MANAGING SOIL COMPACTION TO ENSURE LONG-TERM SITE PRODUCTIVITY IN SOUTH AFRICAN FOREST PLANTATIONS

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Abstract

The widespread use of mechanical harvesting machinery during clear-felling operations in South African forest plantations has led to concern about potential effects on long-term site productivity. This paper outlines the results from a series of long-term field trials examining the effect of harvesting operations on tree growth and presents an approach to managing the effects of soil compaction and disturbance in a forest plantation context. In addition, a series of ratings are presented based on the susceptibility of South African forestry soils to compaction, hardsetting and erosion. These ratings are related to soil physical properties and the current South African soil classification system. By combining this information, a tentative evaluation of vehicle risk assessment is presented based on soil, seasonal and vehicle characteristics.

Keywords: soil compaction, forest plantations, soil sensitivity, sustainability, site productivity, soil management

Introduction

A principal objective of the South African timber industry is to optimise timber yield at minimum cost by effective utilisation of resources, coupled with minimal environmental impact whilst ensuring sustainability. Harvesting planners, foresters and contractors are faced with a difficult task: balancing the need to maintain high levels of productivity and to keep costs down whilst avoiding environmental damage and ensuring future site productivity. Long-term site sustainability studies in forestry are scarce (Evans, 1999) with few guidelines existing on appropriate management of timber harvesting operations. A great deal of uncertainty prevails concerning the effects of soil compaction on site productivity of commercial forests in South Africa and overseas. This is due in part to the lack of long term growth studies, the complicating effects of previous management operations in retrospective studies (Burger and Powers, 1991), and the modifying effects of residual tree roots from previous rotations (Nambiar and Sands, 1992). Past recommendations on identification and management of sensitive forestry soils in South Africa (Grey *et al.,* 1987) have depended to a large extent on the extrapolation of information from studies elsewhere in South Africa carried out under very different environmental and land use conditions.

Conditions in South African forest plantations are conducive to long-term damage since there is no natural alleviation of compaction in time: soils are predominantly kaolinitic, do not swell and shrink, and do not freeze and thaw. Once compacted, certain soils may remain so for decades or even longer (Jakobsen, 1983; Murphy, 1984). Moreover, axle loads are frequently high (>5 tons per axle), which may lead to considerable subsoil compaction (Soane, 1983).

The objectives of this paper are to show the progress that has been made in the past ten years with regards to evaluating the effects of soil compaction on tree growth and the development of guidelines to manage the problem in a forest plantation context.

Methods

Scope of the study, sites and treatments

Details of the trial sites are included in Table 1. The sites cover a broad range of site types from the warm and cool temperate regions of the KwaZulu-Natal Midlands and Swaziland (altitude 800 to 1500 m) to the sub-tropical growing region of Zululand in north-east KwaZulu-Natal (altitude 40 to 100 m) and the cool temperate year round rainfall region of the southern Cape. The mean annual precipitation (MAP) varies from 800 to 1300 mm in these growing regions with a mean annual temperature ranging between 14.5 and 21.5 °C depending on altitude. Table 2 summarises the treatments tested in each trial.

Site sensitivity classification

Susceptibility to compaction was assessed by both the potential compactibility and compressibility of a soil according to Smith *et al.,* (1997a; 1997b). Compactibility is defined as the maximum bulk density the soil will attain during a standard Proctor Impact Test (American Society for Testing and Materials, 1985). Compressibility refers to the ease with which a soil decreases in volume for an increment of applied pressure at a particular water content (Gupta and Allmaras, 1987). Susceptibility to erosion and hardsetting was drawn up from a variety of sources (e.g. Smith and Norris, 1995) and personal experience.

Vehicle risk assessment

Relationships established between applied load and soil compaction as affected by soil physical properties (Smith *et al.*, 1997a) and by rating the various harvesting extraction operations according to an impact rating allowed the determination of an impact rating for various categories of harvesting extraction operations. This impact rating has been assigned based on a weighting procedure evaluated from a combination of the potential areal extent of a harvesting operation and the maximum potential effect at a point. The weightings utilised were 0.5 for soil compaction and 0.5 for site disturbance. These were multi-

Table 1. Site characteristics of the trials.

