A Method for Evaluating the Cumulative Impact of Ground-Based Logging Systems on Soils

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ABSTRACT

A method for determining the Effective Ground Pressure (EGP) of tracked or wheeled logging machines that can be directly and unambiguously related to their impact on soils is described. When several machines operate together in a logging system, the methodology allows their individual EGP's to be combined to derive a System Effective Ground Pressure (SEGP), which measures the impact of the system as a whole. The methodology has been applied to determine the relative impact of logging systems and influence the choice of machine running gear. Given also the temporal variability in the bearing capacity of soils, it has also been applied to forecasting the minimum level of disruption to operations on flat ground arising from limitations placed on soil disturbance. These applications have led to increased efficiency of operations through a reduction in wood stockpiling during wet weather. The method is sufficiently simplistic at the core, that contractors with the aid of appropriate charts have evaluated the relative impact of machines and systems on soils themselves.

Keywords: *environmental impact, ground pressure, logging systems, logging machines, soil disturbance, soil strength, vehicle mobility.*

INTRODUCTION

Australian Newsprint Mills Pty. Ltd. owns and operates a newsprint mill located at Albury in New South Wales, Australia, which uses as feedstock thinnings from Pinus radiata forests in the surrounding district. The company supports a range of heavy machinery and has restricted impacts on soils by requiring that the total depth of ruts caused by the harvesting machinery during both thinning and clearfell operations be less than 150 mm. During winter when the soils are wet and of low bearing capacity, this constraint has led to a number of problems including excessive machine downtimes, deterioration of felled pulpwood that cannot be easily recovered and the need to stockpile timber in order to maintain continuity of wood supply to the mill. Such problems can be overcome by providing contractors with a means of predicting the impact on soils of various machine combinations and operating methods.

Description of Logging Operation and Systems

The pine forests in the region are thinned three or four times before being clearfelled and replanted at about 50 years of age. In a first thinning, the harvesting machines fell every fifth row plus excess trees in the bays on either side of the felled outrow. In subsequent thinnings, machines pass down the same tracks, but there is more room to manoeuvre and consequently the potential intensity of disturbance is less.

The harvesting systems currently in use generally consist of a feller buncher and processor or a harvesting machine which fells, processes and bucks the logs which are then transported directly to roadside by a forwarder. As the forwarder tends to have the highest ground pressures and greatest number of passes, it tends to cause the greatest soil disturbance. This disturbance is reduced considerably if the machine runs on an evenly laid slash bed concentrated on the extraction track by the harvester or processor. A processor operates most efficiently if trees are bunched together by the feller buncher, but if an even slash bed is to be laid then bunching of felled trees is omitted.

When a Kockums 880 feller buncher (a Kockums 880 loader fitted with a feller buncher head) is required to distribute felled trees evenly, the felling is conducted in two stages. In the first stage, the machine travels along the outrow felling trees ahead of it. In the second stage, excess trees in the bays on either side of the outrow are felled as the machine reverses back along the outrow. This two-stage operation provides a complete and uniform slash bed ahead of the processor which follows the system, but requires the machine to undertake two passes. Trees are laid along the outrow or along and at right angles to the outrow.

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Other feller bunchers in use are fitted with a turn-table and can distribute felled trees evenly by cutting a bunch of trees in front and laying the bunch down behind the machine. Accordingly these machines require only one pass to fulfil their function and can lay trees along or at right angles to the track, but there is a greater tendency for the trees to be bunched to minimise the amount of rotation on the turn-table.

There are three main types of processors in use. These are the boom delimbers, which work most efficiently when the trees are laid lengthwise along the track, and twin-grip and single-grip harvesters/processors, which are most efficient processing trees orientated at right angles to the track. Accordingly twin- and single-grip processors/harvesters tend to leave slash on the track orientated at right angles to it, whereas boom delimbers leave the larger pieces of slash (i.e. tree tops) aligned along the track. In all cases, slash is laid ahead of the processor or harvester over which the machine then passes.

A first thinning occurs when the forest is 12-15 years old. After felling, about 30% of the tree's weight is left behind as slash [1]. This is equivalent to 40% of the weight of the timber extracted. Currently, the amount of timber extracted in a first thinning is 100-120 tonne ha^{-1} reducing to 70-80 tonne ha^{-1} on subsequent thinnings. The tree row spacing is 2.5 m and every fifth row is removed. If all the available slash is left on a 3 m wide extraction track, the density of the slash on the extraction track is about 18 kg m^{-2} reducing to 13.5 kg m^{-2} in second and later thinnings.

The maximum distance the forwarder will travel in order to contain travel times to acceptable levels is about 1 km, but in very wet conditions the distance travelled into the forest may be restricted to 200-300 m in order to reduce the amount of trafficking at the road verge. This implies that under relatively dry conditions, about 10 forwarder passes occur near the roadside, but this can be reduced to 2 or 3 under very wet conditions.

