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Guidelines for difficult terrain ground based harvesting operations in South Africa

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Introduction

Steep slope harvesting can be described as the felling, processing and extraction of trees on steep terrain that is beyond the traditional boundaries of ground based systems. Harvesting steep slopes is more difficult and expensive than harvesting flatter terrain, and the potential for environmental damage is greater (Krag and Webb, 1987). There is a lack of knowledge, both in South Africa and abroad, on the restrictions of harvesting equipment in terms of terrain limitations and the combination of machines that make up systems when harvesting trees left on steep pockets and difficult terrain conditions. MacDonald (1999) indicates that the two most important tasks faced by harvesting foresters and contractors are selecting the equipment and systems best suited to the site, and then to use this equipment in the best way possible.

However, slope is not the only factor which can make terrain deemed to be difficult. Soil condition, soil moisture, soil depth, ground roughness (usually rocks) and stumps can also contribute towards limiting machine movement over a site. These all need to be considered along with tree size, tree species, market specifications, weather conditions (e.g. rain and mist) (AFAG, 2006) and operator skills.

Terrain has the greatest influence on system selection, with slope being the most important (MacDonald, 1999). Gentle terrain provides the most system options, and as terrain becomes increasingly difficult, so the options reduce (Parker and Bowers, 2006). Slope is usually the primary factor that determines whether a cable yarding or ground based system is selected. In harvesting operations, steep slopes have traditionally been considered being above 30 to 35% (Krag *et al.*, 1991). Excessive ground roughness can also greatly influence machines and systems. Ground roughness in South Africa, as defined by the National Terrain Classification system (Erasmus, 1994), refers to the presence, height, proximity to each other and quantity of rocks and depressions. Large stumps also affect machines in the same manner as rocks. Terrain also determines the type of ground based systems that will be used. Even though ground based harvesting in the past has been associated with excessive ground disturbance on steeper slopes, the equipment and techniques available today are able to reduce machine ground pressures and reduce disturbances (Kosicki, 2003).

Steep pockets of trees can be described as standing timber, usually found on steep inaccessible areas, left behind after the existing ground based harvesting system has finished felling the compartment. This can often be linked to the difficult ground conditions and excessive ground roughness when harvesting steep areas using ground based harvesting equipment, and to planning deficiencies, incorrect equipment selection, and the high costs of harvesting these areas.

Comprehensive planning is required for proper system selection for difficult terrain conditions, and to determine exactly where the systems and machines will work, including innovative techniques to harvest areas beyond the normal machine limitations. All harvesting systems have to be cost effective, safe and environmentally acceptable.

Although cable yarding and aerial logging systems are still used today to harvest trees in steep pockets and difficult terrain, the evolution of ground based equipment over the last few years has made the use of this machinery feasible on terrain previously considered unsuitable. This is apparent by the development of ground based harvesting systems, which are normally more cost effective than cable and aerial harvesting systems.

In the report much of the focus is on using ground based systems to harvest the steep and difficult areas, but it cannot be expected that ground based systems will be capable of harvesting all difficult terrain. When ground based equipment operates above its design limits, machine stability decreases and traction is reduced. Safety risks can also become unacceptably high. Cable yarding will still have a key role to play. Furthermore, certain new innovative cable yarding systems might even extend into some of the areas traditionally reserved for ground based systems. The ultimate aim must be the selection and professional implementation of the system most suited to the given conditions. “Most suited” is defined as meeting economic, social, environmental and silvicultural goals. As with any harvesting operation, the first consideration on difficult terrain must always be safety (FAO, 1996).

The main objective of the literature review is to determine which ground-based harvesting systems are available internationally to address the challenge of steep slope harvesting, as well as the methods and equipment available. The research attempts to identify the problem areas restricting harvesting equipment; and to identify the best operating practices for difficult terrain harvesting that could be applicable to South African conditions. The information contained in this report was obtained by literature searches, interviews with experts and surveys.

Harvesting on difficult terrain is intricate and requires specialised technology adaptations to make it feasible and safe. Specific modifications that have been integrated into the harvesting equipment and their benefits to difficult terrain harvesting are given emphasis in the report. The technology and techniques identified will allow the modern forester to correctly identify harvesting systems suitable to harvest steep or difficult areas and then operationally implement the systems and techniques to obtain the full benefit.

A possible output of this study was the use of decision trees, whereby equipment could systematically be matched to appropriate terrain. However, like Boswell (1998), it was discovered that this was not possible as there are always exceptions to every rule used to construct the decision tree. This report also does not attempt to summarise literature that covers the site disturbance of various machines and systems.

Terrain classification

South Africa harvesting operations subscribe to the National Terrain Classification (NTC) for Forestry (Erasmus, 1994). The aim of this section is to familiarise readers with the terminology used in the document, and not be a comprehensive repeat of the original document. Erasmus (1994) describes terrain classification in forestry as “the characterisation and grouping of forest land according to the physical **accessibility** of an area for forest operations”. The objective is to ensure a standard and consistent way of classifying terrain so that all users are able to communicate and document their actions efficiently. The NTC does not consider the environmental or silvicultural sensitivity of soils, as this is dependent on the type of machine, system and work method. The inherent sensitivity of the soil to compaction, erosion and hard-setting would need to be determined, and the influence of each machine on this determined.

The NTC considers the following aspects:

- **Ground conditions** – The bearing capacity of the soil is considered in the dry, moist and wet conditions. Soils with high bearing capacity for a given moisture condition will be able to carry higher wheel or track pressures, while soils with low bearing capacity could have the wheels or tracks of machines sinking into the ground if they do not have sufficient flotation. The bearing capacity is mainly determined using the soil type, clay content and soil moisture content.
- **Ground roughness** – This factor considers obstacles that will prevent vehicle movement. The larger the obstacles are, the more frequently they occur, and their proximity to each other will provide an indication of the ability of ground based machines to access the land. Depressions are also considered, but are not usually problematic in South Africa.
- **Slope** – The gradient of the land (expressed as a percentage) and the topographic form of the slope are considered.

Table 1 shows the limits of the various classes occurring in each of the above factors. The NTC document should be consulted for more detail. This information is important during harvest planning to ensure that the correct harvesting machines and equipment are selected, and they are applied to the terrain according their specific limitations.

Table 1. NTC classes for each feature (Erasmus, 1994)

Ground conditions	Ground roughness	Slope (%)
1: Very good	1: Smooth	1: <11 = Level
2: Good	2: Slightly uneven	2: 11 to <21 = Gentle
3: Moderate	3: Uneven	3: 20 to <30 = Moderate
4: Poor	4: Rough	4: 30 to <35 = Steep 1
5: Very poor	5: Very rough	5: 35 to <40 = Steep 2
		6: 40 to <50 = Steep 3
		7: ≥50 = Very steep

Background information of harvesting systems

Each possible harvesting system usually has a wide range of operating conditions. There can be considerable overlap between the applications of different systems. For a given site, several systems could be considered. Besides the many external factors that affect system decision making, a thorough understanding of the implications of selecting different equipment type's needs to be understood (MacDonald, 1999). Understanding equipment entails an understanding of its interaction with terrain (slope, ground roughness and ground conditions), its effectiveness in different weather conditions, tree characteristics, its implication on business success, silvicultural systems, legal requirements, operator training and skill and many others. Therefore, understanding the ability of a certain machine to handle difficult terrain is only one part of equipment and system selection.

Extraction equipment in harvesting must be matched appropriately to the felling equipment to balance the system. This is because extraction equipment is usually the restricting factor for a harvesting system to function effectively on steep terrain.

International standards have had an influence on the technological development of harvesting equipment in South Africa, as most purpose-built equipment used is imported. These technological developments in particular address environmental suitability, productivity, safety, ergonomic suitability as well as the demanding terrain conditions of the forestry industry. The influence of technological development has led to the grouping of harvesting equipment into systems, and has been seen as a way of improving efficiency in harvesting operations on difficult terrain (Beuk *et al*., 2007). Harvesting in forestry is characterised by three general categories of felling and extracting timber, namely; ground based, cable yarding and aerial systems.

Chainsaw felling, chainsaw processing, manual processing, manual stacking and manual extraction can be used on slopes where most mechanised and semi-mechanised machines are not able to traverse. MacDonald (1999) indicated that chainsaw felling can take place on slopes of 100% or more. However, as the terrain increases in difficulty, the safety risk factor increases. The New Zealand forestry industry is currently underway with a project to have no people operating on steep slopes unless they are in a well-protected cab, and it is even preferred to have no-one in the cab on extreme terrain and have the machine operated remotely.

Specific background is provided below for some of the harvesting categories. Even though much research has been carried out on various machines and systems, the starting place to determine machine limitations is always the manufacturer specifications provided.

Ground based systems

Ground based harvesting systems, contrary to cable yarding and aerial systems have extraction machines that travel on the ground surface. Rough and steep terrain causes machine instability and or a loss of traction. Therefore machines with a low centre of gravity often handle difficult terrain better. The trees being extracted by skidders for example provide additional stability, whereas a forwarder will be more unstable as its load is held high off the ground (MacDonald, 1999). However, forwarders can more easily manoeuvre between obstacles, whereas a skidders load will drag over the obstacle when trying to navigate around it. Soft ground can result in one side of the machine sinking in, while obstacles can lift one side of the machine up, effectively changing the slope of an area. Machines with a long wheel base and good weight distribution show good performance during felling on rough terrain. The long wheel base of the machine provides stability during operations on steep slope when travelling straight up and down the slope.

The greatest risk for forestry machine operators when working on steep slopes and rough ground is that of the machine turning over. Therefore, all machines used on steep slopes should have suitable and certified roll-over protection structures (ROPS). However, even these structures can only protect operators effectively if they wear seat belts, and the seat belts are functioning and in good condition. **ROPS and functioning seat belts are non-negotiable items for operating on steep slopes** (see **Figure 1**). Non-purpose-built forestry machines operating on steep slopes will need to have ROPS fitted, and proof should be provided (AFAG, 2006) that they confirm to the necessary SANS (South African National Standards) requirements.

Figure 1. Effectiveness of FOPS and ROPS structures (http://customproductsinc.files.wordpress.com/2011/10/skidder-versus-tree.jpg)

In South Africa, the ground based system that was commonly used for harvesting steep slopes consisted of chainsaw felling and processing with a cable skidder extracting. The cable skidder is able to use its winch to effectively harvest areas much steeper than where the machine can actually travel. Silayo *et al.* (2010) indicates a trend towards the increased use of harvester and forwarder systems. However, this can be debated, as full tree systems are still commonly used in North America, and many new full tree systems have been implemented in plantations in South America and Australia. In South Africa, even though chainsaw felling, de-branching and crosscutting is still widely used, the use of fully mechanized systems with higher production levels is becoming more prevalent. Machines with levelling upper structures have become common in forestry. These machines maintain stability, slewing power and the lifting motion of the boom, and also improve operator safety and ergonomics (Saunders, 2011). These levelling machines are able to operate on terrain that previously had to be felled with chainsaws and extracted with cable yarders.

Mechanised ground based CTL systems have traditionally been able to harvest more difficult terrain than ground based full tree or tree length systems. This is due to the forwarder carrying the entire load off the ground resulting in less load frictional drag and the load helping with traction. Also, the forwarder is able to travel on slash mats constructed by the harvester (see **Figure 2**) which reduce the chance of the wheels penetrating through on soft or sensitive ground.

Figure 2. Driving on slash mat (www.ponsse.com)

Boswell (1998) listed the following terrain advantages of CTL systems:

- Effective harvesting in riparian areas
- Easier placing of logs on roadside landings in steep areas
- Longer operating window in the year
- Less roads to build
- Less ground disturbance when operating on slash
- If machine selection is correct, steep slopes can be harvested

The following terrain disadvantages were mentioned:

- The forwarder can be very heavy if there is no slash mat or the slash mat is not sufficient to prevent wheel ground penetration.
- Forwarder instability on cross slopes

Often forestry machines make use of the same carrier, but have different attachments. An example is excavators used as harvesters, feller bunchers, loaders and shovel loggers. Parker and Bowers (2006) provide a rough slope limit of 35% to 45% for excavators, but this classification would be too coarse for operational implementation. Acuna *et al.* (2011) provided information from various sources to prove that it is common for suitable feller bunchers and harvesters to operate on slopes over 35% to 45%.

Even though mechanised systems have pushed the slope limits for ground based machines to levels previously not thought possible, manual systems are still capable of accessing terrain where these machines cannot access. Chainsaw operators are able to fell on very steep slopes, and manual extraction of smaller logs on short steep slopes is often still viable. However, safety concerns on these steep slopes are resulting in these motor-manual and manual operations becoming less acceptable to use.

What follows is a discussion of the commercially available ground based harvesting equipment and systems applied in timber harvesting on steep terrain and difficult ground conditions.

Harvesters

Garland (1997), and Parker and Bowers (2006), indicated that harvesters can work on slopes of up to 45%. However, subsequently much technological advancement has taken place, and certain harvesters can operate on much steeper slopes. Improvements in technology have made the harvesting of steep terrain possible with the use of levelling systems on harvesters (Stampfer, 1999). Harvesters used on steep slopes should use the lightest head possible. This allows extra reach without affecting machine stability as much, which helps to maintain rack width. On steeper slopes, it might be necessary for the operator to leave slightly higher stumps to prevent logs from rolling down the slope. Smaller stacks should also be constructed and the harvester should not try to sort into different product assortments. The forwarder will take all products out together and sort on the landing.

Levelling harvesters

According to Stampfer and Steinmuller (2001), the track-based levelling harvester performs well on slopes of up to 60% in areas with good soil conditions. However, high ground roughness prevents tracked machines operating. Saunders (2010a) studied the Tigercat LH845C tracked harvester (**Figure 3**) with a LogMax 6000 harvester head in Sitka spruce on steep slopes. Tree sizes ranged from 0.266 m^3 on level areas to 0.654 m^3 on steep areas. Harvesting took place on slopes of up to 57% and the machine travelled on slopes of up to 67% (with the boom extended out in front of the machine). At the 57% harvesting limit, an expected rocking motion occurred during slewing. All harvesting took place straight up and down the hill. The upper structure was able to level itself up to slopes of 55%. Even though the boom had a 10 m reach, on the steep slopes the operator only used seven to eight metres of reach. This was to maintain stability. Due to the reduced rack width, the slash mat width decreased from 6.8 m on level ground to 4.9 m on the steeper slopes. The operator indicated that reversing down the slope to access a new rack was only done if the slopes were too steep to move forward. The preferred option was to access a level area higher up the slope and create a circular route. This was due to the lack of vision and possible machine instability when reversing down steep slopes with the cab facing forward.

Figure 3. LH845C tracked harvester (www.tigercat.com)

The Neuson Ecotec 242HVT tracked harvester (**Figure 4**) is another example of a stable harvester for difficult terrain. It can be fitted with track grousers which can be constructed from metal, hard rubber or plastic depending on terrain roughness. Its levelling mechanism is able to level to 47% in front and 27% to the side, and it has an optional 14 m boom (www.neuson-ecotec.com).

Figure 4. 242HVT tracked harvester (neuson-ecotec.com)

Saunders (2010b) studied the Silvatec Sleipner TH8266TH 8-wheeled harvester (Figure 5) with a Silvatec 560 harvester head on steep terrain. Both front and rear bogies were fitted with bandtracks and the wheels were filled with saline water ballast. The cab was able to tilt 18% forward and 27% to the rear. The boom could tilt 29% forward and 58% to the rear. During the studies, the machine harvested 0.424 m3 Sitka spruce on slopes of up to 47% and travelled on slopes of up to 53% with no stability concerns. The harvester had been fitted with the Bogie Optimisation Stabilisation system (BOSS), where each bogie has a hydraulic ram that places force on the bogie to maximise traction and stability on slopes. When the BOSS system was deactivated, there was greater side to side movement of the machine. The harvester achieved an output of 19.93 m3 per PMH.