Trial	Location	Species	Altitude (m)	Rainfall (MAP) (mm)	Soil form SA*/Soil Taxonomy#	Soil texture A/B horizon	Organic carbon content (%) - A horizon	Bulk density range (Mg m-3)	Age when last measured (yrs)
K1	Shafton KZN Midlands	*E. grandis*	1020	850	Kranskop 1100/Humic Haplustox	Silty clay/Clay	5.8	0.78 - 1.28	7
K2	Highflats KZN Midlands	*E. grandis*	1140	950	Lusiki 1220/Aquic Kanhaplustalf	Loam/Clay loam	2.4	1.18 - 1.64	6
K3	Kwambonambi KZN - Zululand	*E. grandis, E. grandis x camaldulensis & E grandis x urophylla* clonal hybrids	60	1100	Fernwood 1210/ Typic Quartzipsamment	Sand/Sandy loam	0.5	1.48 - 1.64	5
K4	Nseleni KZN - Zululand	*E. grandis, E. grandis x camaldulensis & E grandis x urophylla* clonal hybrids	50	1300	Constantia 2100/ Quartzic Haplustult	Sand/Loamy sand	0.6	1.55 - 1.74	5
K5	Bluelilliesbush Eastern Cape	*P. radiata & P. elliottii*	60	650	Kroonstad/Cartref	Silt loam/silt loam	3	n.d	2
K6	Usutu Forest Swaziland	*P. patula*	1450	850	Magwa/Kranskop	Sandy clay/clay	2.2	n.d	0
K7	Kwambonambi KZN - Zululand	*E. grandis x camaldulensis*	80	1000	Fernwood 1110/ Aquic Quartzipsamment	Sand/Sand	0.3	1.63 - 1.77	2

* Soil Classification Working Group (1991) # Soil Survey Staff (1990) n.d. = not determined

plied by another weighting for each maximum potential impact (from 0.0 to 1.0 incrementally going from very low to very high). Finally, these were multiplied by the percentage of the area impacted (0.0 to 1.0) to obtain a final impact rating. This was then further multiplied by 100 for convenience of expression as a percentage (100 being the maximum).

$$IMPACT = 100 \times (0.5C + 0.5D) \qquad \text{Equation [1]}$$

where C and D are the weightings of potential impact with respect to compaction and erosion respectively.

The advantage of the weighting system is that it is flexible and can be adjusted as new research results become available, and for different species, e.g. where surface disturbance may be more consequential than deep compaction for shallow rooted species. Also the rating allows comparisons in sensitivity between different operations to be expressed numerically and as such can be incorporated into harvesting planning systems.

Results and Discussion

Effect of harvesting operations on tree growth

For convenience, growth loss is presented as the percentage decrease in basal area of the treatment compared to the control. The exception to this is the trial K5 where biomass indices were compared (volume of the stem calculated from ground line diameter and height) (Figure 1). Unfortunately in the trial K5 a fire destroyed several control plots and it was not possible to analyse the results statistically. The results for trial K6 (Swaziland) are omitted since it was only recently re-planted following a fire when the trees were one year old.

Effects of soil compaction on tree growth

- In general, soil compaction/disturbance has resulted in a range of growth responses from a 6% increase to an 21% decrease in growth for *Eucalyptus* spp. and a 47% decrease for *Pinus* spp. depending on site characteristics and age of trees (Figure 1).
- Growth differences between harvesting impact treatments and control on the trial K5 are between 27 and 50% for two *Pinus* spp. depending on level of impact (Figure 1). The results are similar to those for *P. radiata* by Sands and Bowen

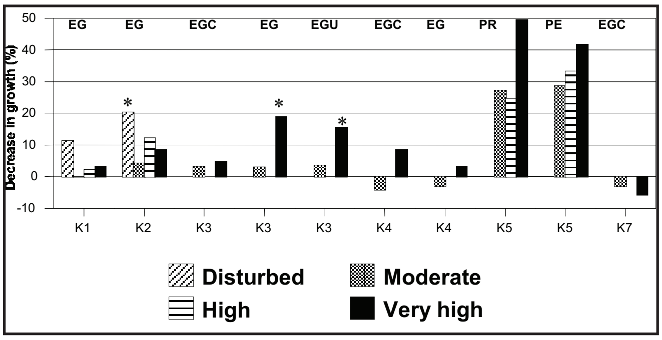

Figure 1. The effect of a range of intensities of harvesting operations (see Table 2) on growth, as expressed by the change in growth of a treatment compared to the control, for six trial sites and a range of plantation tree species in South Africa. EG - *E. grandis;* EGC - *E. grandis* x *camaldulensis*; EGU - *E. grandis* x *urophylla;* PR - *P. radiata*; PE - *P. elliottii*. Asterisks above a growth bar indicate where treatment basal areas were significantly different at the P<0.05 level from the control.

