under the tracks the gross thrust of the tracks is given by

$$Thrust = G_1 + G_2 + G_3 \quad (21)$$

where G_1 is the thrust contribution from soil cohesion and ($G_2 + G_3$) are the thrust contributions from the pressure-dependent, frictional strength of the soil. These terms can be defined as

$$G_1 = 2(c)(TW)(LE)(a)\left(1 - \left(\frac{K}{(S)(LE)}\right)(1 - e^{(-S)(LE)/K})\right) \quad (22)$$

$$G_2 = 2(TW)(LE)(P_f)\left(1 - \left(\frac{K}{(S)(LE)}\right)(1 - e^{(-S)(LE)/K})\right) \times (b)\ \tan\phi \quad (23)$$

$$G_3 = (TW)(LE)(P_r - P_f)(b)\left(1 + \left(\frac{2K}{(S)(LE)}\right)(e^{(-S)(LE)/K}) - 2\left(\left(\frac{K}{(S)(LE)}\right)(1 - e^{(-S)(LE)/K})\right)\left(\frac{K}{(S)(LE)}\right)\right)\tan\phi \quad (24)$$

where additional details can be found in Bekker (1956), Wills (1963), and Fiske (1973). At a constant velocity, vehicle traction at the maximum permissible slip plus tether line tension must equal the sum of the resisting forces due to gravity plus motion resistance as described in Equation 8. It is assumed that the development of soil reactions to constant braking and constant thrust are equal. Specifically, the percentage of track skid and percentage of track slip produce equal soil reactions in Equation 17.

The apparent coefficient of traction (relative thrust developed under the given configuration) in this analysis, μ, is defined as

$$\mu = \frac{Thrust}{R} \quad (25)$$

Additional forces due to vehicle acceleration are not included for this baseline analysis but could be added to the sum of the resisting forces. Track tension and discrete roller wheels are not explicitly considered. Wong and Gao (1994) showed that increasing the number of road wheels, initial track tension, and track pitch contributed to increasing net thrust, primarily through reducing motion resistance, in a parametric analysis of tracked wheels with rigid links in a very soft clay.

Applications and Sensitivity Analysis

The baseline conditions shown in Table 1 were used in the model presented to calculate equipment gradeability, maximum pressure, and traction (Table 2, scenario a). With these conditions, a sensitivity analysis was performed, varying tether tension, grouser depth, grapple loading, track width (Table 2), hitch height (Table 3), and soil strength (Table 4). The direction of movement was uphill and a small motion resistance coefficient (0.025 kilograms-force [kgf] per kgf of normal force) was considered as acting against the direction of tether pull. However, it should be noted that although equipment movement was uphill, the orientation and operation of the boom was downhill in all scenarios in Table 2 except scenario f, where the boom is facing uphill. The soil characteristics for the analysis were for soils with both friction and moderate cohesion, typical for native soils in the Pacific Northwest, USA, and derived from data presented by Le et al. (1997). The baseline case is typical for soil classified as a sandy clay loam where c is 14 kPa and ϕ is 30°. To illustrate some of the effects of soil, a second, weaker soil representative of clay loam was used ($c = 7$ kPa, ϕ is 15°). A representative shear modulus of deformation of 1.3 cm was used for the analysis. To limit soil disturbance, baseline slip was limited to 15% for all cases unless stated.

Varying Tether Tension

For the baseline case, the maximum slope (gradeability) that a feller-buncher could ascend while limiting track slip to 15% varied from 64 to 85% slopes for 0 kgf (untethered condition) and 6,750 kgf of cable assistance, respectively (Table 2, scenario a). For these scenarios, ground pressures increased as the effective track length decreased. Maximum ground pressures varied from 503 to 807 kPa as the slope and tether tension increased. The average pressure, considering the entire track area, was approximately 70 kPa but manifested as significantly larger, localized pressures up to 1 order of magnitude larger than the conditions realized on flat ground due to increasing track eccentricity (e.g., $x_r/L < 1/3$) with increasing slope. For these scenarios, the equivalent coefficient of traction varied from 0.63 to 0.67, within the range of suggested coefficients of 0.50 and 0.70 for wet sand and wet clay loam, respectively (Caterpillar 2014). For dry clay loam, the maximum effective traction coefficient is 0.90.