Figure 5. TH8266TH harvester (www.interempresas.net)

Factors to assist wheeled harvesters on steep terrain

The research carried out by Saunders into the use of harvesters on steep slopes (Saunders, 2010a; Saunders 2010b) also identified the following points to assist using wheeled harvesters on steep terrain:

- Evaluate machine access into and out of the compartment.
- Reduce rack width to maintain machine stability.
- Remove existing stumps where necessary.
- Cut stumps as low as possible to facilitate extraction.
- If possible, remove large stones or rocks in the machine path that can cause stability problems.
- Fill hollows with slash.
- Place large or rough material outside of the slash mat.
- Slash should be cut into shorter lengths when used on slash mats.
- Build up the lower side of the slope with slash.
- Tyre selection and traction aids must receive careful attention.

The Tigercat 1135 wheeled harvester (**Figure 6**) is an example of a specialised eight-wheeled harvester used for thinning on steep slopes and rough ground conditions. The narrow design allows it to harvest first thinning compartments with narrow tree espacement. It can access timber on slopes of 60% up slope and 45% down slope. This harvester has been fitted with a parallel linkage crane and a 2 m of additional reach with a telescopic stick. The crane base levels to the front and rear, enabling it to maintain stability and slewing power when operating on steep terrain. The crane also has a side tilt function to obtain better reach around standing trees.

Figure 6. Tigercat 1135 wheeled harvester (www.tigercat.com)

Motor-manual felling for harvesters

Short, steep slopes that a harvester cannot access can be felled with a chainsaw in a direction that will allow the harvester to grab the trees from a more suitable terrain area and process them. Selected trees should be felled straight down the slope and then de-branched. The following trees are then felled across the slope and allowed to slide down to where the harvester can access.

Harvester felling where forwarders cannot access

If the harvester has steeper slope handling abilities than the forwarder, it might be necessary for the harvester to fell a tree and then move to an area accessible to the forwarder for processing, and repeat this until all trees on the steep section are felled. This will naturally reduce the productivity of the harvester significantly, but might still be cheaper than bringing in an alternative system for a small pocket of timber. Also, these pockets often have to wait some time before the alternative system can arrive, which complicates reestablishment activities. An alternative to the harvester walking each tree down the slope is for the harvester to fell a tree, de-branch and top it, and then feed it feed down the slope with the boom at full reach down the slope. Once a number of trees have been fed down the slope, the harvester walks down the slope, picks up the trees by the butt and feeds them again until the slope is sufficient for forwarder travel, where the stems are processed into logs.

Harvesters and steep road embankments

Often steep areas are also associated with steep banks next to roads that prevent machine access. Harvesters are able to break down certain embankments using the de-limbing knives. Naturally the soil should not be rocky or be excessively hard.

Harvesters and cable yarders

Harvesters that can operate on steep slopes of up to 55% are increasingly being used with cable yarders to extract steeper slopes without the risks associated with motor-manual felling and processing (Owende *et al.*, 2002).

Feller bunchers and feller directors

On steeper terrain, it is important for the felling machine not to drive to individual trees due to stability problems. The carrier of the swing-to-tree feller buncher needs to be larger to have more stability due to trees being handled further away from the machine. Therefore, swing-to-tree feller bunchers are usually tracked machines. Tracked feller bunchers are capable of operating on steeper slopes if the upper structure can be levelled, which maintains stability. Tracked machines are also capable of working on steep slopes or wet sites where flotation needs to be maintained (McNeel, 2004). A feller buncher operating on steep slopes and rough terrain should be equipped with a rotating felling attachment.

When feller bunchers are used on flat terrain, it usually operates backwards and forwards across the slope, starting at the top of the slope so the trees can be placed into the cleared area with their butt ends facing the direction travel. On intermediate slopes, tracked feller bunchers travel up and down the slope to maintain machine stability, and the trees are bunched to the side. On very steep slopes, the feller buncher only fells while travelling up the slope. When it reaches the top, it reverses back down the slope without felling any trees and starts again from the bottom (MacDonald, 1999).

Steep slopes reduce the effective reach of the boom. When the boom is fully extended, stability is reduced and considerably more engine power is required to turn the upper structure of the machine on the slope with a full load. Because of this, the working radius is increasingly reduced as the slope increases.

Wheeled feller bunchers are usually restricted to flat terrain due to stability problems and because they have to drive to each tree. Even high wind speeds can make wheeled feller bunchers tip over. Wheeled feller bunchers cannot drive with a load over rocks or large stumps.

A cost effective option for thinning small trees on steeper terrain, is to fell and bunch trees, and then have a forwarder load the entire trees, carry to a landing, and then carry out processing there.

A Timbco 400-C Series Hydro-Buncher (similar to **Figure 7**) with a designed levelling capability of 51% was observed felling a compartment of up to 55% slopes during a trial, with the operator indicating that he could have felled steeper areas if they were available (Boswell, 1998). The operator indicated that he needed to take care at the 55% slope, but that he felt like “he was on flat ground” up to 45%. However, there was a section of the trial on a 47% slope that had boulders of between 0.25 and 0.75 m^3 in size. This section had to be left standing.

Figure 7. Timbco 415-C similar to the 400-C (www.lumbermenonline.com)

Skidders

Skidders extract timber by lifting the ends of the trees or logs off the ground and pulling them to the roadside landing (Hall, 2005). However not all skidders drag their loads, some fully support the load with only the tree tops touching the ground, such as the clambunk skidder. A variety of skidders is available for timber extraction depending on the volumes to be carried, extraction method and site characteristics. A distinction of the type of skidder can be made by its tractive system and the technique that it uses to grab the timber from infield to roadside or landing (MacDonald, 1999). Skidding machines on steep slopes can potentially cause much damage. They may be technically capable of operating on steep slopes, but in doing so may cause excessive soil disturbance and even machine damage (FAO, 1996). Prior to the mid 1990's, skidders were generally restricted to slopes of less than 30% except for very short distances (FAO, 1996). Garland (1997) provides the slope limits for tractors and wheeled skidders as 35% to 45%, and downhill extraction is preferred. However, as discussed further in this report, modern specialised skidders do have the ability to traverse steeper slopes.

Even though different configurations of skidders are able to operate on relatively steep terrain, there is usually a payload sacrifice when skidding uphill. Sarles and Luppold (1986) indicated that when tractors and skidders extract uphill, there is a 2.5% reduction in maximum payload for every one per cent slope increase over 10%. It is therefore preferred to carry out downhill extraction. However, this downhill skidding can result in greater soil disturbance due to slash being swept down the slope and increased and concentrated water flows over the soil. Skidders also usually require a dense road network when extracting in steep areas. The construction and maintenance costs, and the associated environmental issues, should also be considered during system evaluations.

In order for skidders to traverse steep slopes they need to remain on well planned skid trails. This will enable the skidder to remain stable. A lack of planning of skid trails, poor felling direction or incorrect pre-choking of trees can result in the skidder having to travel off the planned route, resulting in safety risks and potential site damage. Skid trails should be as straight as possible unless it is necessary to deviate to miss, for example, a sensitive area. When extracting downhill, skid trails should preferably be slightly angled across the slope (FAO, 1996) to ensure that water running down them runs into surrounding land as opposed to gathering speed and volume down the skid trail. On sensitive sites on steep slopes, uphill skidding is preferred as water is dispersed into vegetation as opposed to being concentrated at the downslope landing (FAO, 1996). Larger loads are also easier to control and the safety risk to operators is less. However, uphill skidding can cause excessive soil disturbance and operator training and discipline cannot be underestimated.

Options available for skidding are rubber-tyred and tracked skidders (Ebert and Mackes, n.d.). The problem associated with wheeled skidders was their inability to tackle steep slopes because of a lack of traction (MacDonald, 1999).

Wheeled skidders

According to Tomasic *et al.* (2009), the largest slope limitations for a wheeled skidder not using band tracks or wheel chains travelling uphill is 30% and an average of 40% downhill. Wheeled skidders have reduced ability to turn on steep slopes due to stability problems during articulation. This is exacerbated by the presence of rocks, depressions or windfalls. Parker and Bowers (2006) provide a slope limit of between 35% and 45% for wheeled skidders, but do not differentiate between machine configurations or applications. Wheeled skidders operating on steeper slopes need to have more power (>110 kW) and need to be large to maintain stability and traction.

Tyre size

Purpose-built, wheeled, articulated forestry skidders usually have tyre diameters of 71.4 cm. Wider tyres are used to improve flotation for soft ground. Research has shown that wider tyres can improve productivity on soft ground. Brinker *et al.* (1997) presented FERIC results which showed that 173 cm and 127 cm tyres improved productivity on soft ground by 13% and 23% respectively. Less soil disturbance also resulted. Other research showed productivity increases of 14.5% and 60% for wide tyres. Fuel consumption savings were also shown. Tests on dry ground showed no productivity improvements.

Use of bandtracks and dual tyres

Bandtracks are fitted around a set of wheels with centre bogeys; these tracks increase traction and flotation on the machine and can reduce the rolling resistance on slopes. The type of tyres fitted on the wheels of skidders can also play a significant role in increasing the machines ability to operate on steep slopes. The tyre specifications, flotation and tyre tread are important factors to consider before adding any other traction aids. Using dual wheels on skidders increase flotation because the footprint is larger. More information on this topic is provided under the section covering tractive systems.

Use of a slash grab

When skidders are used with full-tree harvesting systems on steep areas, slash build up on small landings can be problematic. An option to overcome this is to have a slash grab mounted either in conjunction with, or replacing the skidding blade. The skidder is able to collect slash and return it infield, freeing up space on the landing.

Bundle skidders

For smaller trees, the bundle skidder is often used on steeper areas (**Figure 8**). Bundle skidders are conventional wheeled cable skidders that suspend short length bundles of wood behind it. Because no part of the load is dragging on the ground (that is, the entire load is on the drive wheels) and it is carrying a relatively small load, the bundle skidder is able to handle steeper slopes and still remain relatively stable (MacDonald, 1999). The cut-off limits of the bundle skidder have however not been researched, so there is no literature available to provide guidance. Bundle skidders are known to operate on slopes up to 40%, and using the winch can access even steeper areas. The limitations on very steep slopes become the safety of labour that must construct the bundles and the chokerman who have to place the long chain lengths under and around the bundle. There are therefore safety risks when choking bundles on such steep terrain (MacDonald, 1999). In addition, because the bundle hangs behind the rear axle of the skidder, stability could also become a concern on very steep and rough terrain, especially with lighter skidders. Often manual rolling of logs takes place in conjunction with bundle skidders, where the slope is too steep for the skidder to access. Timber stacks must be constructed with logs parallel to the slope so that the skidder does not have to move across the slope to access them, but can approach straight up or down the slope. Stack position on the slope must also not be arbitrary. Stackers must attempt to find a position on a slightly more level section on the slope to improve the safety of the stackers and the chokermen. Because bundle skidders access such steep areas and must usually reverse to the bundle, a turnaround seat is an advantage.

Figure 8. Bundle skidding (www.tigercat.com)

Crawler skidders

Tracked skidders are capable of operating on steeper slopes than rubber-tyred skidders; however, they are more expensive (Ebert and Mackes, n.d.). Tracked skidders are slower but cause less soil disturbance and have better climbing capabilities (MacDonald, 1999). Krag and Webb (1987) found small crawler tractors to be a more expensive extraction option than rubber-tyred skidders, but were a viable cost alternative to cable yarding. Crawler tractors are more stable when turning on steep slopes than wheeled skidders, but are also unstable in the presence of obstacles. Sarles and Luppold (1986) also indicated that small crawler tractors were more stable on steep slopes than rubber-tyred skidders, and could construct their own skid trails if necessary.

Parker and Bowers (2006) indicate that crawler tractors (**Figure 9**) can operate on slopes up to between 45% and 55%, with downhill extraction preferred. A Cat 527 grapple crawler tractor was used under trial conditions to extract on very steep slopes of up to 55%. The operator indicated that at 55%, he needed to take care during the operation, but up to 45% he “felt like he was on flat ground” (Boswell, 1998). This skidder was used to extract trees (up to 250 m) on the very steep section of slope, and would extract to the bottom of the steep slope, where after a rubber-tyred skidder extracted the trees to the landing. Skidding uphill, the crawler skidder was able to extract up to 30% with the same productivity as downhill skidding. However, ultimately the operator set the slope limits, as when the operator felt uncomfortable with the slope, he stopped, and management supported his decision.

Figure 9. CAT crawler grapple skidder (www.cat.com)

Cable skidders

The most commonly used semi-mechanised ground based system for steep slope harvesting in South Africa consists of a chainsaw for felling and debranching, and a cable skidder for extraction. Slope limitation values for cable skidders only apply when the machine is extracting a load. In reality, much steeper areas can be accessed by pulling out the cable to areas where the skidder cannot drive to.

However, the productivity of the skidder is negatively affected when extracting on these steeper areas. The skidder is still limited by cable length (usually about 25 m), but smaller diameter cable can be fitted onto the winch drum to increase this distance, but payload is then reduced. The skidder can also reverse down or up steeper slopes, winch trees to the skidder, then drop the load and drive forward again, sometimes repeating this multiple times, until the skidder is situated at an area where it can safely travel with its load. During extraction, the skidder may also encounter difficult terrain, and it will release the winch drum to drop the load, then drive forward to beyond the difficult area, winch the load in again and then continue with extraction.

Cable skidders have traditionally been limited to slopes of 35% if extracting downhill and 20% if extracting uphill, although as indicated, the winch can access steeper areas if it is within the reach of the cable (Erickson *et al.*, 1991). Even though the downhill slope limits appear conservative, safety is the main consideration as tree lengths can slide forward and strike the skidder or cause it to lose control (MacDonald, 1999).

A smaller skidder that is suitable for extraction on steeper ground is the Awassos MD 60C articulated mini skidder (**Figure 10**). It looks very similar to conventional wheeled cable skidders used in forestry. It is very manoeuvrable and can work on slopes of up to 70%. The engine has a steep slope oil pan. The MD 60C is usually used in thinning operations and is a relatively low productivity machine due to its lower payload.

Figure 10. Awassos MD 60C (www.awassos.com)

Grapple skidders

Because the grapple skidder can carry higher volume loads compared to the cable skidder, it is often utilised in fully mechanised systems. The grapple skidder has to drive to trees to extract them, because in its standard configuration it has no winching capabilities, which is a limiting factor with difficult terrain extraction. Grapple skidders can however be fitted with a winch to overcome this limitation. However, if a grapple skidder is spending excessive time using the winch to access timber from difficult terrain; it is an indication that equipment selection was maybe incorrect.

In order to prevent excessive ground disturbance, felling direction and tree or bunch placement for the grapple skidder is very important. MacDonald (1999) indicated that should grapple skidders have to do much manoeuvring to grab the load on steep slopes, it increases the chances of it tipping over. High ground roughness exacerbates the situation. Swing-boom grapples reduce the amount of manoeuvring which must take place, however it only has approximately three metres of reach, and it also has reduced payload compared to conventional grapple skidders.