Table 2. Harvesting treatments used in the harvesting impacts trials.

Trial	Location	Treatments	Impact level*
K1	Shafton KZN Midlands	Forwarder extraction (1, 5 and 10 passes)	L - VH
		Tractor/trailer extraction loaded by crane	M
		3-wheel logger/bundler	D
		Manual extraction (control)	O
		High impact corridor (all vehicles)	VH
K2	Highflats KZN Midlands	Forwarder extraction (1, 5 and 10 passes)	L - VH
		Tractor/trailer extraction	M
		Agricultural tractor loaded by 3-wheel logger/bundler	D/M
		Manual extraction (control)	O
K3	Kwambonambi KZN – Zululand	Extraction row – centre	VH
		Extraction row - adjacent to wheel rut	H
		Between extraction rows (no compaction)	O
K4	Nseleni KZN – Zululand	Extraction row – centre	VH
		Extraction row - adjacent to wheel rut	H
		Between extraction rows (no compaction)	O
K5	Bluelilliesbush Eastern Cape	Mechanical felling/grapple extraction	H
		Manual felling/cable extraction (moderate impact)	M
		Minimum impact treatment (control)	O
		Landing decks (very high impact)	VH
K6	Usutu Forest Swaziland	Control where the timber was cut into short 2,4 m lengths and carried off by hand;	O
		Tree-length harvesting by a cable skidder	M
		Tree-length harvesting by a grapple skidder/logger pre-bundling	H
		A combination grapple skidding and extraction of the short-lengths which were stacked adjacent to the control plots and extracted by a timber truck working in-field.	VH
K7	Kwambonambi KZN – Zululand	Felled by 3-wheel logger with harvesting head	D
		Felled by tracked harvester	L
		Manual clearfelling with slash broadcast	O
		Manual clearfelling with slash wind-rowed	O
		5 fertiliser treatments (1) No fertiliser (2) 45g N 18g P (3) 30g N 12g P (4) 45g N 30gP (5) 30g N 20g P	
		Extraction route	VH

* O - No impact; D - considerable surface disturbance; L - low impact; M - moderate impact; H - high impact; VH - very high impact

(1978) and *P. elliottii* reported by Haines *et al.* (1975). Soil damage was extensive in this soil (rutting and smearing) causing excessive waterlogging resulting in poor aeration and nutrient loss.

- The extent of growth reductions appear to be related to the subsoil texture of the 'sandy' Zululand soils and are in the order of 5% and 18% on soils with loamy sand or sandy loam subsoils respectively (Figure 2). A growth increase of 6% was recorded on a Fernwood sand. These results can be explained by a combination of changes in mechanical resistance and AWC (Hill and Sumner, 1967; Smith *et al*., 2001).

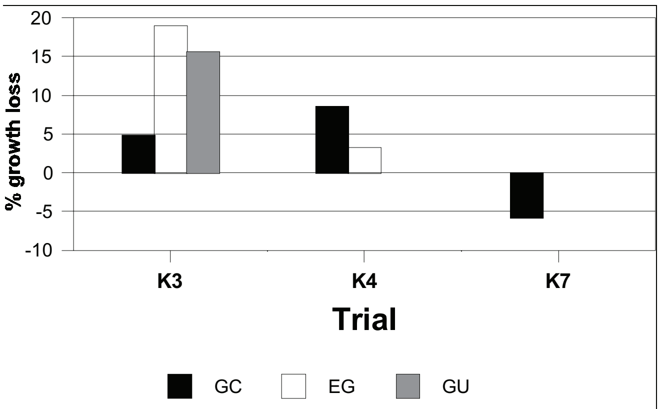

Figure 2. Growth loss (expressed as percentage of basal area) between control, i.e halfway between extraction routes, and centre of extraction route for three trials K3, K4 and K7. EG - *E. grandis*; EGC - *E. grandis* x *camaldulensis*; EGU - *E. grandis* x *urophylla.*