Table 1. Definitions and base equipment, soil, operating conditions for examples.

Variable	Definition	Units	Value (boom downhill)	Value (boom uphill)
P	Cable (tether) tension	kgf	Varies	Varies
R	Resultant	kgf	Dependent	Dependent
W_T	Weight of tree	kgf	Varies	Varies
W_H	Weight of cutting head	kgf	2,610	2,610
W_S	Weight of stick	kgf	2,270	2,270
W_B	Weight of boom	kgf	3,630	3,630
W_1	Weight of cab/engine	kgf	14,520	14,520
W_2	Weight of undercarriage	kgf	12,700	12,700
x_P, y_P	Coordinates of hitch point	m	(3.81, 0.76)	(3.81, 0.76)
x_r	Distance to pressure resultant	m	Dependent	Dependent
x_T, y_T	Coordinates of tree CG	m	(−7.37, 10.16)	(9.75, 10.16)
x_H, y_H	Coordinates of cutting head CG	m	(−7.37, 0.91)	(9.75, 0.91)
x_S, y_S	Coordinates of stick CG	m	(−6.10, 3.05)	(7.01, 3.05)
x_B, y_B	Coordinates of boom CG	m	(−2.03, 3.05)	(5.79, 3.05)
x_1, y_1	Coordinates of cab/engine CG	m	(L, 1.83)	(0L, 1.83)
x, y_2	Coordinates of undercarriage CG	m	(0.5L, 0.84)	(0.5L, 0.84)
P_f	Pressure at front of tracks	kPa	Dependent	Dependent
P_r	Pressure at rear of tracks	kPa	Dependent	Dependent
S	Slip		0.15	0.15
ϕ	Soil internal angle of friction	°	15, 30	15, 30
c	Soil cohesion	kPa	7, 14	7, 14
K	Soil deformation modulus	cm	1.27	1.27
HG	Grouser height	cm	5.10	5.10
L	Sprocket to sprocket length	m	4.27	4.27
LE	Effective track length	m	Varies	Varies
TW	Track width	m	0.61	0.61
μ	Apparent traction coefficient		Dependent	Dependent
MR	Motion resistance coefficient	kgf/kgf-normal	0.025	0.025

Varying Grouser Height

Grousers perform two functions. In nonhomogeneous soils, the grouser may act as a cutter to remove the weak surface layer to reach a firm stratum that has enough shearing strength to provide the necessary tractive effort. Secondarily, it provides extra pull due to shearing within the grousers against the soil wall adjacent to the track. For steep slope applications, we have observed grousers extended to a total of 10–15 cm. As expected, increasing grouser depth increased traction and thrust. For example, when grouser depth was increased from 5.1 to 20 cm (Table 2, scenario b), gradeability increased from 5 to 8%, ground pressure increased, and the effective length of track on the ground decreased. With 6,750 kgf of cable tension, gradeability increased to almost a 90% slope, the proportion of track length in contact with the ground was less than 10%, and the maximum ground pressure under the leading edge of the track varied from about 800 kPa to about 1,317 kPa, depending on tether tension. However, maximum pressures for a given slope could be decreased with increasing tether tension or by reducing eccentricity with less extension of the boom/stick/cutting head or uphill operation.

Varying Grapple Load

The high center of gravity of trees being harvested may lead to notable eccentric loading of the feller-bunchers. Under baseline conditions with the grapple supporting a 1,361 kgf tree, gradeability declined while ground pressures increased (Table 2, scenario c). This is directly related to the additional weight of the system and a shift of the lumped center of gravity further from the undercarriage and cab. It is noted that uphill operation can significantly reduce the subgrade pressures and greatly increase gradeability due to an advantageous shift of the lumped center of gravity upslope. This leads to more even engagement of track length for bearing (Figure 3). This is especially marked when using tracks are used (i.e., lower baseline pressures due to more bearing area).