Grapple skidders usually operate with feller bunchers when used as part of a fully mechanised system. On steep slopes, levelling tracked feller bunchers are used. A conventional four-wheeled grapple skidder is slope limited compared to the levelling feller buncher, resulting in the true capabilities of the feller buncher not be realised. To improve the steep slope handling ability of the grapple skidder, options such as using bogie axles (on the rear of the machine usually), band tracks, chains and additional machine power (larger machine) are required.

A grapple skidder that is able to operate on steep slopes is the TransGesco 88C (TG 88C) grapple skidder. The TG 88C can skid long distances of 500 m and more (Bill, 2003). This grapple skidder has chains and a longer wheel base which makes climbing on steep slopes of up to 50% possible and is also well suited to sensitive sites (Kryzanowski, 2008). The chains on the wheels are an accessory for the machine to enhance climbing capabilities on steep slopes. An additional example is the Tanguay 88E (TG88E) grapple skidder (**Figure 11**). The TG88E skidder is eight wheeled and has a hydrostatic drive system combined with an engine pan which enables it to operate on slopes of 45% (Tanguay, 2010.).

Figure 11. Tanguay 88E (www.tanguay.com)

Grapple skidder grapples

Grapples skidders operating on broken or steep terrain should have grapples with a relatively large opening and a long reach behind the rear wheels (Kosicki, 2003). This, together with the grapple rotator, enables easier accumulation of loads. Dual-arch grapples skidders (**Figure 12**) allow for more reach compared to single-arches. This reduces the amount of manoeuvring required on soft soils and rough terrain, and allows the load to be held higher to reduce load drag. Swing-boom grapples supply even more flexibility than the dual-arch, and allow loads to be collected from the side of the skidder, and not just behind it, providing even better terrain handling than the dual-arch skidders. Swing-boom skidders have lower payloads and increased maintenance requirements, which therefore only allows them to be used for specific difficult terrain types.

Figure 12. CAT grapple skidder (www.cat.com)

Clambunk skidders

Clambunk skidders (**Figure 13**) are the most unstable skidder type due to the height that the load is carried above the ground. Therefore, turning on steep slopes under load is not possible. The presence of rocks further reduces its slope handling abilities (MacDonald, 1999). If clambunk skidders are able to travel straight up and down the slope and ground roughness is not problematic, then the clambunk skidder can negotiate steep slopes. MacDonald (1999) indicated that clambunk skidders are able to operate on slopes of up to 60%. Boswell (1998) presented information on a harvesting system that included a Timbco 445 feller buncher and a TransGesco TG80 clambunk skidder. The skidder and feller buncher were both able to safely handle slopes between 60% and 65%, although this was considered their upper limit. The clambunk skidder had 91 cm wide tracks on the front bogie and 107 cm wide tracks on the rear bogie, which improved stability and allowed it to skid across 30% slopes. However, on a different site in winter, when the ground was hard, the skidder could not climb slopes greater than 30%. This was due to insufficient traction from the wide band tracks. Narrower (71 cm) single grouser tracks were purchased which had 6 cm grouser bars. The narrower tracks improved the uphill slope capability of the skidder to 40%. The contractors responsible for this operation indicated that their usual slope cut-off for the skidder was 30 to 40%, but with the correct operator and site conditions, it could operate to an ultimate maximum of 70%.

Figure 13. Timberpro 840 Feller buncher clambunk skidder combo (www.timberpro.com) and John Deere 1710D clambunk skidder

Forwarders

During forwarding, logs are lifted free off the ground to the landing or depot. The weight of the load is directly exerted on the drive wheels of the machine, thus no friction is caused by the dragging of the load, which requires to more traction. Because the load is directly on the machine the forwarder is able to handle steeper terrain. Good traction and differential locks are very important on steep and rough terrain (Richardson and Makkonen, 1994). Forwarders result in less soil disturbance than skidders due to the improved weight distribution on the ground (Tiernan *et al.*, 2004).

It is also important to note is that when a forwarder extracts timber across slopes, the machine becomes unstable because the centre of gravity of the machine is shifted significantly. Unlike skidders, forwarders need to travel straight up and down the slope (FAO, 1996). The forwarder should always follow the exact route of the harvester. There are four, six or eight wheeled forwarders available. Some forwarders can even be fitted with ten wheels for extra flotation, such as the Ponsse indicated in **Figure 14**.

Figure 14. Ten wheeled forwarder (www.ponsse.com)

On very steep slopes it can become necessary to use circular routes to access the steeper terrain when extracting downhill with the load. Reversing up a steep slope is sometimes necessary where turning on the slope is not possible. This is also necessary to ensure that when loaded, the logs do not fall off the rear of the forwarder. However, reversing up steep slopes with a loaded machine is not recommended as vision is obscured (AFAG, 2006). The forwarder must rather reverse to the highest point necessary to obtain the desired load, and then move forward down the slope. The introduction of cameras has resulted in the operator being able to see behind the forwarder when reversing with a load, but it is still not as safe as direct site. In order to access very steep slopes, the forwarder should access the steep slope and then only load half of its payload. It can then move to a more level area and complete loading. Only having half the bunk loaded on steep slopes keeps the centre of gravity lower and therefore improves stability.

Load sizes of forwarders must always match the slope and stability conditions. The operator should bring the loaded grab close to the forwarder before lifting the boom. On steep slopes, forwarders struggle to slew the timber into the bunk, as the machine is facing downhill which requires that the logs be slewed uphill. To overcome this, the forwarder might have to grab fewer logs per grab, and if the logs are too large (one log per grab), it might not even be possible to load on very steep slopes.

To maintain stability when loading, the “hill and valley” principle is used when travelling straight up and down slopes. The first logs are placed in the centre of the bunk above the chassis. Once a small “hill” has formed, logs are place on either side against the bolsters until a valley forms. Logs are then placed in the middle again and the procedure repeated until payload is achieved. When loading on side slopes, logs are first placed on the upslope side of the bunk, and an angled profile maintained while loading (the top layer of logs should be level with a zero per cent slope). As each new layer is added, the operator starts on the upslope side.

Agricultural tractors

Agricultural tractors have not been designed to operate on difficult terrain. Using them beyond their design limitations could result in serious mechanical problems and safety issues. Parker and Bowers (2006) provided a slope limitation of 5% for tractors, with downhill extraction preferred. Even though agricultural tractors have poor terrain handling characteristics, this slope handling limit is too conservative. If tractors are to be used in the forestry environment where moderate terrain is unavoidable, the tractor should have the following attributes (Forest Research, 2004; Russell and Mortimer, 2005; Jones, 1995a):

- Four-wheel drive.
- Equal or similar sized wheels front and rear.
- Large tyre footprint (large diameter wheels and wide tyres).
- Cross-ply tyres.
- ROPS and FOPS.
- Equal weight distribution over front and rear axles. 50:50 is preferred for tractors, but two-wheel drive tractors often have a 30:70 weight split and four-wheel drive 45:55. Excess weight on the rear axle results in steering and stability problems. The addition of front-end weights is required (45 kg for every 7.5 kW is recommended).
- Low tyre pressures (the lowest setting that the tyre manufacturers recommend).
- Tyre chains in certain conditions.
- A low centre of gravity by obtaining the ideal wheel spacing for the conditions.
- Adequate ground clearance. To handle rough ground, tractors should have at least 50 cm of clearance. The drawbar is usually the lowest point and it is often possible to have this raised.
- An adequate power to weight ratio. An additional 10 to 20 kW above what is required just to drive the tractor is required for the difficult terrain.
- Adequate gearing. Low range gears that allow very slow movement are needed on difficult terrain. This also assists with steep descents.
- With winch: A powerful and responsive winch and a skidding cone for rough ground.
- Loader fed processors with the tractor: A long boom to allow for poor terrain and also to allow a thicker slash mat. A powerful slew action will also be required.
- Winching cones can reduce snagging on rough terrain. This method can apply to all small-scale harvesting systems.

Tractors have much flexibility regarding the types of attachments that can be used. Common examples include for winching of small trees or for thinning, and with trailers for log extraction (see **Figure 15**). Tractors with winches (either single or double drum) have the flexibility of being able to use the cable to reach difficult terrain areas that the tractors cannot access. Tractors with winches have been used safely on slopes up to 30% on level, firm ground in research trials (Forest Research, 2004).

Figure 15. Farmi tractor winch, (www.farmiwinch.com), tractor with trailer and double drum winch

When tractors draw trailers for timber extraction, their terrain handling properties reduce considerably. Terrain handling can be increased slightly through the use of driven trailers and steerable trailers. They do however have higher capital costs and increased maintenance requirements. However, this can increase their slope handling ability to between 33% and 50% if ground conditions and slope are very favourable (Jones, 1995b). The bogies of the driven trailers might even require bandtracks and the tractor will need to have sufficient power.

Most agricultural tractors used in forestry have forward facing seats. However, almost all processing and loading activities occur behind the tractor. On steep slopes with self-loading trailers, this creates difficulties in that the operator must remove his safety belt to access the controls for loading. The two "golden" safety rules for operating on steep slopes are that the machine must have a certified ROPS structure and the operator must always wear a safety belt.

Summary of ground based equipment slope limitations

Any terrain limitations and specifications provided must be considered as guidelines, or cautionary indicators (Garland, 1997), as many other factors are at play. As can be seen from the literature above, the slope limitations for a given machine are affected by many factors. These include operator skill, ground conditions, ground roughness, weather conditions and tree characteristics. One can also differentiate between the uphill and downhill slope handling, between general slope handling characteristics and the extreme limits with good operators, and between low-risk and high-risk slope limits. Each machine type is suited to a range of conditions as defined by its basic features (MacDonald, 1999). In addition, regardless of the slope limits of the felling machine, it is usually limited to the slope handling capability of the extraction machine. It is therefore difficult to accurately indicate slope limits for machines. Machines also need to be ranked according to their complexity to operate on difficult slopes. For example, a feller buncher that is technically capable of operating on slopes of up to 50%, may either be operated by an inexperienced person capable of only operating up to 30%, or a very competent operator who might be comfortable working up to 60% under the same conditions. **Table 2** indicates the operator skill level required to operate the machine (MacDonald, 1999). The slope limitation needs to be considered in conjunction with this skill level rating to possibly increase or decrease the slope limits for specific operators, and still not lose sight of the other factors which could also influence slope handling (e.g. ground conditions).

Table 2. Operator skill levels required for different harvesting equipment (MacDonald, 1999)

Wheeled cable skidder	Low
Wheeled grapple skidder	Low
Crawler skidder	Low
Clambunk skidder	Medium
Forwarder	Medium
Horse	Medium
Chainsaw felling	High
Feller buncher	Medium
Feller director	Medium
Single-grip harvester	High
Carrier – tracked swing-to-tree	Medium
Carrier – wheeled swing-to-tree	Medium
Carrier – wheeled drive-to-tree	Low to Medium

MacDonald (1999) then described different risk classes to be used when evaluating terrain. These classes can be seen in **Table 3**. These are used in conjunction with the risk factors to determine the terrain application of equipment.

Table 3. Risk descriptions for machine operation (MacDonald, 1999)

Risk level	
1	Minimal risk, best operating conditions.
2	Generally acceptable; normal operating conditions. Unusual circumstances may increase risk.
3	Acceptable under many conditions, but exercise caution.
4	Risky; good reasons or special operating techniques required to operate under these conditions.
5	Highly risky; exceptional circumstances required to operate under these conditions. Special planning and operating techniques will be required.
6	Not recommended.

Table 4 shows the risk factors applicable to all harvesting equipment (MacDonald, 1999). These factors need to be considered with the slope limitations to eventually arrive at terrain limitations that match the machine, site and operator. Even though the table considers risks in general, they are still very applicable to the general risks that affect operators and the machines ability to work on difficult terrain.

Table 4. Risk factors applicable to harvesting equipment (MacDonald, 1999)

Factor	Description
Operator experience, attitude and history	Risk is decreased with an experienced operator who has worked successfully under similar conditions in the past, and has demonstrated a desire to do a proper job.
Contractor experience	Risk is decreased with an experienced contractor who has worked successfully under similar conditions in the past, and has demonstrated a desire to do a proper job. Effective communications between the planners and the workers and adequate supervision decrease the risk of a mishap caused by misunderstood instructions.
Weather	Inclement weather, especially excessive rainfall, increases the risk. The risk of causing soil disturbance increases with higher soil moisture content. Maintaining a flexible schedule, with the ability to work on different areas as required by weather conditions, reduces the risk.
Sensitive zones	Working in the vicinity of riparian zones, or other sensitive zones, increases the risk. Operators should always take extra care when working in sensitive zones.
Tree size	Risk is minimised when the tree size is matched to machine size. Trees that are too small decrease productivity and increase costs, while trees that are too large can overwork the machine, causing mechanical failure or environmental damage.
Timber quality	Risk is reduced with poor-quality timber because of reduced values. Poor-quality timber requires as much, or more, time for processing, yet returns a smaller profit.

Even though a total risk analysis of machines is beyond the scope of this report, it is worthwhile to refer to the equipment flowcharts developed by MacDonald (1999). These charts consider the risk levels (as per **Table 3** above) for the operating conditions of specific categories of machines. These operating conditions include soil texture, soil moisture, slope percentage, slope form, ground roughness, truck configurations, extraction distance, road conditions, silvicultural systems and other factors. In considering all of the terrain conditions, the forester or contractor can see the risk factor associated with his operating environment, and put necessary measures in place, or decide not to use the machine or operator available on this site. However, it must be noted that the flow charts cover broad equipment categories (e.g. wheeled skidders and forwarders) and therefore are only an indication of high-level risk. The specific machine being used will have to be examined, and the flowchart modified accordingly.

Once all machine selection options have been considered, and all operational planning techniques have been exhausted, one of the final techniques than can be used to access difficult terrain is payload reduction. This allows the machine footprint to be lighter, lowers the centre of gravity for better stability, and increases the uphill slope point where traction is lost and wheel slip occurs. **Annexure B** provides the results of the steep slope harvesting survey carried out.

Cable yarding

The use of cable yarding extraction systems on steep slopes has become comprehensive and intricate; many variations exist for different conditions. For example, highleads and skylines and mono-cables are all different systems with specific applications. Further options with regard to different types of carriages, cables, rigging, sizes of yarders, spanning possibilities and more exist.

Two of the largest limitations of a cable yarder are the time taken for setting up the system (Conway, 1976), and that the yarder needs to be set up on, or very close to a road. The space at roadside for stacking and further processing is usually limited, especially if the method applied is that of full tree or tree lengths (Saunders, 2006). Due to this reason, the excavator based cable yarder (see **Figure 16**) has become increasingly popular. Redundant excavators can be modified to create cost-effective cable yarders that have fast set-up times (no yarder anchors required), are multipurpose (if still equipped with a bucket), are easy to operate and have relatively good off-road abilities (Owende *et al.*, 2002).

Figure 16. Excavator based cable yarder (www.loggingon.net)

Slope is not a deterrent for cable yarding systems, and they can be used on slopes of up to 100% and more. Due to the fact that the trees or logs are partially or entirely suspended during the extraction, there is no significant soil disturbance on the ground. Stenzel *et al.* (1985) mentions that cable yarders have the ability to operate up and down the slope or along contours and depending on the yarder's power output, its productivity can be very high per productive machine hour.