- The results clearly demonstrate that the effects of soil compaction must take into account changes in the entire range of soil physical properties (Gupta and Allmaras, 1987) e.g. mechanical impedance, available water capacity and soil aeration.
- Effects of harvesting impacts were greatest on soils exhibiting poor aeration following compaction rather than those developing high soil strength.
- The lack of major growth decreases of *Eucalyptus* spp. following substantial compaction and disturbance in some cases can be attributed to the good physical condition of soils in forest plantations and perforation of compacted soils by root channels from previous rotations (e.g. Nambiar and Sands, 1992).
- The effect of soil compaction on tree growth depended on soil texture and depth. The greatest negative effect on tree growth occurred on silt loam soils and a slightly positive effect occurred on very sandy soils.
- The effects of soil disturbance, e.g. rutting, loosening and compaction in close proximity caused by logger operations, have had a greater affect on growth than operations causing deep compaction. This suggests that key growth processes, such as fine root development and nutrient cycling in the topsoil, have been affected.

Implications for forest management

- The extent to which these losses are translated on major site productivity decline will depend on the areal extent of the harvesting operation. For example, a 40% growth loss over 10% of the area is very small compared to a 20% growth loss over 80% of the area, which is considerable.
- The preceding two points mean that extensive operations, for example logger bundling and loading operations in field or wheeled tree to tree felling operations preceding skidding, are very high impact operations.
- Cumulative effects of site damage are unknown and will be difficult to detect without multi-rotational trials being established.

Soil sensitivity to compaction, hardsetting and erosion

Soil sensitivity has been presented in Table 3 with regard to compaction risk, erosion hazard, and potential for hardsetting behaviour. Altogether, eight soil groupings have been identified according to particular soil physical behaviour. Soils within the group are differentiated on the basis of texture or other attributes related to soil form and family definitions of the South African soil taxonomic classification system (Soil Classification Working Group, 1991). This sensitivity classification has been compiled from work linking compressibility and compactibility characteristics of soils in forest plantations to soil physical properties (Smith *et a*l., 1997a and 1997b).

It is noticeable that the current soil classification system at the soil form level only coarsely differentiates between the various soil sensitivities. Ratings vary more within soil forms, due to changes in soil texture, than between soil forms. From a forestry plantation management perspective more emphasis should be placed on soil texture, organic carbon content and soil depth than soil form alone.

Vehicle risk assessment

Table 4 outlines a generalised impact rating for many combinations of harvesting operations and attaches a further risk scenario with respect to a combination of season and soils. The list is not prescriptive or definitive, but is a tentative classification of harvesting operations with respect to impact to assist the harvesting forester and strategic planner with tools to reduce site damage and protect long-term sustainability. Table 4 therefore allows the determination of the potential risk of site damage for different seasons (or water contents), vehicle categories (reflecting different applied loads) and soil properties to be ascertained. For example, most of the soils in categories 3, 4 and 5 (i.e. sandy clays, sandy clay loams and clay loams) are very sensitive to soil compaction when wet under moderate loads and are therefore darkly shaded to indicate a severe risk of site damage. Sandy soils on the other hand, which are only sensitive to moderate compaction across a wide range of water contents when subject to heavy applied loads, are shaded lightly to indicate a moderate risk of site damage when subject to those vehicle categories at the water contents indicated.

In Table 4 the dark shading indicates a high risk of soil compaction and site damage if the chosen operation is carried out on that soil in that season. The light shading indicates the potential of a moderate risk of soil compaction and site damage. This information can be used to determine the relative risk of site damage occurring with a combination of vehicle and site factors. Using this information, managers can weigh up the relative risks involved and are given choices with respect to vehicle, season and soil in order to reduce soil compaction and site damage which can result in long-term site productivity declines.

Conclusions

The lack of major growth decreases of *Eucalyptus* spp. can be attributed to inherent low bulk densities due to high topsoil organic carbon contents of the soils in the trials which are typical of freely drained soils in many South African forest plantations. Negative effects of compaction on root development may be offset by perforation of compacted soils by root channels from previous rotations and by root systems gradually overcoming compacted zones. It was apparent that negative effects of soil compaction were greatest for *Pinus* spp. which have shallow root systems and on more poorly aerated soils rather than on those which developed high levels of soil strength. A major problem when addressing long-term affects of site damage is that cumulative effects of site damage are unknown and will be difficult to detect without multi-rotational trials being established. A factor hindering the development of practical indicators for sustainable soil management is the lack of information on factors which drive forest productivity, and the complex interplay between these factors and soils.