The main operational factors which management can control and which influence the impact on soils are

- the ground pressure and number of passes required by each machine to fulfil its function;
- the efficiency of the harvesting/processing system at laying slash bed on the extraction track used by the forwarder;
- the distance from roadside the forest is logged.

THEORY

Impact of Machines on Soils

The most convenient objective measure of the impact of a machine on soils is the rut depth caused after a given number of passes. This measure incorporates both a visual impact of the operation and a measure of the potential impact on soil physical conditions. It also reflects, to some extent, the potential effect of operations on tree growth. Accordingly the basic strategy employed in this study is to compare machines and logging systems on the basis of the depth of ruts they cause during normal operations.

Rut Development by Wheels

Application of the principles of dimensional analysis to describe the soil-wheel interaction and neglecting minor effects associated with wheel speed has led to a formulation of wheel sinkage, traction, motion resistance and torque expressed in dimensionless form in terms of a basic wheel-soil numeric. In the case of wheel sinkage, wheel sinkage can be expressed in dimensionless terms by the parameter z/D where z = rut depth, D = wheel diameter and we can write

$$z/D = f_z(N) \tag{1}$$

where N is the basic universal prediction parameter that incorporates the strength of the soil, the weight on the tire and its basic dimensions and f_z is a universal function to be determined by experiment.

Freitag [2] was one of the first to specify the form of N, but later work has seen the original formulation modified to account for differences in the shape of available tires. On the basis of numerous observations of the soil-wheel interaction in experimental laboratories, it has been concluded that a good and convenient fit to the available data is [5]

$$\begin{aligned} N &= CI(bD/W)\,(1+b/2D)^{-1}(1-s/h)^{-2} \\ &= 2(CI/NGP)\,(1+b/2D)^{-1}(1-s/h)^{-2} \end{aligned} \tag{2}$$

where

NGP= 2W/bD is the nominal ground pressure of the tire
CI = cone index of the soil (soil strength)
b = tire width
D = tire diameter
W = wheel loading
s/h = (tire deflection/undeflected section height)

With reference to the last two terms in Eqn. 2, the normal range of tire deflections and wheel dimensions encountered in forestry operations is such that the product of these terms is 1.0 +/- 0.15 and the basic prediction parameter reduces to CI/NGP or in the case of a remoldable soil (a soil which loses strength during trafficking, either through an increase in volumetric water content after compaction or a loss in structure) RCI/NGP where RCI is the rating cone index (soil strength after soil has been remolded) [3].

Observations have been made of the increase in rut depth (z) of a powered wheel with increasing number of passes (n) on a prepared, fully remolded uniform soil [3, 6]. They indicate that the form of the universal function f_z is (Figure 1)

$$z/D = 4.61 \times n^{0.5} \times (CI/NGP)^{-2.6} \quad (3)$$

Useful conclusions provided by Figure 1 are

- Immobilization during the first pass (z/D = 0.3) occurs when the soil strength is about 3.0 times the NGP of a wheel and at 50 passes when it is 5 times the NGP (z/D = 0.5).
- If a vehicle which has two axles fitted typically with 1.5 m diameter wheels is to obtain a single pass without causing a rut deeper than 150 mm, the CI/NGP ratio must exceed 4.5. If it is to obtain 10 passes under the same constraint, then the CI/NGP ratio must exceed 7.2.
- If a wheel (or vehicle) can obtain just 1 to 2 passes before becoming immobilized, halving the ground pressure by, for example, fitting dual wheels or wide, high flotation tires will allow it to obtain 10 times as many passes without causing a rut deeper than 150 mm.

While the cumulative effect of multiple passes by a single wheel is adequately described by Eqn. 3, it is also necessary to consider how multiple wheel passes of different ground pressure affect the cumulative rut depth. A complex expression for the increment in rut depth in terms of soil-strength parameters, wheel loading and dimensions of the wheel and the rut depth prior to its passage has been derived [6], but it can be demonstrated that a good approximation to this relationship (+- 15%) for a wide range of soils [2] is that the final rut depth z following the passage of a wheel in a rut is given by

$$z = (z_1^2 + z_2^2)^{1/2} \quad (4)$$

where z_1 is the initial rut depth prior to the passage of the wheel and z_2 is the expected rut depth if the soil had been undisturbed.

Effective Ground Pressures of Wheeled and Tracked Machines

A nominal ground pressure can be calculated for both tracks and wheels. There are other factors which influence the depth of ruts caused by tracked machines, and in the case of a wheeled machine the NGP's of individual wheels need to be combined into an Effective Ground Pressure (EGP) for the machine which reflects its gross impact on the soil. The EGP of a machine (tracked or wheeled) is defined as the nominal ground pressure of each wheel on a virtual machine with twin axles of equally loaded wheels of 1.5 m diameter, which would produce the same depth of ruts on bare, fully plastic, remolded soil as the machine under consideration.

Given a machine's EGPs the estimation of the rut depth produced after a given number of passes becomes a simple matter of referring to Figure 1 and determining the CI/EGP ratio, while remembering a single vehicle pass involves two wheel passes.