Varying Track Width

Under baseline conditions employing a wider track system (increased TW from 0.61 to 0.91 m), maximum pressures are decreased proportionately (Table 2, scenario d). This is due to a linear increase in bearing area for the tracks along a given effective length, LE. The same gradeability to limiting frictional resultant forces still occurs, but wider tracks may present a means of reducing soil disturbance by means of reduced track pressures, demonstrated by comparing the top row ($TW = 0.61$ m) and bottom row ($TW = 0.91$ m) in Figure 3. Although track width is limited by practical and manufacturing constraints, the reduced soil impacts may justify their application.

Varying Slip

Excessive slip and shearing of the surface soil can be a critical mechanism of disturbance, but simultaneously enables increased gradeability and traction. For example, if acceptable slip was 0.90 (90%) rather than the baseline 0.15, the maximum slope attainable would increase by approximately 1 to 2% (Table 2, scenario e) with an equivalent coefficient of traction varying from 0.68 to 0.65. However, a slip of 90% implies that 10 revolutions of the tracks would only move the machine forward one track length, a potentially unacceptable threshold for soil disturbance. However, consideration of more slip is important with respect to the realistic variability in terrain and soil conditions. Safe operation may require more-than-expected thrust for mobility, realizing more soil track slip under marginal conditions. It is, however, up to the operator or land manager to manage slip occurring during operation. The relatively low gain in gradeability with increasing slip is affected by the soil deformation modulus.

Varying Boom Position

The locations of the boom, stick, cutting head, and tree may lead to large eccentricity in lumped equipment center of gravity, especially when the boom is operated downhill. However, this negative

Table 2. Sensitivity analysis for baseline soil, sandy loam (c = 14 kPa; ϕ = 30°), uphill travel unless specified.

P (kgf)	Θ_{max} (%)	P_{max} (kPa)	LE/L	μ
Scenario a: Baseline soil, HG = 5.1 cm, TW = 0.61 m, W_T = 0 kgf, S = 0.15				
0	64.7	503	0.22	0.67
2,250	71.3	572	0.19	0.66
4,500	78.2	669	0.16	0.65
6,750	85.2	807	0.13	0.63
Scenario b: Baseline soil, HG = 20 cm, TW = 0.61 m, W_T = 0 kgf, S = 0.15				
0	72.5	800	0.14	0.75
2,250	78.3	938	0.11	0.73
4,500	84.1	1010	0.09	0.70
6,750	89.9	1317	0.08	0.67
Scenario c: Baseline soil, HG = 5.1 cm, TW = 0.61 m, W_T = 1361 kgf, S = 0.15				
0	49.7	2109	0.06	0.52
2,250	53.2	2510	0.05	0.49
4,500	56.6	2972	0.04	0.45
6,750	60.0	3523	0.03	0.41
Scenario d: Baseline soil, HG = 5.1 cm, TW = 0.91 m, W_T = 0 kgf, S = 0.15				
0	65.4	345	0.22	0.68
2,250	71.8	393	0.19	0.66
4,500	78.4	455	0.16	0.65
6,750	85.2	538	0.13	0.63
Scenario e: Baseline soil, HG = 5.1 cm, TW = 0.61 m, W_T = 0 kgf, S = 0.90				
0	65.8	531	0.21	0.68
2,250	72.7	620	0.18	0.67
4,500	80.1	765	0.14	0.66
6,750	88.0	1047	0.10	0.65
Scenario f: Baseline soil, HG = 5.1 cm, TW = 0.61 m, W_T = 0 kgf, S = 0.15, fully extended uphill				
0	84.3	131	0.81	0.87
2,250	92.5	130	0.76	0.86
4,500	101.3	133	0.71	0.86
6,750	110.9	137	0.66	0.85
Scenario g: Baseline soil, HG = 5.1 cm, TW = 0.61 m, W_T = 0 kgf, S = 0.15, downhill travel				
0	62.3	455	0.25	0.60
2,250	68.4	496	0.22	0.58
4,500	74.6	549	0.20	0.56
6,750	81.1	614	0.17	0.54