This document has presented the latest information regarding the potential effects of harvesting operations on long-term site productivity in forest plantations. The results to date indicate wide-ranging effects of site damage on tree growth depending upon harvesting operation, soil type and species. By combining the results from field trials regarding the effects of soil compaction on soil physical properties and tree growth with a vehicle risk assessment and soil sensitivity index, information presented in this paper provides a background for management of forest plantations to sustain plantation productivity within the demands of the forest certification process.

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Table 3. A sensitivity index based on soil physical properties of South African forestry soils.

Soil Forms	Soil texture in A Horizon	Risk Assessment		
		Compaction susceptibility[a]	Erosion Hazard [a]	Hardsetting [b]
1. HUMIC SOILS				
Kranskop Inanda Maqwa Nomanci	SL	low-moderate	moderate	-
	L SiCL SiL	moderate-high	moderate	-
	SC SCL	high	moderate	-
	CL C(1)#	moderate-high	low-moderate	-
	SiC C(2)#	low-moderate	low	-
Sweetwater Lusiki	SL	low	moderate	-
	L SiCL SiL	moderate	moderate-high	-
	SC SCL	high	high	-
	CL C(1)#	high	moderate	-
	SiC C(2)#	moderate	moderate	-
# Cl(1) Clay soils with <75% clay plus silt. Cl(2) Clay soils with >75% clay plus silt. $ If topsoil is grey then permeability willbe one grade less.				
2. ORTHIC A / APEDAL B OR NEOCUTANIC B[+]				
Hutton Clovelly Griffin Glencoe * Bainsvlei * Avalon Pinedene * Bloemdal * Oakleaf Tukulu *	SL	moderate-high	high	H
	L SiClL SiL	high	moderate-high	PH
	SC SCL	very high	very high	PH
	CL C(1)#	moderate	high	
	SCl Cl(2)#	low - moderate	moderate	
+ For soils of these forms less than 60 cm in depth the sensitivity index should be increased by 1 grade, e.g. "low" becomes "moderate". * These soils have a permeability 1 to 2 gradesLESS than indicated and an erosion hazard 1 MORE grade than indicated. # Cl(1) Clay soils with <75% clay plus silt. Cl(2) Clay soils with >75% clay plus silt. $ If topsoil is grey then permeability will be one grade less.				
3. ORTHIC A / ROCK OR LITHOCUTANIC B OR HARD PLINTHIC B				
Mispah Glenrosa Dresden	SL	moderate-high	very high	H
	L SiCL SiL	very-high	high	PH
	SC SCL	high	high	H
	CL C(1)#	high	moderate-high	PH
	SiC C(2)#	moderate-high	moderate	-
4. REGIC SAND AND STRATIFIED ALLUVIUM				
Namib	S	low-moderate	moderate-high	-
	LS	moderate	high	-
Dundee	L SCL	high	very high	-
5. ORTHIC A / E HORIZONS				
Cartref Longlands Wasbank Kroonstad Klapmuts Estcourt	S LS	moderate	high	PH
	SL	high	very high	H
	L SiL SiCL	very high	very high	H
	SC CL SCL	high	high	H

Vilafontes Constantia	S LS	moderate	moderate	-
	SL	high	high	PH
	L SL SCL	very high	high	PH
	SC CLS CL	high	moderate	PH
Fernwood	S LS	low-moderate	moderate	-
	SL	moderate-high	moderate-high	PH
# Cl(1) Clay soils with <75% clay plus silt. Cl(2) Clay soils with >75% clay plus silt.				
6. ORTHIC A / PEDOCUTANIC B				
Swartland Sepane	SL	moderate	High	PH
	L SCL SiC	high	High	PH
	SCL SCL	very high	High	PH
	CL C(1)#	high	moderate-high	-
	SC C(2)#	moderate-high	Moderate	-
7. MELANIC SOILS AND ORTHIC A / RED STRUCTURED B*				
Bonheim Mayo Milkwood	n/a	low	low – moderate	-
Willowbrook Inhoek	n/a	low	moderate-high	-
Shortlands	n/a	low	low-moderate	-
8. ORTHIC A / GLEY OR SOFT PLINTHIC B OR PRISMACUTANIC B*				
Katspruit Westleigh Sterkspruit	n/a	very high	very high	-
9. ORGANIC SOILS *				
Champagne	n/a	high	High	-

\# Cl(1) Clay soils with <75% clay plus silt.
Cl(2) Clay soils with >75% clay plus silt.
$ If topsoil is grey then permeability will be one grade less.
* These soils are normally not recommended for commercial afforestation.
n/a not applicable

Table 4. Site damage impact ratings for a range of harvesting operations depending upon season and sensitivity.