Cable yarders are usually operated as semi-mechanised harvesting systems. Labour is still required to fell, process, choke and dechoke trees. This use of labour on high-risk steep slopes in cable yarding is one of the reasons why safer mechanised ground-based systems are increasingly being used on steep slopes. However, if cable yarding could become more mechanised without becoming more expensive, then it may remain a viable option for steep slope harvesting. Boswell (2004) examined a cable yarding system that included a feller buncher on slopes of up to 60%, with the remainder of the slopes being felled using chainsaws. Swing yarders extracted the timber, and made us of mechanical slack pulling carriages and radio-controlled chokers to reduce labour requirements. Mobile backspars were also used where possible. When the trees arrived at roadside, they were debranched and cross-cut into logs on a landing using dangle-head processors. The dangle-head processors also stacked logs in different assortments on roadside. Stem size was the only variable which had a significant effect on processor productivity, with ground slope, deck slope, tree defects and branchiness not influencing productivity. The study results showed that mechanised processing at roadside can be cost effective when cable harvesting steeper slopes.

Acuna *et al.* (2011) also investigated using levelling tracked feller bunchers to fell for cable yarders in pine sawtimber operations on steep slopes of between 36% and 47%. The feller buncher improved the productivity of the cable yarder by 25% compared to felling with chainsaws. It is therefore clear that a combination of ground based mechanised systems and cable yarding systems can also achieve good results.

One of the restrictions of using cable yarders is that the yarder itself is usually restricted to roads. Usually all trees within the yarders reach need to be harvested to achieve sufficient production to offset the high setup and dismantling times. Any creaming of more moderate terrain areas within the yarders reach with lower cost ground based systems only results in an increased weighted harvesting cost. However, an option to address this is to mount the yarder onto an off-road vehicle, and position the yarder as close as possible to the difficult terrain area and then optimise its reach within these areas. This also prevents the large build up of harvesting residue commonly found on cable yarding landings. Saunders (1998) studied two cable yarding systems (All Terrain 65 Skyline and Cable King 230/18T) mounted onto forwarders. Both had independent power sources to the forwarder which enabled them to be moved from one carrier to another. Trees were felled by chainsaw, and once extracted by the cable yarders, they were processed by excavator based harvesters. Logs were then transported to roadside landing using a forwarder. High forwarder performance was expected due to the concentrated logs at the cable yarder.

Aerial Systems

Aerial logging or aerial timber extraction is the extraction of timber by a helicopter (and very rarely by balloon) from harvested stands that are inaccessible to ground based systems or on sensitive sites (Stampfer and Gridling, 2002). Helicopter logging is possible in thinning and clearfelling applications (Rummer, 2001). James and Norton, (2002) point out that the advantage of using helicopters in forest operations is their ability to extract scattered trees with higher productivity over the harvested site with no adverse effects on forest ecology, especially on the soil component. Due to its costs, helicopter logging is usually the last resort when no other system can be used (Boswell, 1998).

Saunders *et al.* (2003) confirms that aerial log extraction (also known as heli-logging) is not limited by slope. Slopes as steep as 89% have been accessed for extraction, though this may not be the maximum slope limit. The utilisation of helicopter extraction however, comes with high unit production costs, initial purchase price and fixed costs (MacDonald, 1999). Boswell (1998) indicated that helicopters carried out harvesting operations of slopes up to 90%.

Machine components

The working capacity of machines on steep slopes has been improved by the application of special modifications, and additional attachments on various ground based harvesting equipment. This is due to the increased demand for more efficient and reliable ground based machines operating on steep slopes. The next section reviews the technology that can be added to the equipment in order to improve the ability of the machines to operate on steep terrain. The machine components discussed include available tractive systems; different options for cab and upper structure modifications, boom configurations, and modifications that can be made to the machine as a whole.

Tractive system

Traction and flotation are two of the key issues that need to be understood to be able to operate ground-based machines on difficult terrain. These are the forces that tyres and tracks apply to the ground (Smidt and Blinn, 1995).

- **Flotation**: The vertical force applied, and it relates to the soils ability to support a machine.
- **Traction**: The horizontal force applied, and relates to the movement of the machine.

When soils are dry and hard, flotation can negatively affect traction as the contact area with the ground is too large resulting in excessive wheel slip. However, soils sensitive to compaction, or where there are soft underfoot soil conditions, may require flotation to reduce rut depth and soil damage. Flotation is increased by spreading the machine weight over a larger contact area with the ground (and/or by reducing payload). Machines are considered to exert low ground pressures (and are considered high floatation) if their kPa values are below 41 kPa. Machines working on very soft underfoot conditions need to have ground pressures of lower than 28 kPa (Smidt and Blinn, 1995).

During machine selection, or when determining whether a particular machine can work on a specific site or not, the ground pressure exerted by the machine must be known, and the ground pressure that the soil can handle under a given moisture condition needs to be determined. When calculating ground pressures, forwarders and other extraction machines that support the load substantially need to have their payloads added to the machine weight.

Ground pressure can be reduced using the following methods:

- Reducing payload
- Increasing tyre diameter and width
- Reducing tyre inflation (but never below manufacturer limits)
- Increasing the number of wheels
- Using slash mats
- Using smaller machines
- Using flotation aids such as band tracks

Forwarders have higher ground pressures than skidders, but skidders need more power to overcome the effect of load friction with the ground. Therefore, for a given load, skidders need to be heavier and more powerful than a forwarder. Because forwarders carry larger loads than skidders of the same power, forwarders can reduce their payload to achieve lower ground pressures if necessary, while reducing the payload of the skidder comes with a much larger productivity and cost consequence (Smidt and Blinn, 1995). Compaction is operationally controlled by measuring rut depth for a certain soil. South Africa does not have standards for rut depth. The Forestry Commission of the UK (Nisbet *et al.*, 1997) recommends that operations be suspended or re-organised should ruts be encountered that are deeper than 10 cm and longer than 5 m. However, South Africa’s standards cannot be based on international literature; specific standards would have to be developed that consider soil type, soil sensitivity and moisture status if necessary.

Steep slopes require that the machine has sufficient traction to move. A particular machine has slope limits either due to its technical limitations, the limitation of operator experience, or there are terrain related problems such as rocks, soft ground, adverse weather or even very hard ground. For example, a 40% slope can be more dangerous than a 55% slope if the conditions are not correct (Crawford, 2010). It must also be remembered that engine power is not a complete indicator of terrain handling ability. High engine power is of no use if the machine does not have traction. Tractive effort is discussed further under “Levelling upper structures and cabs”

Ground pressure

The bearing strength of the soil has a direct impact on the ability of a machine to negotiate steep terrain. This is because the deeper the wheels or tracks penetrate into the soil, the higher the rolling resistance becomes which in turn requires greater tractive effort to keep the vehicle moving. Apart from limiting the trafficability of harvesting equipment, low bearing strength soils increase the risk of environmental damage occurring in the form of rutting, compaction and erosion.

The interaction of machine and soil is measured by comparing the ground pressure exerted by the machine relative to the bearing capacity of the soil. Ground pressure is the measure in kPa of the manner in which the weight of an object is distributed to the ground supporting the object. Ground pressure is calculated by dividing the weight of the machine by the area of the machine that is directly in contact with the soil (machine footprint). The most commonly used ground pressure indicator method for forestry equipment is Nominal Ground Pressure (NGP).

Saarilahti (2002) warns that several authors have indicated that NGP is a very simplified measure of ground pressure. NGP tends to overestimate the tyre footprint when compared to other more complicated ground pressure models. The overestimated footprint leads to a dramatic underestimation of the ground pressure of the machine. NGP does not take into account the effects of tyre dynamics such as wall stiffness and inflation pressure, or the influence of different soil conditions (Saarilahti, 2002). **Figure 17** illustrates the influence of soil condition on tyre footprint which the NGP model does not take into account. The figure refers to the penetration level of the tyre into the soil as the soil becomes wetter and therefore softer (for clay soils). Nevertheless, NGP remains a valuable simple ground pressure indicator for comparing the ground pressures of various harvesting system options.

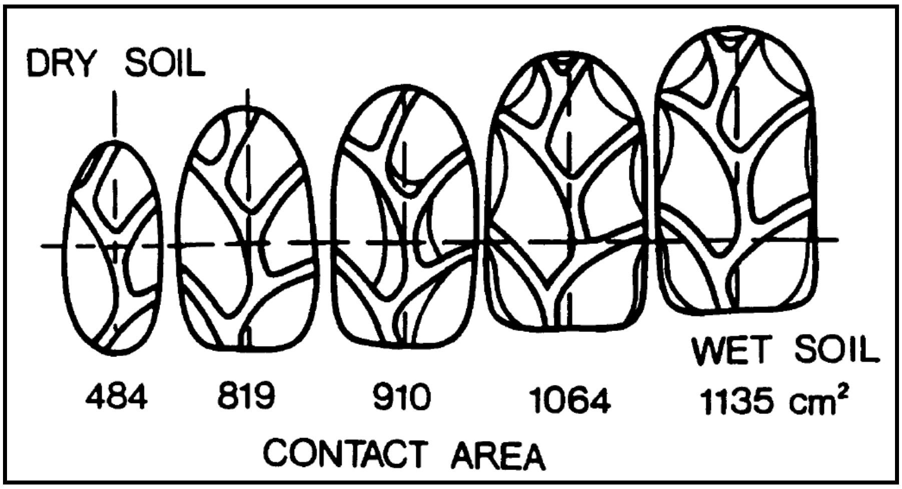


Figure 17. Effect of soil moisture content on tyre footprint. (Hallonborg, 1996)

The formulas below are adapted from Owende *et al.*, 2002 and Ireland, 2006. The adapted formulas aim to cover the most common wheel, track and band track combinations utilised in forestry operations.

- Ground pressure:

$$P = \frac{W}{A}$$

- Wheel load:

$$W = m \times 0.00980665$$

- Total machine footprint:

$$A = r \times b \times n$$

- NGP per wheel of wheeled machine

$$NGP_{W^{-1}} = \frac{W}{r \times b}$$

- NGP per track of tracked machine:

$$NGP_{T^{-1}} = \frac{W}{b \times (1.25 + L)}$$

- NGP for tracked machine:

$$NGP_{T} = \frac{W}{b \times (1.25 + L) \times n}$$

- NGP per band track of band tracked machine:

$$NGP_{BT^{-1}} = \frac{W}{b \times (1.25 \times r + L)}$$

- Total NGP for wheeled machines with the same tyres fitted front and rear:

$$NGP_{W_{F=R}} = \frac{m \times 0.00980665}{(r \times b \times n)}$$

- Total NGP for wheeled machines fitted with different sized front and rear tyres:

$$NGP_{W_{F \neq R}} = \frac{m \times 0.00980665}{(r_1 \times b_1 \times n_1) + (r_2 \times b_2 \times n_2)}$$

- Total NGP for machines fitted band tracks:

$$NGP_{BT} = \frac{W}{b \times (1.25 \times r + L) \times n}$$

- Total NGP for machines fitted with wheels and band tracks:

$$NGP_{W+BT} = \frac{m \times 0.00980665}{(r_w \times b_w \times n_w) + ((b_t \times (1.25 \times r_{w2} + L) \times n_t)A_{bt})}$$

Where:

A = Machine footprint (m^2).

A_{bt} = Band track plate gap correction factor. For example if 25% of area is track plate gaps then A_{bt} = 0.75, if 75% of area are gaps then A_{bt} = 0.25.

b = Wheel / track width (m).

b_1 = Width of front tyres (m).

b_2 = Width of rear tyres (m).

b_t = Width of band tracks (m).

L = Distance between wheel centres / centre of sprocket and idler (m).

m = Mass of machine (kg).

n = Number of wheels / tracks.

n_1 = Number of front wheels.

n_2 = Number of rear wheels.

NGP = Nominal Ground Pressure (kPa).

n_t = Number of band tracks.

P = Ground pressure (kPa).

r = Wheel radius (m).

r_1 = Radius of front wheels (m).

r_2 = Radius of rear wheels (m).

r_{w2} = Radius of wheels without band tracks (m).

W = Wheel / track load (kN).

The tables below illustrate the influence of machine weight, tyre size, track size, number of wheels and the use of band tracks on NGP. NGP values of less than 28 kPa are regarded as very high flotation (indicated as blue in the tables). NGP values of greater than 28 and less than 41 kPa are deemed to be high flotation (indicated as green). John Deere's forestry equipment was arbitrarily chosen for the comparisons.

Table 5 and **Table 7** clearly indicate that lighter machines with wider and longer tracks have lower ground pressures and are therefore better suited to sensitive sites. Similarly **Table 6** and **Table 8** denoting the wheeled varieties of these machines indicate that machines fitted with lighter attachments and wider tyres have smaller NGP values.

It is also noted that the tracked machines have much lower ground pressure ratings than their wheeled counterparts. The tracked harvesters listed have an average NGP of 42 kPa compared to 56 kPa (all wheeled harvesters listed), 65 kPa (wheels only) and 44 kPa (fitted with band tracks) for the wheeled harvesters. The tracked feller bunchers have an average NGP of 48 kPa compared to 59 kPa for wheeled feller bunchers. The fact that the tracked machines weigh more than double that of the wheeled machines highlights the effect of the bigger footprint of the tracked machines on NGP.

Table 9 and **Table 10** indicate that having more wheels increases the footprint of the machines and thus lowers the NGP of the machines considerably. For example the 18 ton 848H skidder halves its NGP from 61 to 30 simply by using dual wheels (having a total of 8 wheels instead of 4). Likewise an 810E forwarder can reduce its NGP from 76 kPa to 52 kPa by having band tracks fitted to its rear bogies or to 39 kPa by having four band tracks fitted. The NGP of the same forwarder could also be reduced to 65 kPa by using 710 mm wide tyres instead of 600 mm wide tyres.

The NGP of all the machines was calculated while static. The unloaded tyre radius of wheeled machines was used. The weight of forwarders was the weight with a full load and the weight of skidders was without timber in the grapple or hoisted with the cable. Band track widths were 900 mm and it was assumed that inter plate gaps were equal to 25% of the total band track contact area.

Table 5. NGP of Tracked Harvesters.