EGP of Wheeled Machines

Consider first a machine with twin axles, wheels of diameter D_1 and D_2 and ground pressures P_1 and P_2. Using Eqn. 3 and Eqn. 4, the sinkage z is given by

$$\begin{aligned} z &= C[D_2{*}P_2^{2.6}\{1+(D_1/D_2)^2(P_1/P_2)^{5.2}\}^{0.5}] \\ &= C * D_2 * [P_2 * F]^{2.6} \quad (5) \end{aligned}$$

where C is a constant incorporating soil-strength parameters and other constants and $F^{-2.6}$ is the function contained in $\{\}^{0.5}$.

Based on our definition of the machine's EGP

$$z = C * 1.41 * D_s * EGP^{2.6} \quad (6)$$

where D_S = 1.5 m (a standard fixed wheel diameter that will give a valid comparison between machines) and the factor 1.41 takes into account that there are two wheel passes for the virtual machine and wheel sinkage increases as $n^{0.5}$ (the number of wheel passes, n=2).

Comparison between Eqn. 5 and Eqn. 6 yields for the EGP of the machine

$$EGP = 0.88*(D_2/D_S)^{0.384}*F*P_2 \quad (7)$$

where

$$F = \{1 +(D_1/D_2)^2 (P_1/P_2)^{5.2})\}^{0.192} \quad (8)$$

and is plotted in Figure 2 as a function of P_1/P_2 and D_1/D_2. For the normal range of wheel diameters found on logging machines EGP is obtained to 5% accuracy assuming $D_2/D_S\,^{0.384} = 1.0$.

We now consider machines with 3 or 4 axles. Any pair of axles with wheels of diameters D_1 and D_2 and respective NGP's of P_1 and P_2 can be replaced by a single axle with a virtual wheel producing the same rut depth, of diameter D_2 and NGP = F * P_2 (Eqn. 5) where $P_2 > P_1$. In this way the number of axles of a multiaxled machines can be reduced to 2 virtual axles, with appropriate NGP's which can be substituted into Eqn. 7 to obtain the machine's EGP.

EGP of Tracked Machines

No simple reliable relations are published for predicting the sinkage of tracked machines in terms of soil strength and basic parameters describing the track geometry. For the range of tracked vehicles of interest in this study (Table 3), it can be demonstrated, using relations for computing vehicle mobility given by Knight and Freitag [3], that the soil strength required to obtain 50 passes before a machine bellies and is immobilized is 3.4 to 4.3 times its NGP, whereas for wheeled logging machines it is 5.0 times the average NGP of its wheels. This suggests that the rate of rut development of a tracked logging machine is generally about the same as that of a wheeled machine of 25% greater average ground pressure.

The pressure distribution beneath a track is far from uniform. Rowland [4] studied a range of military vehicles and concluded that a tracked vehicle's mobility should be related to the mean maximum pressure (MMP) beneath the track, rather than the NGP. On the basis of a semi-empirical study Rowland proposed that the MMP was given by

$$MMP = 1.26\, W / \{2mB(pD)^{0.5}\} \quad (9)$$

where W = vehicle weight
m = number of road wheels per track
B = track width
p = track plate pitch
D = road wheel diameter

Rowland claims that an index of the efficiency in design of a track is the ratio MMP/NGP. Among conventional vehicles this ratio varies between 1.4 - 3.0, with crawler tractors and World War 1 tanks taking values below 2.0, modern tanks with overlapping wheels (Tigers and Panthers) taking a value of 1.8 and most other tracked military vehicles with values in the range of 2.5-3.0. Application of Rowland's formula to the tracked machines given in Table 3 yields MMP/NGP ratios averaging 2.2.

Rowland also presents data indicating that the sinkage of tracks varies with the relative value of $MMP^{3.2}$. Combined with the result for the tracked vehicles in this study based on the formula given in [3], this implies that a track with a MMP/NGP ratio of 2.0 (and the same number of road wheels) would be equivalent to a pair of wheels of ground pressure 0.8 times the NGP of the track.

Assuming that rut development increases as $NGP^{2.6}$ (Eqn. 2) for both wheels and tracks with a MMP/NGP ratio of 2, it is taken, on the basis of the above results, that the Effective Ground Pressure (EGP) of a tracked machine is given by

$$EGP_{tracks} = 0.8\, NGP \times (MMP/2NGP)^{1.23} \quad (10)$$

This result was tested in a trial comparing the rates of rut development of a standard Kockums 85-35 forwarder when fitted with and without wide plate tracks to the rear bogie [7]. At moderate soil strengths (CI/NGP = 6), the fitting of tracks resulted in reduced wheel sinkage equivalent to a 25% reduction in wheel ground pressures (based on Eqn. 2). The NGP of the bogie wheels was 1.8 times the NGP of the bogie with tracks fitted, and application of

Rowland's formula to the tracked bogie yielded a MMP/NGP ratio of 3 (track contact length = 3.75 x D/2, p = 0.15 m, D = 1.3 m). This implied that the equivalent, in terms of rut development, of a track with a MMP/NGP ratio of 3, is a pair of wheels of 1.3 m diameter and NGP 1.35 times that of the track. Substitution of a MMP/NGP = 3.0 into Eqn. 10 gives about the same result, which supports the validity of Eqn. 10.