Table 3. Sensitivity analysis for effects of hitch height, uphill travel.

y_P (m)	θ_{max} (%)	P_{max} (kPa)	LE/L	μ
0.8	85.2	807	0.13	0.63
1.0	87.1	669	0.15	0.64
1.3	88.8	565	0.18	0.66
1.5	90.4	483	0.21	0.67

Baseline soil, HG = 5.1 cm, TW = 0.61 m, W_T = 0 kgf, S = 0.15, P = 6,750 kgf.

phenomenon, which increases maximum track pressures, reduces gradeability and effective track length, and necessitates higher cable tensions can prove advantageous when the boom is operated uphill as it may reduce eccentricity when facing upslope (Table 2, scenario f). For comparison, in Table 2, scenarios a and f illustrate operating conditions when the boom is downhill and uphill, respectively (dimensions are presented in Table 1). For a machine with baseline soil properties, gradeability was increased from 65 to 84% at a zero line tension and from 85 to 111% at 6,750 kgf of line tension. Maximum soil pressures exerted by the machine are reduced, owing to better distribution of component centers of gravity, decreasing to less than 140 kPa. Furthermore, the apparent coefficient of traction

Table 4. Sensitivity analysis for weak soil, clay loam (c = 7 kPa; ϕ = 15°), uphill travel.

P (kgf)	θ_{max} (%)	P_{max} (kPa)	LE/L	μ
Scenario a: Weak soil (clay loam), HG = 5.1 cm, TW = 0.61 m, W_T = 0 kgf, S = 0.15				
0	33.4	221	0.58	0.36
2,250	39.9	231	0.54	0.36
4,500	46.7	243	0.50	0.35
6,750	53.9	256	0.46	0.35
Scenario b: Weak soil (clay loam), HG = 20 cm, TW = 0.61 m, W_T = 0 kgf, S = 0.15				
0	40.2	249	0.50	0.43
2,250	46.7	262	0.47	0.42
4,500	53.6	278	0.43	0.42
6,750	60.9	297	0.39	0.41
Scenario c: Weak soil (clay loam), HG = 5.1 cm, TW = 0.61 m, W_T = 1,361 kgf, S = 0.15				
0	29.9	407	0.33	0.32
2,250	35.8	469	0.28	0.32
4,500	42.0	552	0.24	0.31
6,750	48.3	669	0.19	0.30
Scenario d: Weak soil (clay loam), HG = 5.1 cm, TW = 0.90 m, W_T = 0 kgf, S = 0.15				
0	35.4	152	0.56	0.38
2,250	41.8	159	0.52	0.37
4,500	48.5	167	0.48	0.37
6,750	55.7	177	0.44	0.36

increased to approximately 0.85, owing to better engagement of the track and grouser system by means of more track contact length for the uphill boom position. Current tethered operations usually fell a tree with the boom downhill for flexibility in tree placement and to stay clear of the tether line for safety reasons. However, at least one operator uses a chain section between the hitch and the cable tether to permit moving the tether with the boom and to prevent damage to the cable when the boom is operated uphill (Figure 4). The results of this theoretical approach suggest that operability conditions improve significantly and soil disturbance may be limited under uphill boom conditions.

Varying Travel Direction

Traveling uphill (Table 2, scenario a) with the boom facing downhill had slightly higher gradeability than traveling downhill (Table 2, scenario g) with the boom facing downhill for the motion resistance assumed. There are two compensating effects. Traveling uphill requires a machine to overcome motion resistance but has the benefit of having the normal force on the track largest at the rear of the track where the soil deformation is greatest (Table 2, scenario f). Traveling downhill has motion resistance helping to brake the vehicle but has the disadvantage of having the largest normal force at the leading edge of the track where it contributes relatively less to traction.