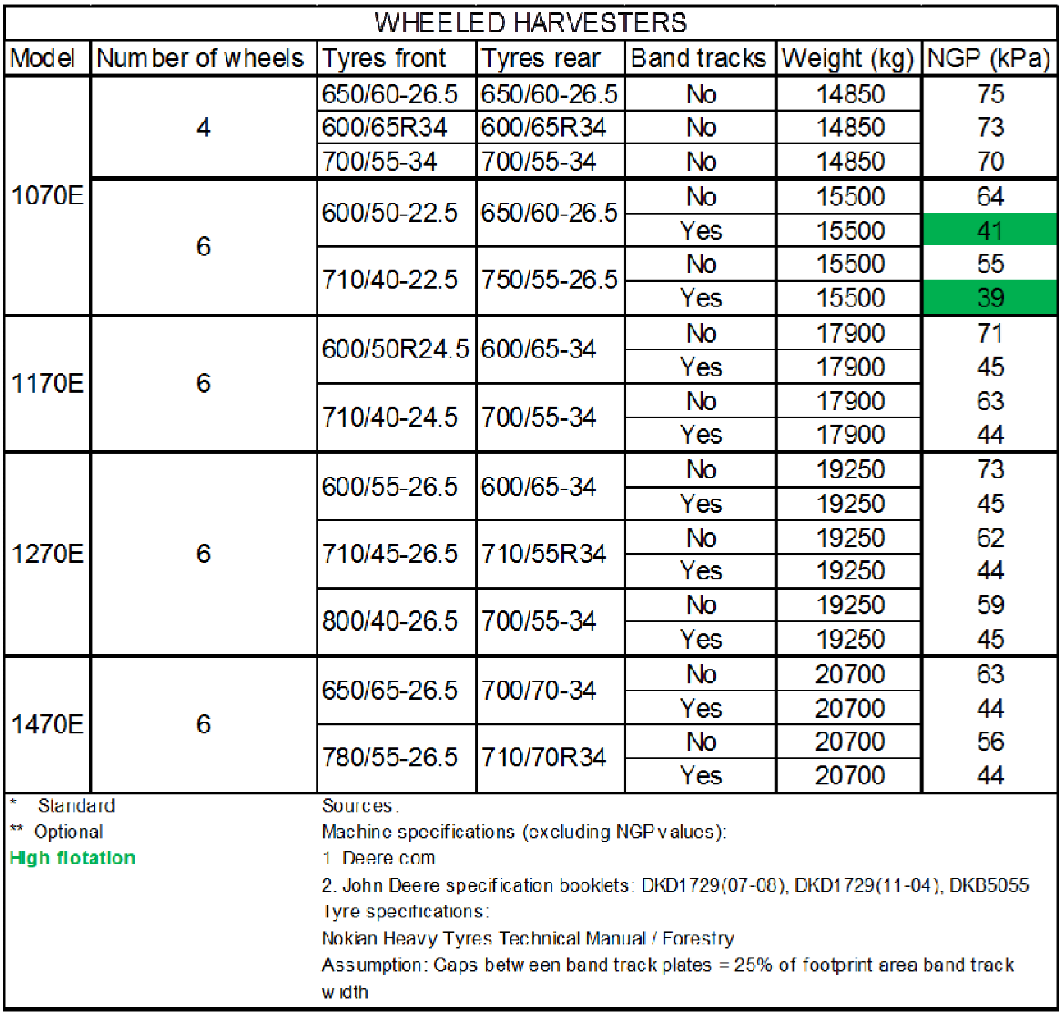
TRACKED HARVESTERS							
Model	Carriage	Attachment	Weight (kg)	NGP (kPa)			
				Track width (m)			
				0.61	0.711	0.76	0.914
703JH	U6 *	HTH616C	25351	44	38	35	29
		HTH622B	25809	45	39	36	30
		HTH623C	26490	46	40	37	31
753JH	U6 *	HTH616C	25292	44	38	35	29
		HTH622B	25750	45	38	36	30
		HTH623C	26431	46	39	37	31
	U7 **	HTH616C	25292	42	36	34	28
		HTH622B	25750	43	36	34	28
		HTH623C	26431	44	37	35	29
759JH	U6 *	HTH616C	28690	50	43	N/A	N/A
		HTH622B	29148	51	44	N/A	N/A
		HTH623C	29828	52	45	N/A	N/A
903KH	U7 *	HTH623C	32845	54	47	44	36
		HTH624C	33434	55	47	44	37
	U6 **	HTH623C	30658	53	46	43	36
		HTH624C	31248	54	47	44	36
909KH	U7 *	HTH623C	38687	61	53	N/A	N/A
		HTH624C	39277	62	53	N/A	N/A
	U7 ExD **	HTH623C	38896	62	53	N/A	N/A
		HTH624C	39485	62	54	N/A	N/A

* Standard
** Optional
High flotation
Very high flotation

Assumptions:
1.Weights of U7 carriage the same as U6 for 753JH (no data available).
2.Track lenght w as taken from sprocket centre to idler center.

Sources:
Machine specifications (excluding NGP values):
1. Deere.com
2. John Deere specification booklets: DKD1729(07-08), DKD1729(11-04), DKD100034.

Table 6. NGP of Wheeled Harvesters.



WHEELED HARVESTERS						
Model	Number of wheels	Tyres front	Tyres rear	Band tracks	Weight (kg)	NGP (kPa)
1070E	4	650/60-26.5	650/60-26.5	No	14850	75
		600/65R34	600/65R34	No	14850	73
		700/55-34	700/55-34	No	14850	70
	6	600/50-22.5	650/60-26.5	No	15500	64
				Yes	15500	41
		710/40-22.5	750/55-26.5	No	15500	55
				Yes	15500	39
1170E	6	600/50R24.5	600/65-34	No	17900	71
				Yes	17900	45
		710/40-24.5	700/55-34	No	17900	63
				Yes	17900	44
1270E	6	600/55-26.5	600/65-34	No	19250	73
				Yes	19250	45
		710/45-26.5	710/55R34	No	19250	62
				Yes	19250	44
		800/40-26.5	700/55-34	No	19250	59
				Yes	19250	45
1470E	6	650/65-26.5	700/70-34	No	20700	63
				Yes	20700	44
		780/55-26.5	710/70R34	No	20700	56
				Yes	20700	44

* Standard
** Optional
High flotation

Sources:
Machine specifications (excluding NGP values):
1. Deere.com
2. John Deere specification booklets: DKD1729(07-08), DKD1729(11-04), DKB5055
Tyre specifications:
Nokian Heavy Tyres Technical Manual / Forestry
Assumption: Gaps between band track plates = 25% of footprint area band track width

Table 7. NGP of Tracked Feller Bunchers.

TRACKED FELLER BUNCHERS							
Model	Carriage	Attachment	Weight (kg)	NGP (kPa)			
				Track width (m)			
				0.61	0.711	0.76	0.914
753J	U6 *	FS20 *	26317	46	39	37	31
	U7 **	FR21B **	29080	48	41	39	32
759J	U6 *	FS20 *	29819	52	45	42	35
	U6 *	FR21B **	30227	53	45	N/A	N/A
903K	U7 *	FS22B *	32944	54	47	44	N/A
		FR22B **	33407	55	47	44	N/A
	U6 **	FS22B *	30822	54	46	43	36
		FR22B **	31284	54	47	44	36
909K	HD *	FR22B *	39349	62	53	N/A	N/A
		FS22B **	38886	62	53	N/A	N/A
	ExD **	FR22B *	39707	63	54	N/A	N/A
		FS22B **	39245	62	53	N/A	N/A
953K	Standard *	FR24B *	35289	58	50	47	N/A
959K	ExD *	FR24B *	40914	65	56	N/A	N/A

* Standard
** Optional
High flotation

Assumption:
Track lenght was taken from sprocket centre to idler center.
Sources:
Machine specifications (excluding NGP values):
1. Deere.com
2. John Deere specification booklets: DKD1729(07-08), DKD1729(11-04), DKA5004

Table 8. NGP of Wheeled Feller Bunchers.

WHEELED FELLER BUNCHERS					
Model	Number of wheels	Tyres	Attachment	Weight (kg)	NGP (kPa)
643K	4	28L-26 14*	FD45 twin post	14896	62
			FD22B single post	15708	66
		30.5-32 **	FD45 twin post	14896	51
			FD22B single post	15708	54
843K	4	28L-26 14*	FD22B single post	15708	66
		30.5-32 **	FD22B single post	15708	54

* Standard
** Optional

Sources:
Machine specifications (excluding NGP values):
1. Deere.com
2. John Deere specification booklets: DKD1729(07-08), DKD1729(11-04), DKA643KFB

Tyre specifications:
Nokian Heavy Tyres Technical Manual / Forestry.

Table 9. NGP of Wheeled Skidders.

SKIDDERS						
Model	Number of wheels	Tire configuration	Tyre size	Attachment	Weight (kg)	NGP (kPa)
540G-III	4	Single	23.1-26 *	Standard blade *	10333	53
	8	Dual		Standard blade *	10333	26
	4	Single	28L-26 **	Standard blade *	10333	43
	8	Dual		Standard blade *	10333	22
640H (Direct drive)	4	Single	30.5-32 *	Standard blade *	13745	47
				Heavy duty blade **	13995	48
	8	Dual		Standard blade *	13745	23
640H (Torque converter)	4	Single	30.5-32 *	Standard blade *	13904	47
				Heavy duty blade **	14214	48
	8	Dual		Standard blade *	13904	24
548G-III	4	Single	23.1-26 *	Single function *	10746	55
	8	Dual		Single function *	10746	28
648H (Direct drive)	4	Single	28L-26 **	Single function *	14258	60
	4			Dual function **	14638	61
	8	Dual		Single function *	14258	30
648H (Torque converter)	4	Single	30.5-32 *	Single function *	14417	49
				Dual function **	14798	50
	8	Dual		Single function *	14417	25
748H (Direct drive)	4	Single	30.5-32 *	Dual function *	17028	58
	8	Dual		Dual function *	17028	29
848H (Torque converter)	4	Single	30.5-32 *	Dual function *	17826	61
	8	Dual		Dual function *	17826	30

* Standard
** Optional
High flotation
Very high flotation

Sources:
Machine specifications (excluding NGP values):
1. Deere.com
2. John Deere specification booklets: DKD1729(07-08), DKD1729(11-04), DKBGPLSKDR, DKBCBL.

Tyre specifications:
Nokian Heavy Tyres Technical Manual / Forestry.

Table 10. NGP of Forwarders.

FORWADERS						
Model	Number of wheels	Tyres front	Tyres rear	Band tracks	Weight (kg)	NGP (kPa)
810E	8	600/50-22.5	600/50-22.5	No	21950	76
				Rear	21950	52
				Front and rear	21950	39
		710/40-22.5	710/40-22.5	No	21950	65
1010E	6	600/65-34	600/50R24.5	No	24679	98
				Rear	24679	62
		28L-26	710/40-24.5	No	24679	83
	8	600/55-26.5	600/55-26.5	No	26479	81
				Rear	26479	54
				Front and rear	26479	41
		710/45-26.5	710/45-26.5	No	26479	68
		800/40-26.5	800/40-26.5	No	26479	61
1110E	6	600/65-34	600/55-26.5	No	26385	100
				Rear	26385	62
		710/55R34	710/45-26.5	No	26385	84
		28L-26	800/40-26.5	No	26385	78
	8	600/55-26.5	600/55-26.5	No	28186	86
				Rear	28186	58
				Front and rear	28186	44
		710/45-26.5	710/45-26.5	No	28186	73
		800/40-26.5	800/40-26.5	No	28186	64
1210E	6	600/65-34	600/55-26.5	No	28903	109
				Rear	28903	68
		700/55-34	710/45-26.5	No	28903	96
		28L-26	800/40-26.5	No	28903	85
	8	600/55-26.5	600/55-26.5	No	30799	94
				Rear	30799	63
				Front and rear	30799	48
		710/45-26.5	710/45-26.5	No	30799	79
		800/40-26.5	800/40-26.5	No	30799	70
1510E	6	600/65-34	710/45-26.5	No	30109	102
				Rear	30109	71
		710/55R34	800/40-26.5	No	30109	89
	8	710/45-26.5	710/45-26.5	No	32008	82
				Rear	32008	62
				Front and rear	32008	50
		800/40-26.5	800/40-26.5	No	32008	73
1910E	6	700/70-34	750/55-26.5	No	36344	104
				Rear	36344	80
		710/70R34	800/50R-26.5	No	36344	97
	8	750/55-26.5	750/55-26.5	No	39045	86
		800/50R26.5	800/50R26.5	Rear	39045	69
				Front and rear	39045	58
				No	39045	81

* Standard
** Optional
High flotation

Sources:
Machine specifications (excluding NGP values):
1. Deere.com
2. John Deere specification booklets: DKD1729(07-08), DKD1729(11-04), DKB810E, DKB8056

Tyre specifications:
Nokian Heavy Tyres Technical Manual / Forestry.
Assumption: Gaps between band track plates = 25% of footprint area band track width = 900mm

Wheeled machines

Due to limited traction, wheeled machines are not well suited to very steep slopes. Unless traction aids are used, aggressive tread patterns are usually needed to obtain sufficient traction.

Tyre tread patterns

Tyre tread patterns differ when traction is required for mud or to climb steep slopes. Tyres used in muddy conditions need a tread pattern which is angled in order to cut into the soft surface and disperse the mud from between the tread. If the tread is unable to disperse the mud, the tyres assume a smooth profile and traction is lost. The tread used on tyres which need to climb steeper slopes should be straighter across the tyre than the tread used in mud. A slight tread angle is still required as softer conditions will still be encountered. Flotation tyres need to have a large footprint area to reduce ground pressure (**Figure 18**). In forestry, traction is always required, and therefore even flotation tyres need traction tread patterns. The number of brands, models and configurations of tyres is large, therefore foresters need to understand their flotation and traction requirements in order to make correct tyre decisions.

Figure 18. Flotation vs. traction tyres (www.nokianheavytyres.com)

Tyre pressure

On very hard and dry soils, it might be necessary to reduce tyre pressure slightly to obtain more contact with the ground for traction. Operational experience has shown that once the tyre has below 50% tread wear left, it loses traction on steep slopes and excessive wheel slip occurs. The implication of this is that tyre costs will increase when using skidders on steep slopes as the tyres will have to be replaced sooner than usual. Tyre pressures should constantly be changed to match weather and soil conditions. Machine owners should be in possession of a tyre inflation matrix for their various machines that allows them to always select the most suitable tyre pressures. If there is uncertainty regarding the most suitable pressures, most manufacturers of forestry and agricultural tyres will willingly visit the operations and assist.

Water in tyres

Placing water in the tyres is an additional option to increase machine weight for increased traction and to lower the centre of gravity for improved stability. This is more important for skidding machines than forwarders. Placing water in the front tyres helps maintain balance when large loads are being extracted. Water also reduces the centre of gravity improving machine stability. Agricultural tractors used for skidding are very light at the front, and the winch protrudes back some distance from the rear axle, and water in the front tyres might be a necessity. Lighter machines may also require water in the rear tyres to provide extra traction when travelling up steeper slopes with no load. However, the extra weight can also result in increased fuel consumption and less power available for the load.

Tyre construction

Cross-ply tyres are tyres with a strong structure that can withstand high pressures, high loads and are good at withstanding penetration from objects such as stumps or rocks (**Figure 19**). Radial tyres are more flexible and have a longer contact area, which improves traction and flotation. Much debate still exists regarding which tyre construction is the most suitable for forestry operations. If the tyres are used exclusively off-road where there is a chance of tyres being cut, cross-ply tyres are still often preferred.

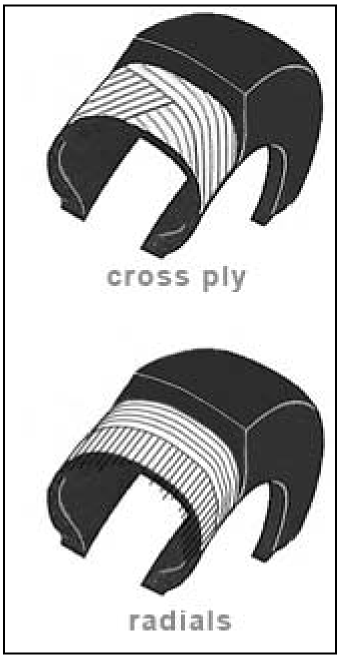


Figure 19. Cross ply vs. radial tyres (www.tructyre.com)

Bogie axles

Bogie axles (**Figure 20**) are tandem axles that are driven by a single differential which makes equipment fitted with them climb better on steep slopes (Kellogg *et al.*, 1993) by increasing traction and flotation (Ireland, 2006). They supply lower ground pressure when compared to single axles, with the bogie wheels having more tyre surface area which is in contact with the ground, thus creating better distribution of the wheel load. Bogies act like tracks and spread the machine weight over a larger surface area (Smidt and Blinn, 1995). Larger diameter tyres have lower ground pressures, but the use of bogie axles restricts tyre diameter, therefore only allowing tyres to be wider. However, the other benefits associated with bogie axles usually outweigh this disadvantage.