Operating Effective Ground Pressure

When operating in a logging system, some machines require more passes over the ground than others to fulfil the same function, e.g. Kockums 880 feller buncher and this magnifies the impact on the soil by the machine. Some of the machines also operate on a slash bed and this reduces the impact of the machine on the soil. To account for both effects adjustments are made to the machine's EGP to obtain an operating effective ground pressure for the machine defined as that EGP for the machine that would produce, after a single pass on bare soil, the same maximum depth of ruts as the machine under consideration when fulfilling its function as prescribed by the logging plan.

The OEGP is given by

$$\text{OEGP} = \text{EGP} \times \text{Fn} \times \text{Fs} \quad (11)$$

where $\text{Fn} = n^{0.19}$ is a factor accounting for the maximum number of passes on the soil by a machine and Fs is a factor that accounts for the reduction in rut depth when a slash bed is present.

The number of passes that a feller buncher, processor or harvester undertakes is determined by operating procedures. The maximum number of passes required by a forwarder of load capacity W to extract the timber to roadside is given by

$$n = (D * L * T) / W \quad (12)$$

where T is the intensity of thinning, e.g. kg m^{-2}, D is the distance from roadside the forest is logged (m), W is the forwarder log load (kg) and L is the separation of the extraction tracks (m).

The dependence of the factor Fs on slash density has been previously determined from observed reductions in rut depth obtained over various densities of slash [7]. It is given by

$$\text{Fs} = 1/(0.033S_D + 0.93) \quad (13)$$

where S_D is the density of the slash bed in kg m^{-2} yielding values of Fs after first and second thinnings of 0.66 and 0.73 respectively.

System Effective Ground Pressure

Finally if logging systems are to be evaluated relative to one another there is a need to combine the OEGP of each machine in the system into a System Effective Ground Pressure (SEGP), defined as that nominal ground pressure which when applied to the soil by a twin-axled machine with equally loaded wheels of 1.5 m diameter would produce, after a single pass *on bare soil*, the same maximum depth of ruts as the system under consideration when operating according to a specified logging plan. It is computed two machines at a time in the same way as the EGP for a machine with 3 or more axles is computed. For two machines of operating effective ground pressures OEGP(1) < OEGP(2) their combined SEGP is given by

$$\text{SEGP} = \text{OEGP}(2) \times F \quad (14)$$

where F is the same function defined above in Eqn. 8 but with D_1/D_2 set to unity.

METHODS

Evaluation of Logging Machines and Systems

The basic data required to evaluate EGP's of machines was compiled from machine specification sheets for each machine and field measurements of wheel dimensions. In the case of tracked machines another factor which was computed to give an indication of their relative impact on soils was their steer ratio (the ratio of the ground contact length to width of a machine). Machines with a low steer ratio turn more easily and consequently disturb the soil less [1].

When calculating the EGP's of forwarders, it was assumed that the total log load is borne by the rear axles of forwarders, whereas previous work has indicated that there can be a transfer of 6% - 10% to the front axle. In winter, tracks are also fitted to forwarders which can lead to reductions in effective ground pressures of the order of 25%, but this has recently been discouraged because of the adverse effect of tracks on logging roads. Therefore all calculations have assumed no tracks are fitted.

Statistics of Variation in Soil-Bearing Capacity

In a previous study [7], a simulation model of the soil moisture variation in the region was developed and calibrated against 5 years of soil moisture observations. This allowed the statistics of the soil moisture variation at a series of representative sites to be determined from a 100 year rainfall record input into the model .

At each representative site, the relationship between the soil strength (cone index) and soil moisture was also determined during drainage. Trials were also conducted relating the rate of rut development by forwarders to the soil strength measured with a penetrometer, and these confirmed the applicability of Eqn. 3 to the sites of interest, provided it was assumed there was a 20% reduction in soil strength consequent to trafficking.

RESULTS

Machine Effective Ground Pressures

The NGP's calculated from the machine specification data and derived EGP's and OEGP's of all the machines of interest appear in Table 1, Table 2 and Table 3. When evaluating the various harvesting systems (as distinct from a logging system which includes a forwarder) currently in use, OEGP's of the feller bunchers were calculated assuming both bunching (Fn=1.4) and no bunching of trees (Fn=1.0).

Sometimes the harvesting operation is separated from the forwarding operation and forwarders are interchanged. Owing to this problem and the dominance of the forwarder impacts on the soil, a harvesting SEGP is evaluated separately from the forwarding and total logging SEGP's (Table 4).

Table 1. Forwarder specifications relevant to determining their impact on soils with no slash bed laid when working 250 m and 1000 m from roadside.