Varying Hitch Height

One potential design condition that influences distribution of pressures and gradeability is location of cable hitch (Figure 4). A higher hitch height increases the resisting moments in a system, simultaneously increasing gradeability and reducing maximum soil pressures (Table 3). For example, doubling the hitch height from 0.75 to 1.5 m under baseline conditions with tether line tension at 6,750 kgf increased gradeability from about 85 to 90% and reduced maximum ground pressure from about 807 to 483 kPa, a reduction

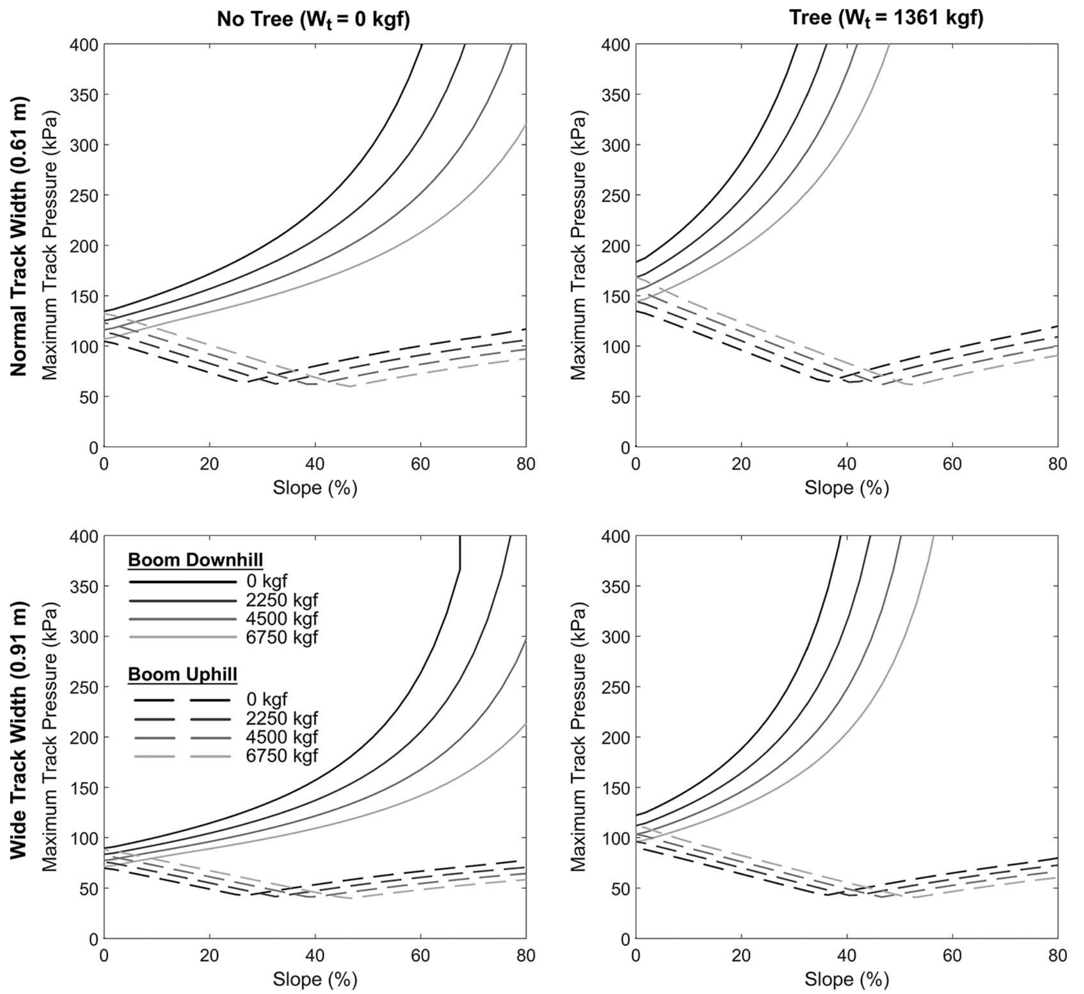

Figure 3. Pressure profiles for tethered (and untethered when $P = 0$ kgf) feller-bunchers for various slopes and tree weights.