Figure 20. Bogie axle driving over stump (www.ponsse.com)

Flotation tyres and dual tyres

Wide tyres and dual tyres, as seen in **Figure 21**, are also used to lower the ground pressure of forestry vehicles (Osenga, 2002). Wide or dual tyres can improve the flotation of equipment, but this can compromise the machines steep slope handling properties due to reduced traction. Skidders are often equipped with wide tyres (up to nearly 2 m) or dual tyres to reduce ground pressure on very soft soils. Dual tyres need to have a sufficient gap between them to allow them to get rid of mud when used in very wet conditions.

Figure 21. High flotation and dual tyres on clambunk skidders (http://nrs.fs.fed.us/)

Traction aids for wheeled machines

Traction aids are components attached to forestry equipment in order to increase the traction between the ground-based harvesting equipment's wheels and the ground surface. Traction aids can be also used to increase the load distribution over the ground if they increase the machines footprint. Traction aids can also improve stability and protect tyres. However, improper selection can excessively disturb forest soil, damage the standing trees and negatively affect the machine mechanics and operator ergonomics (Ireland, 2006).

Machines must be carefully matched with the site conditions to obtain maximum results when planning to use tractive systems. Before traction aids like wheel chains and tracks can be selected for use on specific terrain, the ground conditions have to be evaluated to ensure that the suitable traction aids are installed on the machine. Important to note is that the tyre specification will also have an effect on the level of traction gained. This means that the different tread patterns on the tyres will have varied effects on the grip, load distribution, flotation and self-cleaning properties of the wheels of the equipment when operating on steep slopes. Traction aids available for attachment on machines include bandtracks (also called bogie tracks), wheel chains, and monotracks amongst others. Monotracks are similar to bandtracks but they can only be attached to one wheel (Ireland, 2006). Readers are referred the document titled "Traction Aids in Forestry" produced by the Forestry Commission, as it contains comprehensive and useful information - http://www.forestry.gov.uk/pdf/fctn013.pdf/$FILE/fctn013.pdf. The sections below provide an overview of traction aids and their relevance to steep slope harvesting.

Traction aids for wheels – bandtracks

To enhance the traction on wheels and obtain better weight distribution onto the ground, bandtracks can be fitted around the bogie wheels (Kellogg *et al.*, 1993). As per **Figure 22**, bandtracks are "metal plates connected by heavy-duty linkages that fit over a pair of bogie wheels. Varying designs and plate profiles give different flotation, traction and steep ground working capabilities to the machine" (Ireland, 2006). Band tracks can result in improved soil bearing capacity and better traction on soft soils as the tyres remain cleaner (Suvinen, 2006). Most bogie axles on mechanised forestry equipment can be fitted with bandtracks (Owende *et al.*, 2002). Two different types of bandtracks are commonly used, being side links and side paws. Side link tracks are better suited to machines that do not need to move often between sites, as the tracks can damage roads. Side link tracks cost less, but do not fit as well as side paws on the tyres. Bandtracks can add to weight of the machine and increase rolling resistance (Ireland, 2006). However, the benefits obtained from increased traction and/or flotation can still make them beneficial. The additional weight reduces the centre of gravity of the machine, which makes it more stable on steep or rough terrain.

Figure 22. Traction band tracks fitted to a forwarder

Band tracks have the potential to significantly reduce ground pressures, enabling machine operation on much softer and/or sensitive soils. Owende *et al.* (2002) indicated that a loaded four-wheeled forwarder could have nominal ground pressures (NGP) ranging from 80 to 100 kPa. Utilising a six-wheeled forwarder with one bogie axle can reduce this to between 70 and 80 kPa, and placing band tracks on this bogie can reduce it further to between 50 and 60 kPa. An eight-wheeled forwarder with two bogie axles could have also have NGP's of between 50 and 60 kPa, but using band tracks on both bogies can reduce this value to between 40 and 50 kPa.

Less aggressive tyre tread patterns are required when using band tracks. The tyre and track must be compatible or tyre wear will increase. There are multiple configurations of bandtracks. Specialised tracks are made for soft ground (flotation requirements), traction requirements or rocky terrain. Smaller gaps between track plates results in higher flotation properties. To access steeper terrain, additional traction is required, which necessitates having wide gaps. Additional anti-skid spikes can be welded onto the bandtracks to provide extra traction. These spikes also can improve the grip to prevent lateral movement of the machine on a particular site (John Deere, 2006). Bandtrack selection is of paramount importance, because if traction is required for steep slope handling, smaller diameter band tracks with narrow plates and larger plate spacing are required. However, this does reduce the stability of the machine, which requires that it must move straight up and down the slope.

Debate has existed surrounding the removal of bandtracks during periods when the soil is dry or has higher bearing strength. Suvinen (2006) showed that fuel consumption of an 8-wheeled Timberjack 1110 forwarder with band tracks on the rear bogie and wheel chains on the 2nd axle increased significantly with bandtracks compared to just wheels when operating on soils of high bearing strength. The laden mass of the forwarder increased by 11% when using band tracks, with each pair weighing 1 850 kg. Fuel consumption increased by six to seven per cent on an uphill slope when empty, but by 40 to 60% when laden. On downhill slopes, the difference was even greater, but due to the base fuel consumption with just wheels being much lower, the actual additional fuel consumed was not great. Band tracks significantly increased fuel consumption under dry conditions when extraction distances were long and loaded driving took place on even or uphill terrain. Using the assumption that it takes 1.5 hours to install or remove band tracks by two experienced workers, the financial breakeven point where the fuel savings warrant the installation or removal can be as little as five hectares harvested. This value is affected by extraction distance, terrain and volume per hectare. Please note again that these results are only applicable to soils with high bearing strength.

Bandtracks can also protect the machines transmission by preventing wheel slip which can create spikes through the transmission.

Monotracks have similar properties to bandtracks. Most of the information above is therefore also applicable to monotracks.

Traction aids for wheels - chains

Wheel chains are “an assembly of specialised chain links and/or rings fitted over the bare tyre to provide additional traction and tyre protection” (Ireland, 2006). Traction can be increased by installing wheel chains, which increase the grip of the tyres allowing the machine to access steeper slopes. Wheel chains do not have an increased effect on the flotation of the equipment. If rings are incorporated into the design of the chains (**Figure 23**), traction can be increased further, but they can increase ground disturbance and should therefore only be used where sites allow. The fitting and compatibility of tyre chains has to be done accurately so they can effectively protect the tyres from being damaged from slippage during the harvesting operations (Ireland, 2006).

Figure 23. Tyre chains with rings (www.babactirechains.com)

Stoilov (2007) showed that wheel chains increased traction of a wheeled cable skidder compared to only wheels. The tractive effort of only wheels increased with decreasing tyre pressure due to an increased wheel contact area and lower sinkage depth. Tyre pressure should not be reduced beyond manufacturer recommendations or tyre damage will occur. For wheel chains to operate effectively, tyre inflation pressure needed to be high (but still within manufacturer recommendations) and the wheels chains needed to be very tight fitting. The tyre should be deflated before fitting the chains and then inflated again. After inflation the chains should be tight fitting. After 10 minutes of operation, the chains should be tightened again. If this procedure is carried out four times, the tension should be correct for some time, although regular checks are still necessary.

As per the section on band tracks, there is debate surrounding the removal of wheel chains during periods when the soil is dry or has higher bearing strength. Suvinen (2006) showed that the fuel consumption of an 8-wheeled Timberjack 1110 forwarder with wheel chains on the 2nd and 3rd axle, only increased marginally when using chains compared to just wheels when operating on soils of high bearing strength. Fuel consumption of the unladen machines was virtually the same for just wheels or wheels with chains. The laden mass of the forwarder increased by 4% when using wheel chains, with each pair weighing 400 kg. Using the assumption that it takes 1.25 hours to install or remove the wheel chains by two experienced workers, the financial breakeven point where the fuel savings warrant the installation or removal was only after a large amount of hectares were felled. It was therefore not justified to remove and attach wheel chains frequently, and this would only take place if the forwarder was to operate on soils of high bearing strength for an extended period of time. Of interest was that wheel chains on a loaded forwarder on steep uphill slopes on high bearing strength soils resulted in more wheel slip (as did the band track test), which made the tyre penetrate into the soil and increase rolling resistance.

Tracked machines

Tracked machines are capable of operating on slopes of up to 50%, with short lengths of steeper slopes of up to 60% being accessed under controlled conditions, and slopes of up to 70% with specialised designs (MacDonald, 1999). Tracked machines also have proportionately better upslope extraction capabilities than wheeled machines. Tracked machines are not able to operate on rock due to limited traction.

Even though tracked machines are considerably heavier than wheeled machines, their NGP is much lower. Owende *et al.* (2002) indicate that a four wheeled harvester could have NGP's of greater than 80 kPa, while a six wheeled harvester would reduce this to between 50 and 70 kPa, and an eight-wheeled harvester to between 45 and 60 kPa. However, a typical non-levelling tracked harvester will have NGP's of less than 30 kPa's.

Narrow tracks improve machine traction, but reduce flotation **(Figure 24**). Wider tracks improve flotation but slide easier with slippery underfoot conditions. Most machine manufacturers offer optional wider tracks to improve flotation. Single, deeper grousers are used on steep slopes. They are able to penetrate into the soil and the spaces between grousers do not fill with mud as easily. Double deep grousers can also be used on steep slopes. Shallow triple grousers have even been known to slip on pine needles that overly wet clay soils.

Figure 24. Single and triple grousers, and traction and flotation tracks (www.tigercat.com)

Flex tracks

The suspension of flex-tracks (**Figure 25**) allows the full length of the tracks to stay in contact with the ground, even when travelling over rough terrain. This provides better traction and therefore better slope handling capabilities. Flex tracks can operate safely on slopes of up to 60% (MacDonald, 1999). However, the purchase and operating costs of machines with flex-tracks are very high, which has resulted in them not commonly being used in harvesting operations anymore. Due to their good difficult terrain handling capabilities, it could be worthwhile to keep these machines as a consideration for future system selection, as they might still have lower costs than cable yarders.

Figure 25. Flex track equipment (www.lumbermen.com and kmc-kootrac.com)

Cab and upper structure

This refers to the seat structure and the self-levelling or non-levelling ability of the upper structure or cab of the harvesting machine. The cab and upper structure of harvesting equipment is important when harvesting on steep slopes because it provides protection for the operator and may also maintain productivity. The upper structure is inclusive of the cab and it refers to the dimensions (zero tail swing/tail swing) of the top unit and its ability to tilt in different directions. It improves operator efficiency, machine stability and performance with its levelling system.

Levelling upper structures and cabs

As already indicated, steep terrain has traditionally been classified as any slope over 35%. Chainsaws were the predominant machines used for felling. Since the 1990's however, steep terrain felling machines have been produced that are capable of operating to nearly 60% slopes. The main contributor to this increase has been the development of levelling operator cabs and machine upper structures (**Figure 26**) that maintain stability and keep the operator in the correct ergonomic position. Previously, the levelling of the upper structure was an automated function, but operators lost perspective of the slopes that they were operating on, and the levelling mechanisms are now controlled by the operator. Continuous rotation turntables with larger 4-way levelling components improve the stability of the machine and the performance on steep slopes. Levelling machines need to be fairly heavy as stability is required due to them operating on steep slopes. With wheeled machines, the actual slope handling ability of the machine is not improved by having a levelling cab. However, due to the operator being kept in a better ergonomic position, they are able to maintain higher levels of productivity and for longer periods.

Figure 26. Harvesters with a levelling upper structure (www.impex-forstmaschinen.de and www.neuson-ecotec.com)

Two of the most important elements that determine the ability of forestry machines to work on steep terrain are the levelling ability of the machines and the tractive force/effort that they generate. **Table 11** to **Table 14** summarises the peak engine power outputs (kW), tractive force (kN) and levelling abilities of the 2011/2012 line-ups of six of the most commonly used forestry equipment brands in the southern hemisphere. The brands selected for the study were Cat, Komatsu, John Deere, Tigercat, Timberpro and Ponsse. The tables list only the feller bunchers, harvesters and forwarder models that have some form of tilting or levelling ability.

Table 11. Feller buncher levelling information

Feller Buncher Levelling					
Model	**Engine power (kW)**	**Tractive Force (kN)**	**Tilting Ability (%)**		
			Front	**Rear**	**Side**
Tracked Zero Tail Swing					
Tigercat LX822C	224	293	49	11	36
Tigercat L830C	224	367	49	12	40
Tigercat LX830C	224	343	49	12	40
Komatsu XT430L-2	224	275	51	9	36
Komatsu XT445-2	224	331	51	9	36
Komatsu XT450L-2	224	331	47	11	32
John Deere 759J	180	256	51	18	32
CAT 522	212	336	31	None	27
CAT 532	212	378	31	None	27
Timberpro TL725-B	224	305	53	12	45
Timberpro TL735-B	224	356	53	12	45
Tracked Tail Swing					
Tigercat L845C	205	293	36	11	32
John Deere 909K	224	331	49	12	25
John Deere 959K	246	384	49	12	25
CAT 552	227	463	31	None	27

Table 12. Tracked harvester levelling information

Tracked Harvester Levelling					
Model	**Engine power (kW)**	**Tractive Force (kN)**	**Tilting Ability (%)**		
			Front	**Rear**	**Side**
Tracked Zero Tail Swing					
Tigercat LH822C	224	293	49	14	40
Tigercat LH830C	224	367	49	14	40
Komatsu XT430L-2	224	275	51	9	36
Komatsu XT445-2	224	331	51	9	36
Komatsu XT450L-2	224	331	47	11	32
John Deere 759JH	180	256	51	18	32
CAT 522	212	336	31	None	27
CAT 532	212	378	31	None	27
Timberpro TL725-B	224	305	53	12	45
Timberpro TL735-B	224	356	53	12	45
Tracked Tail Swing					
Tigercat LH845C	205	293	38	14	40
Tigercat LH855C	205	367	36	12	27
John Deere 909KH	224	331	49	12	25
CAT 552	227	463	31	None	27

Table 13. Wheeled harvester levelling information

Wheeled Harvester Levelling					
Model	**Engine power (kW)**	**Tractive Force (kN)**	**Tilting Ability (%)**		
			Front	**Rear**	**Side**
Wheeled					
Tigercat 1135	170	Not supplied	40*	27*	27*
Komatsu 911.4	170	162	40**	36**	31*
Komatsu 911.5	170	162	40**	36**	31*
Komatsu 931.1	193	175	36**	40**	29*
Komatsu 931	193	175	36**	40**	29*
Komatsu 941.1	210	190	40**	36**	31*
John Deere 1070E	136	130	18*/53**	18*/25**	31*
John Deere 1170E	145	150	18*/53**	18*/25**	31*
John Deere 1270E	170	175	18*/53**	18*/27**	31*
John Deere 1470E	190	180	18*/53**	18*/27**	31*
Ponsse Bear	240	200	36*/19***	36*/14***	None
Ponsse Beaver	129	130	32*/19***	21*/14***	None
Ponsse Ergo	205	160	32*/19***	21*/14***	None
Ponsse Fox	145	155	27*/19***	27*/14***	None
Ponsse Ergo 8x8	205	180	36*/19***	36*/14***	None
CAT 550	147	Not supplied	31*	5*	27*
Timberpro TB 630-B	224	Not supplied	40*	None	None
Timberpro TB 830-B	224	Not supplied	40*	None	None

* Cab
** Crane
*** Seat

Table 14. Forwarder levelling information

Forwarder Levelling					
Model	**Engine power (kW)**	**Tractive Force (kN)**	**Tilting Ability (%)**		
			Front	**Rear**	**Side**
Wheeled					
John Deere 810E	95	110	11*	11*	18*
John Deere 1010E	116	150	11*	11*	18*
John Deere 1110E	136	160	11*	11*	18*
John Deere 1210E	140	175	11*	11*	18*
John Deere 1510E	145	185	11*	11*	18*
John Deere 1910E	186	220	11*	11*	18*
Ponsse Gazelle	129	130	18**/19***	18**14***	None
Ponsse Wisent	129	160	18**/19***	18**14***	None
Ponsse Elk	129	170	18**/19***	18**14***	None
Ponsse Buffalo	205	180	18**/19***	18**14***	None
Ponsse BuffaloKing	205	210	18**/19***	18**14***	None
Ponsse Elephant	205	220	18**/19***	18**14***	None
Ponsse ElephantKing	205	240	18**/19***	18**14***	None

* Cab
** Crane
*** Seat

In general the lay person would be tempted to look only at the engine power output of a machine and make judgement on its slope handling performance based on the kW rating. In such a case it would be assumed that all machines with a peak power output rating of 224 kW will have the same slope handling ability. In reality it is the efficiency of which the power generated by the engine is translated into tractive effort at the wheels or tracks that is the more accurate comparison of the different machines.