Machine	Weight	Load	NGP Front	NGP Rear	EGP	Fn 1000/ 250 m	OEG 1000/ 250 m
	(kg)	(kg)	(kPa)	(kPa)	(kPa)	—	(kPa)
Kockums 85-33	17500	12000	74	155	157	1.5/1.2	242/186
(H.Flot.Tires)	17500	12000	43	108	110	1.5/1.2	169/130
(dual tires)	17500	12000	43	78	80	1.5/1.2	123/95
Kockums 85-35	18500	12000	75	168	170	1.5/1.2	262/201
(H.Flot.Tires)	18500	12000	44	118	120	1.5/1.2	185/142
Kockums 85-35 (Korns mach.)	18500	12000	75	162	164	1.5/1.2	252/194
Valmet 892	15000	14000	71	144	145	1.5/1.2	218/168
(H.Flot.Tires)	15000	14000	40	113	114	1.5/1.2	172/132
OSA 280	15700	18000	82	180	181	1.4/1.1	260/200
(wider tires)	15700	18000	68	142	143	1.4/1.1	206/158
OSA 260	14500	12000	83	126	129	1.5/1.2	198/152
OSA 250	10700	11000	64	95	97	1.6/1.2	154/118

Table 2. Specifications of wheeled processors, harvesters and feller bunchers relevant to determining their impact on soils when no slash bed is laid.

Machine	Weight (kg)	NGP Front (kPa)	NGP Rear (kPa)	EGP (kPa)
Low Ground Pressure Systems				
Valmet 901 Harvester (wide tires)	11000	55	52	54
FMG 990 Harvester	13000	53	46	56
Valmet 901 Harvester	11000	67	63	66
Intermediate Ground Pressure Machines				
Kockums 85-41 Logma Boom DL	22000	77	52(2)*	71
Kockums 880 F/Buncher	15500	58	87	78
OSA 706-250 Twin Gp. Harv.	16100	47(2)	79	80
OSA 707-250 Twin Gp. Harv.	16620	50(2)	80	81
Valmet 902 Twin Gp. Harv.	18000	57(2)	83	85
High Ground Pressure Machines				
OSA 706-260 Twin Gp. Harv.	19800	71(2)	94	98
OSA Helgum Boom Belimber	28000	105(2)	160	163

* (2) implies dual axles

Strength of Soils and Level of Disruptions to Operations

The number of days soil strengths would be expected to fall below a given threshold is given in Table 6. These data were obtained for areas where the annual rainfall is 1150 mm. There is a +/- 20% variation in annual mean rainfall across the region of interest which can change the number of days a given soil strength threshold is exceeded when soil moisture is elevated, by up to 50%. There are errors associated with the measurement of soil water and

Table 3. Specifications of tracked processors and feller bunchers relevant to determining their impact on soils when no slash bed is laid.

Machine	Wt. (kg)	NGP (kPa)	MMP/NGP —	EGP (kPa)	Steer Ratio —
Waratah on Cat E200b Processor	22000	51	3.0	67	1.35
Koering 618 Processor	28000	62	2.3	58	1.23
Cat 219 Feller Buncher	21000	60	1.95	45	1.10
Denis LS2800DL Processor	27000	65	2.1	55	1.21
Timbco Feller Buncher	29000	70	2.0	56	1.23
Catma Boom Delimber	26000	70	1.85	53	1.20

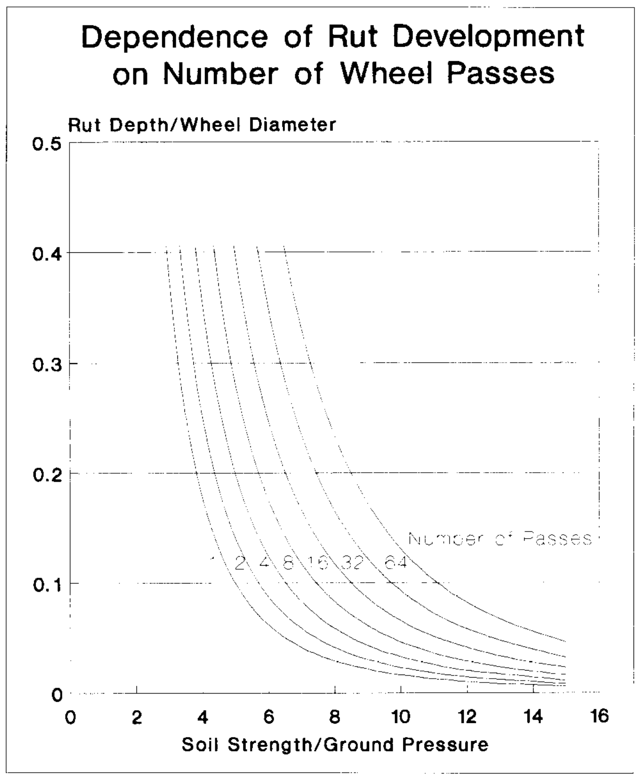

Figure 1. Increase in rut depth (expressed in terms of the ratio of rut depth to wheel diameter) with the number of wheel passes.