Figure 4. Left. A custom designed hitch for a remotely powered, tethered feller-buncher. Right. Protective chain attachment to hitch point.

of 40%. Hence, the location of a hitch point presents a promising aspect of increasing access and reducing soil disturbance.

Varying Soil Strength

The effects of soil strength were observed for the same conditions presented in scenarios a–c in Table 2 by analyzing a weaker soil (c = 7 kPa, $\phi = 15°$) in scenarios a–d in Table 4. By halving the cohesion and angle of internal friction, gradeability of the tethered system was reduced by up to 30% (Table 4, scenario a). Under baseline conditions, gradeability for a zero cable tension case was 65%, whereas under weaker soil conditions, gradeability was limited to about 33% (Table 4, scenario a). With a 6,750 kgf tether tension, the gradeability fell from about 85 to 54% with the change from baseline soil conditions to weak soil conditions. Similar trends were observed when grouser height was increased and a tree weight was imposed (Table 4, scenarios b and c, respectively). As before, wider tracks enabled lower mobilized pressures, but did little for increased traction (Table 4, scenario d). Track pressures were lower and track contact length was longer than the baseline conditions for maximum slope angles, but primarily because the maximum operable slope angle was restricted due to weak soil conditions.

Discussion

Use of cable assistance, or "tethering," demonstrates theoretical efficacy in improving stability and gradeability and potentially reducing soil disturbance for the selected, representative machine configurations, soil conditions, and sensitivity analyses. Although the scale and dimensions of the feller-buncher analyzed within this study are reasonably representative of equipment, it is emphasized that no parallels between the sample machine specifications and current equipment models and manufacturers are intimated as the analyses are for illustrative purposes. One particular note is that extreme variability exists in soil conditions, not only from site to site but also within a given site. Even a given site may encounter notable differences in soil behavior throughout a given year, affecting soil strength, density and subsequently traction. The *Caterpillar Performance Handbook* (Caterpillar 2014) suggests that traction factors can range between 0.30 and 0.90 for various soils, reasonably represented by the weak and strong soils in this analysis (0.35–0.87). A limited sensitivity analysis performed for illustrative purposes indicated that maximum gradeability was affected by tether tension, track slip, soil strength, grouser depth, hitch height, boom position, and grapple load. Theoretical ground pressures were greatly increased when the boom was operated downhill on steeper slopes as the effective length of track in contact with the ground decreased. This may have implications for site disturbance as slope increases or varies locally, primarily through soil rutting and compaction. The average mean ground pressure on level ground was about 70 kPa, whereas maximum ground pressure on steep slopes could be more than 1 order of magnitude higher. Cutting with the boom uphill greatly reduces ground pressure but poses challenges to protect the tether and to avoid hitting the machine with the falling tree.

In these simulations, track slip was arbitrarily limited to 15% as a method for reducing soil displacement. Increasing allowable track slip would increase gradeability for a given tether tension but may have negative impacts on site soil conditions. The effectiveness of wider tracks could be evaluated to reduce ground pressure and slip, although longer tracks would be more effective. Longer tracks would potentially extend further ahead of the machine when operating with the boom downslope, subsequently shifting the rotational axis further away from the heavy, stabilizing undercarriage and cab/engine components. This analysis assumes that traction is a function of soil parameters only, ignoring the impact of woody debris and other biomass along the trail. If residual biomass is found to be effective in reducing soil disturbance, management strategies to increase trail debris could be evaluated, but the effects of debris on traction and safety must be considered. An analysis similar to that described in this article could be extended to both steep slope harvesters and forwarders, to which similar machine considerations apply. For untethered conditions, trail debris has been demonstrated to be an effective means of preventing soil disturbance for harvester operations (Wronski and Humphries 1994, Labelle and Jaeger 2012), presenting an intuitive potential extension to tethered conditions.