Of the 19 machines listed in the tables with a 224 kW rating there were seven different tractive force ratings ranging from 275 kN to 367 kN, resulting in a difference of 92 kN. The difference between engine power and tractive force is made even more significant if it is taken into account that eight of the 19 machines are basically duplications of models with different attachments. This means that 64%

of the machines with a 224 kW rating have different tractive forces. If the 227 kW Cat 552 tracked tail swing harvester is added to the list, it is noted that machines of similar kW rating can have a substantial difference in tractive effort. There is a 188 kN difference between the 224 kW machine with the lowest tractive force rating (275 kN) and the 463 kN rated Cat 552.

Having a high tractive force rating does not however necessarily translate into a higher slope handling ability. If the tyres or tracks of the machine do not provide the correct amount of traction, the excessive tractive force will simply cause an increase in wheel slippage. In fact various authors warn that forestry equipment pose a risk of increased soil damage by having unnecessarily high tractive force. This said, a machine with high tractive force coupled with the correct wheel or track configurations will have much better slope handling capabilities than similar machines with inferior tractive effort.

The principle of high tractive effort also explains why it is preferable to use wider tracks with single grousers and tyres or traction aids that provide greater traction levels on steep terrain.
The second factor that the tables highlight is the different levelling abilities of the machines. There are three main types of levelling devices employed by the manufacturers, being levelling cabs/upper structures, seats and cranes.

Levelling upper structures offer the greatest advance in slope handling ability by shifting the centre of gravity and thereby making the machines more stable on slopes. The levelling upper structures further enable swing to tree machines to slew more efficiently and with less effort since it does not need to overcome gravity due to the upper structure remaining level.
Levelling seats and cabs provide the operator with a mental sense of security by creating a false sense of security by making the slope feel less steep. Ergonomically it also places less strain of the operator. Tilting cranes extend the reach of the crane without excessive movement of the machine and increases its lifting ability while maintaining a better centre of gravity, both factors that aid in stability on steep slopes. Tilting cabs enable the operator to have a better view of his surroundings by allowing him to move the cab in order to see past an obscuring crane for example.

It is worthwhile to note the difference in slope handling capability between machines with and without a levelling function. The results of the steep slope harvesting survey summarised in **Table 15** below highlight these differences.

Table 15. Selected results of steep slope harvesting survey

		Feller Buncher					
		Wheeled			**Tracked**		
		Non-Levelling	**Levelling**	**Difference**	**Non-Levelling**	**Levelling**	**Difference**
Slope (%)	**Uphill**	30	40	10	40	60	20
	Downhill	20	30	10	25	40	15
		Harvester					
		Wheeled			Tracked		
		Non-Levelling	Levelling	Difference	Non-Levelling	Levelling	Difference
Slope (%)	**Uphill**	35	45	10	40	55	15
	Downhill	20	35	15	25	35	10

With no levelling capability on steep slopes, the machine would have to reduce its load because of the additional power required to swing the boom and its load, and rack width would have to be reduced (AFAG, 2006). The comfortable position of the operator in the cab increases safety and productivity contrary to the fact that the machine is on a steep slope. Gellerstedt (1998) showed a 5 to 10% increase in the productivity of a wheeled harvester with a levelling cab compared to a non-levelling cab. Operators working in levelling cabs must always be aware of the actual slopes conditions, as the extraction equipment, which often has a higher centre of gravity, needs to access the timber safely. Operators also need to be aware of the weight transfer that takes place when slewing larger trees that are not close to the machine. It is often better to first draw the tree towards the machine before slewing begins (AFAG, 2006).

A machine equipped with a 4-way levelling system improves the balance required on the machine when operating on difficult ground conditions and steep terrain (Caterpillar, 2009). The levelling mechanism needs to also move the upper structure forward to keep the centre of gravity in the optimal position over the tracks. The upper structure of the machine should keep the centre of gravity in an optimal position regardless of the tilt of the machine. Stability is created when the twin tilt cylinders extend and the upper tilts move forward relative to the tracks. The centre of gravity is then moved more towards the steep side increasing the suitability of equipment to work on steep slope with this technology (Kryzanowski, 2005).

For a construction excavator carrier to be more suitable on difficult terrain, a levelling system can be fitted. Levelmax (**Figure 27**) is a Volvo levelling module which is installed between the undercarriage and the upper structure. This technology was adapted and improved from the New Zealand Sub-Flex system. The Levelmax can improve visibility and stability by levelling the cab in all directions by up to 38.4%. The Levelmax has sensors that monitor the carrier’s position in relation to its ground angle position, the levelling hydraulics are monitored and controlled by the onboard computer (Volvo, 2008). Even though these levelling systems were predicted to become very popular for machines operating on moderate slopes, they are not commonly used. This could be due to the numerous other limitations of using construction excavators on steep slopes.

Figure 27. Volvo Levelmax system in action (www.volvoce.com)

Tail swing and zero tail swing

Machines with zero tail swing allow for good ground and forest stand clearance (Caterpillar, 2009). However, they lack the counterbalancing of a tail swing machine which reduces the machines lifting capacity, especially with large trees at the extreme of the booms reach (**Figure 28**). Tail swing machines are limited on steep slopes even if levelling mechanisms are used, as the tail swing can strike the machine tracks while slewing. Therefore, felling very large trees on steep slopes is problematic as the counter balance is required for machine stability. Therefore, larger zero tail swing machines are needed to retain some of the stability with large trees.

Figure 28. Tail swing vs. zero tail swing (www.tigercat.com)

Booms and boom configuration

The different crane and boom sizes available for the machine must be known to ensure that the machine is suitable for use on steep slopes. A telescopic boom can extend to reach trees located on steep pockets. However, it is not possible for the telescopic boom to process at full reach; the boom must first be retracted. In order to maintain optimal performance from any boom, especially with wheeled machines, lifting of the load and processing should always take place as close to the machine as possible.

Many harvesters and forwarders now have the option of being fitted with a crane with a tilt function which makes it possible for the machine to tackle steeper terrain. The crane tilt function allows the slewing motor to rotate the crane instead of lifting it. The aim is to maintain the boom pillar upright to keep stability and prevent damage where the boom joins the machine. The backward tilting of the crane pillar is commonly from five to fifteen degree angles. More trees or logs can be reached and handled on steeper ground without compromising safety due to the crane or boom not having to use additional power to overcome gravity.

With a standard boom in thinning, only a limited number of trees can be felled from one position. Cranab have produced a crane (**Figure 29**) that has an extra join on the outer boom to allow 30 degrees of horizontal slewing deflection in each direction. The cylinders that allow this movement are placed so that they do not increase the width of the boom. The design is called Cranab Access, and it is available in single and double telescopic designs. This extra movement reduces boom machine movement, which can assist on steep and rough terrain. An additional advantage is less damage to residual trees. Research into this new angled harvester crane revealed that it had used four to six per cent less time compared to the standard crane (Nordfjell *et al.*, 2007).

Figure 29. Angled harvester crane (www.cranab.se)

When travelling up and down the slope on very steep slopes, the boom should be extended out on the upslope side of the machine, with the attachment just above the ground. Even if the operator is reversing down the slope (steep slopes), the boom should still be in the upslope position. However, the operator's vision is then obscured as the upper structure is also facing uphill, and the operator must slightly slew the boom to one side. Over-slewing will affect machine stability. In an emergency, the operator may drop the attachment to the ground to stabilise the machine, and the boom needs to be strong enough to handle this stress. Also, in extreme cases, the boom might be used to pull the machine up a short steep section of slope where traction is being lost.

Machine as a whole

Ground based equipment with long and wide wheelbases are most stable when skidding on slopes or broken terrain (Kosicki, 2003). Kosicki (2003) also states that machines operating on steep and rough terrain should have sufficient power and a suitable transmission. The torque convertor needs to match the pulling force to the various ground conditions, which results in smooth operation on rough ground.

The ability of the machine to work on steep slopes will be determined by the modifications applied to the machine as a whole. Individual components contribute to the increased efficiency, traction and safety of the machine to climb better and be stable on steep pockets.

Fitting skidding blades (**Figure 30**) to machines operating on difficult terrain has advantages. Should the machine start to slide, it can lower the blade to act as a brake. It can also provide additional stability to harvesters when they fell and process trees and to forwarders during loading. They can also move certain obstacles out of the machines path, create minor skid trails if necessary and move slash.

Figure 30. Skidding blade fitted to a tracked harvester (www.neuson-ecotec.com)

Hydrostatic transmissions on skidders allow them to extract larger loads on steeper slopes. This allows controlled increases in speed between zero and top speed with no gear changes. Therefore the load is always matched with the engine power and there is no chance of an incorrect gear or stalling. This can also improve fuel efficiency as less wheel slip occurs.

When operating on difficult terrain, there is no better machine than a well backed-up and supervised, purpose-built machine designed for these conditions, operated by a well trained and experienced operator. The machines which provide the greatest safety and environmental risks and mechanical downtime, are machines not designed for these conditions or machines that require many modifications in order to meet the safety or environmental requirements. MacDonald (1999) points out that purpose-built equipment can operate safely on slopes of up to 60% because they have been designed to operate on such conditions. However, any machine operated irresponsibly can cause environmental damage or be a safety risk.

Operating techniques and equipment for difficult terrain

Operating techniques refers to the different methods that can be used with ground based harvesting equipment in harvesting of trees remaining on small steep pockets. Through innovative techniques, steep pockets can be harvested by using the normal ground based systems instead of introducing other systems to harvest the small areas. Techniques like felling ahead of the harvester, increasing rack width and special machine operating methods can be useful in harvesting the steep pockets.

Innovative techniques and equipment for harvesting on steep slopes

Synthetic ropes

Steel wire rope is traditionally used in harvesting operations in South Africa. This is due to its strength and durability characteristics. However, wire ropes are generally heavy and inflexible, making them difficult to handle, especially on steep slopes. Synthetics ropes (**Figure 31**) have increased in global use as a possible alternative to wire ropes, with examples being in the shipping and towing industries (Boswell, 2008). Synthetic ropes are not common in South African harvesting operations, but as is currently the situation in North American and European forestry, their use is expected to increase. New technology has enabled synthetic ropes to be lighter, stronger and more durable (Garland *et al.*, 2003), although their abrasion resistance properties are still insufficient for high ground roughness areas where the rope will come into frequent contact with the ground. However, if abrasion occurs in synthetic rope, its residual strength declines in proportion to the material lost, whereas steel ropes lose strength more rapidly (Garland *et al.*, 2003).

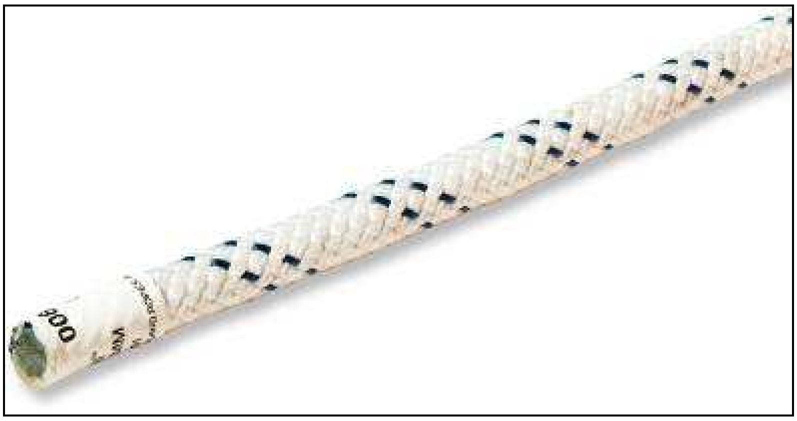


Figure 31. Synthetic rope (www.forestry-suppliers.com)

The benefits of using synthetic rope on steeper slopes is that labour ergonomics is improved due to lighter ropes, and fatigue is reduced (Garland *et al.*, 2003). Synthetic ropes can be manually pulled out up to three times further than steel ropes in cable skidding operations. Ottaviani *et al.* (2011) studied replacing a 3.5 mm steel rope used as a strawline with a 4 mm synthetic rope. The equivalent force to pull the steep rope 300 m up a slope was only reached at 1,200 m with the synthetic rope. When carrying the steel rope 300 m, 21 kJ of energy was used compared to 8 kJ for the same distance with the synthetic rope. The results showed that labour productivity improvements were possible, and possibly reduced labour units as well. Due to the amount of cable skidding (tractor and articulated wheeled) and cable yarding that is carried out in South Africa, research into the use of synthetic ropes under South African conditions is urgently needed.

Anderson (2006) compared steel cables versus synthetic ropes with wheeled cable skidders. The synthetic rope showed 15% higher productivity than the steel ropes. No problems were experienced with rope breakage and operator feedback regarding the synthetic ropes was very positive.

If the synthetic wires in the rope do break, they will not cause injury like the “jaggers” produced by steel wire. Synthetic ropes are very popular with the labour that has tested them, or currently use them. However, synthetic rope suitable for harvesting operations is expensive, and therefore the productivity and ergonomic advantages of the wire rope will have to exceed the cost of the rope (Garland *et al.*, 2003).

Prepared tracks for harvesting and extraction

An excavator based harvester was able to work on slopes of between 20% and 60% with prepared tracks along the contours. Chainsaws were used to fell the trees down the slope along the tracks. The trees lying adjacent to each path constructed were picked up by the harvester and swung around and processed, and then stacked behind the harvester on the track (Spinelli *et al.*, 2002). The machine had a long boom that could slew 360 degrees which enabled it to reach felled trees and process them.

An integration of a number of machines is sometimes required to overcome some steep slope obstacles (**Figure 32**). For example, (Lileng, 2007) found that harvesters and forwarders can function productively on very steep terrain if the skid trails are prepared beforehand by an excavator. The system comprised of chainsaw felling, a harvester (Valmet 911.3), forwarder (Valmet 840.3) and an excavator (Caterpillar 317B). The excavator constructed basic skid roads with a maximum gradient of 40%, but an average of 25 to 30. The side roads were 4.3 m wide with an average cutting height of 1.7 m and fill depth of 1.6 m. The trails were built only using local material and harvest waste. The trees that could not be reached by the harvester were felled in the direction of the skid trails using chainsaws. The skid roads were used by the harvester and forwarder during the harvesting process. The mean slope of the compartment was 59%. The skid roads can be prepared on slopes of up to 75%. The environmental impact of this operation can be severe and the cost implications can be high. The harvesters and forwarders were able to maintain high levels of productivity on these steep slopes.