Table 4. Harvesting System Effective Ground Pressures incorporating the effects of the processor/harvester operating on a slash bed from first and second thinnings and on bare soil respectively. Order of listing is increasing harvesting SEGP's.

Harvesting System Fel/B	Proc/Harv	Fel/B OEGP (kPa)	Proc/Harv OEGP T1/T2/BS* (kPa)	Har.Sys. SEGP T1/T2/BS* (kPa)
—	Val 901	—	36/40/54	36/40/54
—	FMG 990(WT)	—	37/40/56	37/40/56
—	Val 901	—	44/48/66	44/48/66
—	Wtr-CatE200	—	45/49/67	45/49/67
Cat219	Catma B.Del	45/63	35/39/53	48/48/57
Cat219	Lgma B.Del.	45/63	47/52/71	53/56/72
—	OSA 706-250	—	53/59/81	53/59/81
—	OSA 707-250	—	54/59/81	54/59/81
Timbco	Val 901	56/78	36/40/54	57/58/63
—	Val 902	—	57/62/85	57/62/85
Timbco	Koer B.Del.	56/78	41/46/58	58/59/64
Timbco	OSA 706-250	56/78	53/60/80	62/66/83
Timbco	OSA 706-260	56/78	66/73/98	72/78/99
Koc880	Denis B.Del.	88/106	37/40/55	88/88/90
Koc880	Lgma B.Del.	88/106	47/52/71	89/90/93
Koc880	OSA Hlgm.	88/106	107/118/163	112/124/164

* Denotes SEGP for machines operating on a slash bed from first thinnings (T1), second thinnings (T2), and on bare soil (BS) with no bunching.

soil strength when determining the threshold levels, but these are relatively small, amounting to +/- 50 kPa [7].

With the assistance of Figure 1, the data given in Table 6 have been transformed into Table 7, giving the expected level of disruption to a logging or harvesting operation of given SEGP's under the constraints of minimal impact on soils (rut depth < 50 mm - RCI/NGP = 7.0) and tolerable impact (rut depth <150 mm - RCI/NGP = 4.5) on soils. Comparison between a systems SEGP and these data gives an indication of the viability of any particular logging system to operate under the given environmental constraints.

DISCUSSION

Harvesting Systems

It is conceivable that errors appear in the manufacturer's specifications of ground pressures. Assuming an error of 10% in the specified ground pressures of one machine in a harvesting system leads to a variable error in the calculated SEGP depending on the relative ground pressures of the machines making up the system and which machines operate on a slash bed. Reference to Fig. 2 indicates that the propagating of such an error through the calculations would generally result in a substantially smaller error in the calculated SEGP. The exception would be if such an error occurs for a high ground pressure feller buncher operating on no slash bed or in the case of a single harvester. However, the resulting error in the calculated SEGP would still be no greater than 10%.

Calculation of the EGP's of the tracked machines, taking into account the track design and associated pressure variations along it, resulted almost in a complete reversal in the sequence of their listing according to the relative magnitude of their NGP's, indicating that NGP's given in the manufacturer's literature are not a good indicator of the relative impact on soils of tracked machines. An outstanding machine is the Cat 219 feller buncher which has a very low EGP and a steer ratio of only 1.1. Of some concern is the Cat E200b machine which, while having the lowest NGP, has the largest EGP because of its small diameter and widely spaced road wheels relative to the track pitch.

The harvesting systems with minimal potential impact on soils are the single grip harvesters (Valmet 901, Waratah on CatE200, the FMG 990) with SEGP's less than 50 kPa when operating on a slash bed. These single grip harvesters operate best on small trees and are generally confined to first thinning operations.

Harvesting systems should be managed to produce minimal impact on soils, because it is the general experience of the contractors that if the system disturbs the soil excessively during very wet weather, the ruts so caused accumulate water and make forwarding operations virtually impossible until the soils have dried. Comparison between the data in Table 4 and Table 7 indicates that providing an even slash is laid, these single grip machines can work with minimal impact on all soils in the region irrespective of weather conditions. This is consistent with recent experience.

Harvesting systems with intermediate ground pressures and impacts are those with EGP's in the

Table 5. Minimum total logging system effective ground pressures incorporating the effect of logging 250m from roadside and the effects of operations on a bed of slash. The three SEGP's given are for harvesting machines and forwarders operating on an evenly distributed first and second thinnings slash bed and bare soil respectively. The systems are listed in increasing logging system SEGP.