A key assumption in the derivation was that the pressure distribution below the tracks is linear, an assumption used in the literature analyzing pressure distributions under various tracked equipment (Lysne and Burditt 1983, Book and Goering 2000). This statement can be justified with the assumption of using a linearly elastic soil that compresses proportional to pressure coupled with a rigid (in comparison to the soil) track suspension. These assumptions allow a convenient closed-form solution for the pressure along the tracks and resulting thrust. However, should testing demonstrate that displacement is not linear with respect to pressure, the same solution procedure can be used with a nonlinear pressure distribution.

The examples with downhill placement of the boom system realized high resulting ground pressures due to the eccentricity of the system. Operation of a steep-slope feller-buncher on weak soils in New Zealand suggested that using the feller-buncher followed by cable yarding did not significantly increase rutting compared with manual felling followed by cable yarding. (Evanson et al. 2013). However, increased ground pressures may result in soil rutting, sinkage, impacts on tree growth and regeneration, and hydrologic impacts if potentially high ground pressures are realized. A nonlinear soil pressure distribution would probably distribute pressure more evenly and increase the thrust contribution of the cohesion component that depends directly on the ground contact area. Flexible vehicle suspension rather than rigid suspensions would also spread the pressure distribution. For example, the *Caterpillar Performance Handbook* (Caterpillar 2014) estimates that tractors with elevated sprockets and suspended undercarriages have 15% more traction than rigid suspension tractors. Future field testing and measurements will help enable empirical data to corroborate or refine the assumptions regarding maximum ground pressures and the shape of the ground pressure distribution.

The approach to stability and traction presented here was intended to identify the loaded length of the tracks for a given tether tension and to limit track slip to 15%. An alternative approach is to limit the minimum loaded length of the tracks during operations, reducing ground pressures and ensuring stability under less eccentric conditions. Specifically, ensuring that the resultant of the ground pressure acts in a range within the middle third of the tracks is critical for full track-soil normal contact.

Future Work

Future development of this approach to operational stability could include effect of machine acceleration or deceleration on tether tensions, presence of stumps and downed logs, effects of cross slopes, and stability when the boom is not parallel to the tracks. The limiting stability case for untethered feller-bunchers on zero percent slopes is overturning perpendicular to tracks. Overturning stability perpendicular to the tracks remains an issue under steep slope operations. In addition to stability issues, side loading increases the normal force on the inside track and reduces the normal force on the outside track, affecting thrust developed by each track. The pressure distribution across the track is also affected. The effects on stability and traction while the feller-buncher is pulling trees uphill by rotating the turntable could also be modeled with these considerations. Uphill shovel logging with smaller trees has been observed as an alternative to rigging up a yarder for short uphill skids.

Finally, this is a theoretical model intended to present an approach to evaluating field operations and considerations for future operation of tethered equipment. To corroborate this approach, empirical measurements will be taken in a project that will occur with support from the US National Institutes of Health. A combination of manipulative experiments and work sampling will be used to collect data to support the development of safe operating guidelines for tethered felling machines operating in the Pacific Northwest, USA. Manipulative experiments will be used to gather information to support the determination of stability analysis of the machines in consideration of various slopes, available soil types, loading conditions, and boom positions. Finally, work sampling will be used to supplement this stability and traction analysis for the machines by recording changes in dynamic loading on the machines but will concentrate on the interaction of the machine and the operator under a variety of conditions that are currently faced by commercial operators who have deployed these tethered machines in their operations, comparing the operational differences between tethered and untethered equipment.

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