HARVESTING OPERATION				SITE DAMAGE RISK ASSESSMENT (For classes see Table 1)											
Felling	Loading	Extraction	Impact rating	Summer / wet site (OCT to MAR)						Winter / dry site (APR - SEPT)					
Manual	-	Chutes	0	1	2	3	4	5	6	1	2	3	4	5	6
Manual	-	Standing skyline	0	1	2	3	4	5	6	1	2	3	4	5	6
Manual	-	Manual	0	1	2	3	4	5	6	1	2	3	4	5	6
Manual	-	Highlead	2	1	2	3	4	5	6	1	2	3	4	5	6
Manual	-	Running skyline	4	1	2	3	4	5	6	1	2	3	4	5	6
Manual	-	Ground lead	5	1	2	3	4	5	6	1	2	3	4	5	6
Manual	-	Mules/horses	8	1	2	3	4	5	6	1	2	3	4	5	6
Manual	Crane/manual	Tractor-trailer	11	1	2	3	4	5	6	1	2	3	4	5	6
Manual	Logger	Tractor-trailer	44	1	2	3	4	5	6	1	2	3	4	5	6
Manual	Crane	Hauler	13	1	2	3	4	5	6	1	2	3	4	5	6
Manual	Flexi	Timber trucks	15	1	2	3	4	5	6	1	2	3	4	5	6
Manual	Logger	Timber trucks	56	1	2	3	4	5	6	1	2	3	4	5	6
Manual	-	Skidder (AT)	15	1	2	3	4	5	6	1	2	3	4	5	6
Manual	-	Skidder (C)	20	2	3	4	5	6	6	1	2	3	4	5	6
Manual	3W logger bundling	Skidder (G)	45	1	2	3	4	5	6	1	2	3	4	5	6
Harvester (TR-SB)	Crane/manual	Tractor trailer	13	1	2	3	4	5	6	1	2	3	4	5	6
Harvester (TR-SB)	Logger	Tractor trailer	47	1	2	3	4	5	6	1	2	3	4	5	6
Harvester (TR-SB)	Crane	Hauler	15	1	2	3	4	5	6	1	2	3	4	5	6
Harvester (TR-SB)	Logger	Timber trucks	58	1	2	3	4	5	6	1	2	3	4	5	6
Harvester (TR-SB)	-	Skidder (AT)	17	1	2	3	4	5	6	1	2	3	4	5	6
Harvester (TR-SB)	-	Skidder (W)	22	1	2	3	4	5	6	1	2	3	4	5	6
Harvester (TR-SB)	Logger bundling	Skidder (G)	47	1	2	3	4	5	6	1	2	3	4	5	6
Feller/buncher	Crane/manual	Tractor trailer	67	1	2	3	4	5	6	1	2	3	4	5	6
Feller/buncher	3W logger	Tractor trailer	84	1	2	3	4	5	6	1	2	3	4	5	6
Feller/buncher	Crane	Hauler	74	1	2	3	4	5	6	1	2	3	4	5	6
Feller/buncher	Logger	Timber trucks	88	1	2	3	4	5	6	1	2	3	4	5	6
Feller/buncher	-	Skidder (AT)	40	1	2	3	4	5	6	1	2	3	4	5	6
Feller/buncher	-	Skidder (W)	50	1	2	3	4	5	6	1	2	3	4	5	6

Notes: Dark shading: High risk, logging not recommended - move operations to other soil or season

Light shading: Moderate risk, caution required - if possible move operations to other soil or season

Abbreviations: Harvester (TR - SW) - tracked harvester with slew/swing boom

Skidder (AT) - agricultural tractor Skidder (C) - Cable skidder Skidder (G) - Grapple skidder