Fel/B.	Logging System Proc/Harv.	Forwarder	Harv. Sys. SEGP T1/T2/BS* (kPa)	Forwarding SEGP 250 m Track T1/T2/BS* (kPa)	Logging Sys. SEGP 250 m Track T1/T2/BS* (kPa)
—	Val 901(WT)	OSA 250	44/48/66	79/87/118	80/88/120
—	Val 902	Koc 85-33**	57/62/85	87/95/130	88/97/133
Cat219	Catma	Val 892**	48/48/57	88/97/132	89/98/133
Koc880	Lgma B.Del.	Koc 85-33**	89/90/93	87/95/130	100/106/134
—	OSA 707-250	OSA 260	54/59/81	101/111/152	101/111/152
—	FMG 990	OSA 280***	37/40/56	106/116/158	106/116/159
Timbco	OSA 706-250	OSA 280***	62/66/83	106/116/158	107/117/160
Timbco	OSA 706-260	OSA 280***	72/78/99	106/116/158	108/119/161
—	Wtr-Cat E200	Val 892	45/49/67	112/123/168	112/123/168
Cat219	Lgma B.Del.	Koc 85-33	53/56/72	124/137/186	124/137/186
Koc880	Lgma B.Del.	Koc 85-33	89/90/93	124/137/186	128/139/187
—	Val 901	OSA 280	36/40/54	133/147/200	133/147/200
—	OSA 706-250	Koc 85-35	53/59/81	134/148/202	135/148/202
Timbco	Val 901	Koc 85-35	36/40/54	134/148/202	134/148/202
Timbco	Koer.B.Del.	Koc 85-35	41/46/58	134/148/202	134/148/202
Koc880	OSA Hlgm.	Koc 85-33	112/124/164	124/137/186	136/150/202
Koc880	Denis B.Del.	Koc 85-35	88/88/90	134/148/202	137/150/202

* Denotes SEGP for machines operating on a slash bed from first thinnings(T1), second thinnings (T2) and on bare soil (BS).
** Wide high flotation tires fitted
*** Wide tires are fitted.

Table 6. Number of days in any year and number of days in July (95% probable) that soil strengths (penetration resistance) would be expected to fall below a given threshold at one of the worst (Esplanade Rd.) and best (Wondalga Rd.) drained sites in the Greenhills Forest near Tumut, NSW.

No of days in a year	No of days in July	Soil strength threshold at Esplanade Rd. (kPa)	Soil strength threshold at Wondalaga Rd. (kPa)
6	2	800	1200
33	8	900	1320
115	25	1000	1450

50-70 kPa range. These systems include the OSA 706-250, OSA 707-250 and Valmet 902 twin-grip harvesters and the tracked Catma and the Koering boom delimbers and the Logma boom delimber coupled with tracked feller bunchers. These systems can handle the larger trees of second and subsequent thinnings but can experience difficulty with the larger logs encountered in clearfell operations. Provided an even bed of slash is laid, minimal impact on soils is attained providing the harvesting operation is suspended during and a few hours after rain and for a few of the wettest days each month in mid-winter on the worst drained sites (Table 7). On better drained sites, no disruption to operations is required.

High ground pressure systems (SEGP > 70 kPa) are those incorporating the Denis and Kockums Logma boom delimbers in conjunction with the high ground pressure Kockums 880 feller buncher, the OSA 706-260 harvester and the OSA Helgum boom delimber. These systems can handle large logs and usually work in second thinnings. Providing an even bed of slash is laid, minimal impact by these systems is obtained providing operations are suspended when it rains and for 2-8 of the wettest days per month in mid-winter on the worst draining sites. On better drained sites, operations should also be suspended during heavy rain, but providing a slash bed is laid, minimal impacts can be achieved with no more than a few days disruption in any month.

It is evident that the choice of the feller buncher has a significant influence on the system SEGP because this machine cannot operate on a slash bed (Tables 3 &4). Accordingly on sensitive sites, tracked feller bunchers of low EGP or a harvester should be used whenever possible. Unless the Kockums 880 feller buncher is fitted with much wider tires, there is a case for this machine to be removed from the harvesting operation in winter because of its relatively high impact on the soil.

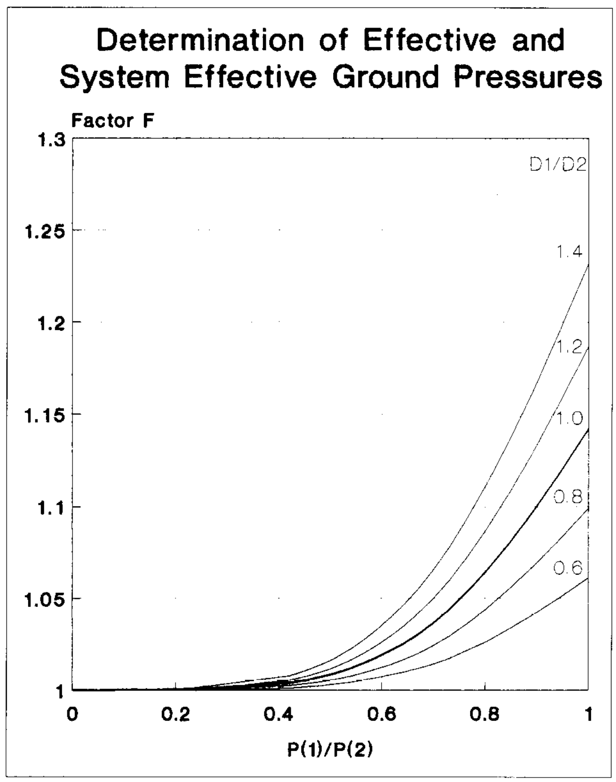

Figure 2. Plot of the factor F as a function of the ratios of the nominal ground pressures (P_1/P_2) and respective wheel diameters (D_1/D_2)

Table 7. Maximum System Ground Pressures required for a given level of disruption to operations under the constraints a) that a rut depth of 150 mm must not be exceeded and b) minimal impact i.e. rut depth < 50 mm. A loss in strength during trafficking of 20% has been assumed in the transformation of the data from Table 6.

Level of Disruption	None	2 days in July	8 days in July	25 days in July
Maximum SEGP (kPa) Poorly drained sites	72[a]/47[b]	140/91	160/104	180/117
Maximum SEGP (kPa) Well-drained sites	132/86	212/138	236/153	260/169

Forwarders

The data in Table 1 indicate two general trends. One is that the more modern a machine, the greater the ratio of the payload to gross weight. The other is that the greater the gross weight of the machine, the greater its ground pressure. Particularly efficient machines in terms of the ratio of their payload to gross weight are OSA 280 and OSA 250 machines with payload to gross weight ratios exceeding 0.5, followed by the Valmet 892, the OSA 260 and the Kockums machines. Lowest ground pressures are applied by the OSA 250 and OSA 260 machines while the highest ground pressures were applied by the OSA 280 forwarder. The fitting of wide, high flotation tires reduced nominal ground pressures by about 30%.

The impact on soils of all the logging systems shown in Table 5 tends to be dominated by the impact of the forwarder, even when the distance from roadside the forest is logged is reduced to 250 m. The main exception is when a forwarder fitted with high flotation tires operates on a slash bed in conjunction with a harvesting system of high SEGP, e.g. harvesting systems which include a Kockum's 880 feller buncher.

Operations on Poorly Drained Sites

Reference to Table 5 and Table 6 indicates that if a slash bed is laid, only forwarders fitted with dual tires, or possibly an OSA 250 forwarder, would be able to operate on a continuous basis up to 1 km from roadside on these sites.

If operations are suspended while the soils are saturated and for a few hours while the soils drain to moisture levels approaching field capacity (field capacity values are elevated on these sites due to drainage impediments at shallow depths), then all forwarders fitted with wide or high flotation tires could operate continuously within the given constraints. Those fitted with standard tires would lose about 10% of working days.

With no even slash bed, several days disruption per month can be expected for machines fitted with wide or high flotation tires. If standard tires are fitted, then the level of disruption is so high operations on such sites are not feasible.

Operations on Well-Drained Sites

Providing operations proceed on a thick slash bed, all forwarders fitted with wide or high flotation tires can operate on a continuous basis provided the distance from roadside the forest is logged is reduced to 250 m. If operations are suspended while these soils are saturated during heavy rain, and a slash bed is laid, then all machines would be able to operate up to 1 km from roadside with disruptions of no more than 2-3 days/month.

GENERAL CONCLUSION

The importance of the slash bed is obvious, especially for the poorly drained sites. Without it, the level of disruption is so great that forwarders with conventional tires could not operate at all on the worst drained sites. Even when fitted with high flotation tires, the level of disruption is such that 25% of working days would be lost during the winter period.

Some contractors are proposing to fit wide tires to the processors. If the machine operates on a slash bed, it can be seen (Table 4) that this will be of little benefit as the soil disturbance in such cases tends to be dominated by the feller buncher. No significant advantage could be expected if wider tires are fitted to harvesters, for in general the impact on the soil by the forwarder tends to dominate. One possible exception is in situations where the forwarder does not follow the harvester immediately. Then a reduced impact by the harvester may lead to a lower loss in soil strength should rain fall between the harvesting and forwarding operations, due to moisture retention and accumulation in the harvester's ruts.

This method of evaluating logging systems can be used in an inverse sense to quantify the bearing capacity of soils. If a machine's or a system's impact on soils is measured and the effective ground pressure of the machine or system has been quantified, then it is possible, using Figure 1, to determine the strength of the soil. If such observations are related to soil-moisture conditions obtained from an appropriately transformed rainfall record and the statistics of the soil-moisture variation are also determined, then a table showing expected levels of disruption to operations can be obtained (similar to Table 6 herein) which can then be used to assess the viability of other machines or logging systems. Such information has proved to be of great assistance to the effective management and selection of logging systems of minimal environmental impact in the Albury region. Until recently, constraints on operations during winter required the stockpiling of one month's wood supply (40,000 tonnes) in the forest over a period of 2-3 months, in order to ensure a continuous wood supply for the mill. Application of this methodology has resulted in better choices of machines and running gear leading to reduced down times, halving of the stockpiles and a reduction in capital costs of in excess of 10%. The reduction in stockpiling has also led to wood of better quality reaching the mill, which in turn has led to other substantial indirect savings [7].

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