Figure 32. CAT317B, Valmet 911.3 and Valmet840.3 (www.entreeding.com, technikboerse.com and www.mascus.com)

An alternative skidding method for wheeled skidders that can be used on steep slopes is one which utilises a system of selected pre-planned bladed skid roads On these roads, the skidder operator can travel on much steeper ground up to points where timber can be choked by pulling the winch line to the felled trees while the skidder remains on the skid road (Erickson *et al.*, 1991).

Saunders (2011) investigated a system whereby a Valmet 941, 6-wheeled harvester felled and processed trees for a John Deere 1710 forwarder on slopes of up to 55% (**Figure 33**). The harvester operated straight up and down the slope. The harvester placed a slash mat in front of it to aid traction on the steeper slopes. On slopes of greater than 55% and up to 80%, an excavator constructed extraction routes across the slope. The trees next to the extraction routes were felled with chainsaws, and the harvester would grab and process them from the extraction route. Trees out of reach of the harvester were felled with chainsaws and winched to the extraction route for processing. In this operation, the forwarder would remove slash from certain extraction routes and place it on other key routes.

Figure 33. JD 1710D and Valmet 941 (www.bellequipment.com and www.komatsuforest.com)

High-rotation feller buncher heads

High-rotation feller buncher heads (**Figure 34**) have become increasingly common. They consist of a swivel that provides for various degrees of movement. The head can be aligned with the tree if it is not standing vertically (MacDonald, 1999). Trees with heavy lean, such as found on certain steep slopes, can be felled and placed in larger bunches at the desired angle for the extraction equipment. Conventional heads only had 20 degrees of movement (MacDonald, 1999) and had to place the trees in line with the longitudinal axis of the machine.

Figure 34. Feller buncher with high rotation head (www.tigercat.com)

Shovel logging

The South African Ground Based Harvesting Handbook (2010) contains detailed information on the operating method of shovel loggers, and characteristics which the machine should have. Shovel logging is usually used in very wet or very steep areas. When used in wet areas, a feller buncher fells and bunches trees. The shovel logger then moves these trees closer to the extraction routes, and some of the trees are placed in a thick mat on the extraction route. Grapple skidders (often with high flotation or dual tyres) then travel on the mat of trees during extraction. The skidder begins extracting from the furthest point and collects the trees from the extraction route as it progresses.

Shovel loggers (example shown in **Figure 35**) are increasingly being used on steep areas to bridge the gap between the slope capabilities of the felling and extraction machines. The slope handling of the felling machine is typically restricted to that of the extraction machine, as the timber needs to be accessed for extraction. Because the shovel logger is usually a levelling tracked machine, it usually has the same slope handling capabilities of the felling machine. It can therefore move trees that are situated on slopes too steep for the extraction machine, to an area where access is possible. This prevents the introduction of a separate system (usually cable yarding) which has management and cost implications. Shovel loggers are commonly used with feller bunchers and grapple skidders. If the extraction distance is not too far on these steeper slopes, it may be more practical for the shovel logger to move the trees to roadside even if flatter areas are encountered close to the roadside, instead of introducing the skidder for very short distances.

Hemphill (1986) already indicated in 1986 that shovel loggers could work on slopes of up to 60%, although the more common limit was 50%.

An idea put forward during interviews was the development of a shovel logger than can also operate as a shovel yarder.

Figure 35. Shovel logger (www.tigercat.com)

The use of slash mats in timber extraction

The use of slash (harvesting residue) on extraction routes should be considered where poor ground conditions are encountered which could result in machinery becoming stuck. However, the first choice is to place extraction routes to avoid these areas. Harvesters are able to construct the best slash mats due to processing taking place at the stump, and the harvesting residue can be placed accurately in the desired location. The residue reduces the contact between the tyres and the soil surface and enhances traction (Tiernan *et al.*, 2004).

The use of slash mats is always preferred where the system allows it. Slash is particularly important for machines with high NGP's such as forwarders, sensitive soils and long extraction routes where multiple passes are expected. Areas where CTL extraction machines travel frequently with full loads, such as close to landings, should also be reinforced. The slash mats of important extraction routes on soft or sensitive soils should be repaired if they start to fail. This could be by a machine such as forwarder bringing slash from another area of the compartment (Owende *et al.*, 2002). Potential weak spots should be provided with extra protection during slash mat construction, and not wait for these areas to break through and then start repairing them. On very sensitive soils it might even be necessary to only extract partial loads. Owende *et al.* (2002) reported that where adequate brash mats were constructed, 50 or more forwarder loads could pass over soils with ground pressure tolerances as low as 30 kPa without excessive soil damage.

Fresh slash usually has better flotation properties as it is more flexible than older slash which becomes more brittle. AFAG (2006) lists key points for the use of slash mats on steeper slopes:

- Using residue to fill natural hollows.
- Place very large residue pieces away from the extraction route.
- Do not place long, slippery lengths of residue in the slash mat. Wheels and tracks easily lose traction and can slide down the slope when encountering this.
- Cut stumps low and prevent the wheels tracks from riding over the stumps if possible.
- If possible, fell to the left and right of the harvester to obtain an even depth of residue.
- Monitor slash mats to make sure that they remain in suitable condition.
- Slash mats and machines can slip on topsoil's that have a very high clay or humus content.

Saunders (2011) investigated the tractive abilities of a levelling tracked excavator (Tigercat LH845C) on steep extraction routes with thick slash mats. It was able to operate until a 57% slope, thereafter the tracks pulled the slash under the machine and it lost traction on the soil beneath it. The test was repeated on an extraction route with very little slash, and the excavator travelled comfortably up to 40%, and finally lost traction at 53%. In a third trial, the excavator travelled downhill where there was no slash on the extraction route and operated comfortably on slopes of up to 40%. However, where the extraction route encountered side slopes of up to 18% coupled with a 35% downhill slope, the machine became unstable and eventually slid 12m down the slope. This highlights the importance of ensuring that extraction routes are straight up and down the slope where possible. It was also clear that thicker slash mats improved machine travel, and on this site, the machine struggled where there were no slash mats. The above trials are specific to the type of soils encountered and machines used. Some of the soils were indicated as being gleyed, and the steeper slopes could maybe have been traversed if the soils were firmer and drier.

Saunders (2011) carried out similar trials on a second site with older slash, where the excavator was able to travel easily on slash mats up to the maximum slope on the extraction route (50%). The trial was repeated after heavy rains, and the excavator could then only operate up to 40% slopes, when the slash started to move under the tracks and traction was lost on the soil below.

Saunders (2010a) noticed that when a tracked levelling harvester operated on slight side slopes on steep terrain, the trees on the lower side of the rack were left with higher stumps than usual. The operator then placed harvesting slash, dead trees and uprooted stumps against these high stumps to level the slash mat for better forwarder access.

Valmet 911 Snake

The Valmet (now Komatsu) 911 Snake, as shown in **Figure 36**, is a tracked harvester designed for steep terrain. What makes this machine feasible for work on steep slopes are the trapezoid track undercarriages that replaced the four single wheels that act as a carrier platform. This modification has resulted in a machine that has better traction, reduced ground impact and greater climbing capabilities. The four independent trapezoidal tracks enable the harvester to work on rough terrain. Steep uphill and downhill harvesting is possible. It is also fitted with a levelling cab, which can be levelled in all directions. It has a boom range of 9.5 m that allows a maximum corridor spacing of 19 m. Stampfer and Steinmuller, (2001) studied the harvester and confirmed that under the study conditions it could be operated up to 70% slopes, while still achieving good productivity levels.

Figure 36. Valmet 911 Snake (www.bct-bioma.de)

Konrad Highlander and Pully

The Konrad Highlander (**Figure 37**) is a specialised four or six wheeled harvester that is able to operate on very steep and difficult terrain due to a synchronised step and drive movement. It is designed to operate on slopes up to 60%, but is often used on steeper areas. The wheels can be independently controlled, steered and driven. The individual steering increases machine manoeuvrability during thinning or when obstacles are present. The cab is levelling and the crane-cabin structure is mounted on an endless turntable. It can also travel on roads at speeds of up to 40 km per hour.

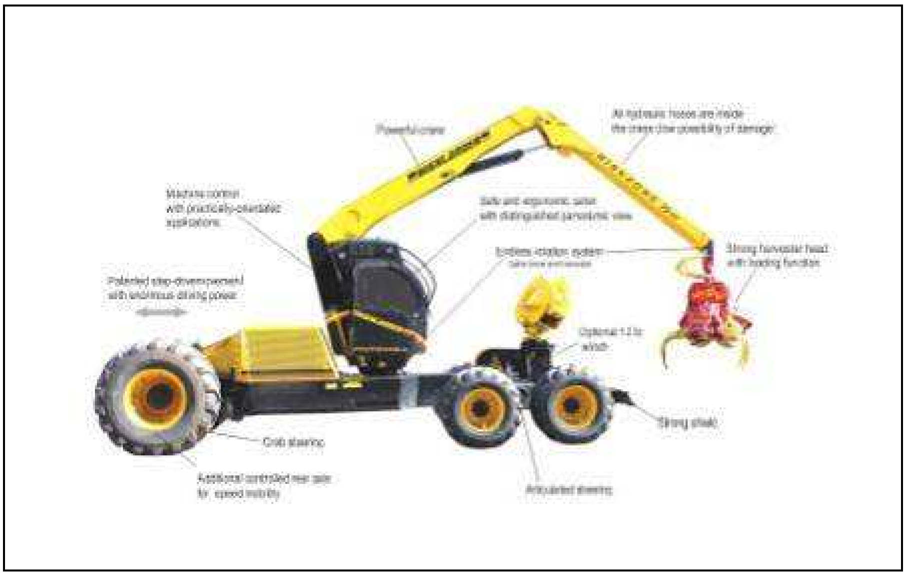


Figure 37. Konrad Highlander (www.forsttechnik.at)

As shown in **Figure 38** below, the step and drive movement consists of pushing the machine forward by hydraulically extending one or both of the rear wheels while they are stationary. The front wheels are then held stationary and the rear wheels are retracted. With this repeated motion, the harvester can travel up slopes much steeper than wheels would conventionally allow.

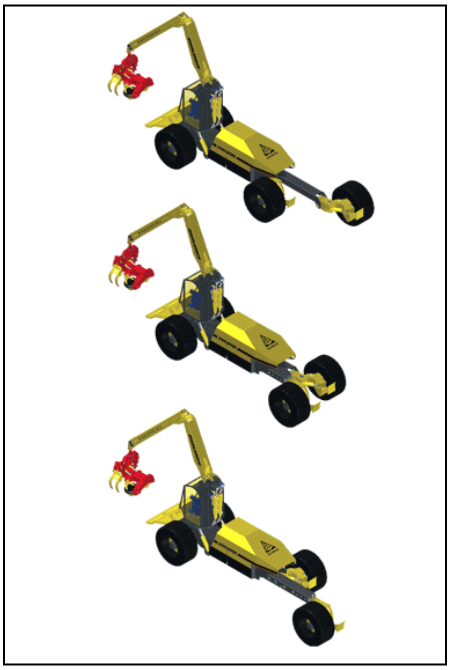


Figure 38. Konrad Highlander demonstrating step and drive movement (www.forsttechnik.at)

Another steep terrain capability of the harvester is the option of using a clambunk (or clamping bench). As illustrated in **Figure 39** below, the harvester can fell trees and place them in the clambunk. When sufficient trees have been felled, the harvester drives to an area where ground-based extraction can access or to a landing, and processes the trees into logs. Other design features which allow steep slope operation include a low centre of gravity, a slanted engine and a special oil pan.

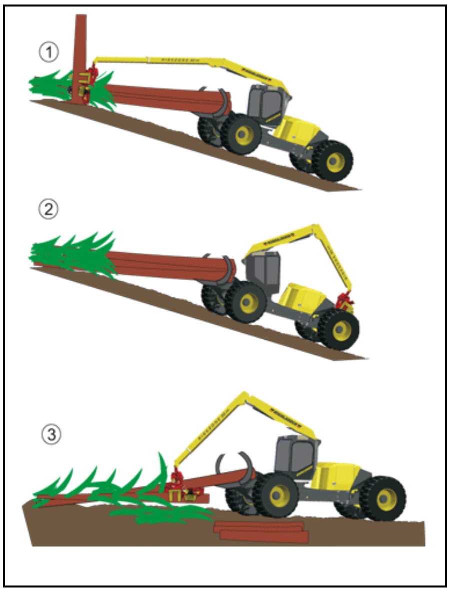


Figure 39. Konrad Highlander felling, extracting and processing trees (www.forsttechnik.at)

As shown in **Figure 40**, the Konrad Pully is a remote controlled extraction machine for steep or soft terrain. It has a winch which enables it to tow itself up or down very steep slopes. It can extract tree lengths by using a telescopic boom to grab trees or logs and place them into a bunk.

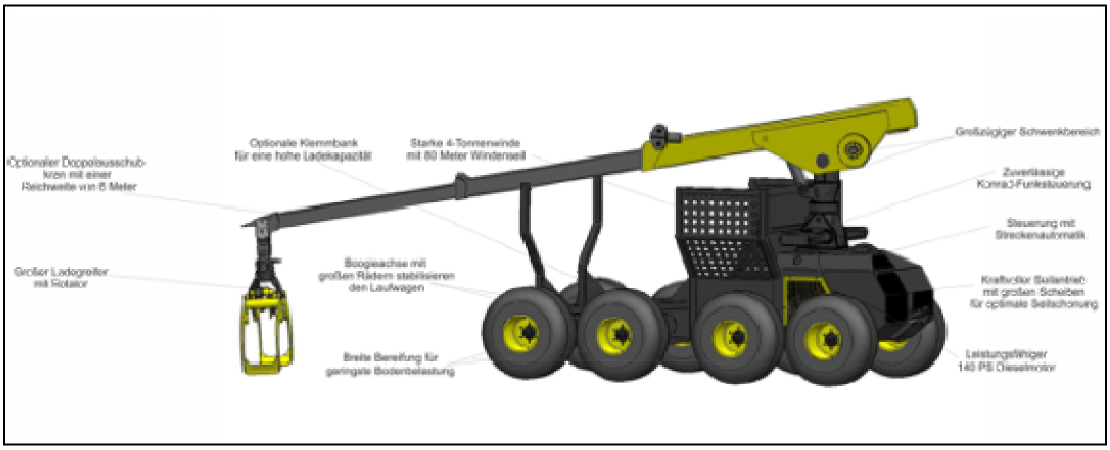


Figure 40. Konrad Pully (www.forsttechnik.at)

All information above was obtained from the Konrad website, which can be accessed at www.forsttechnik.at.

Kaiser Spyder walking mobile excavator

The Kaiser S2 4x4 Cross, as shown in **Figure 41**, is a specialised wheeled excavator with maximum mobility achieved through intelligent all-wheel steering kinematics. When working transverse to the slope, it can operate on 70% slopes; and when working longitudinally to the slope, it can operate on 100% slopes. It has a small turning circle (15 m) and the rear wheels precisely track the front wheels when turning. Movement is designed to be precise which improves stability. Steering options include front wheel, rear wheel, all-wheel or dog steering. The wheels can be hydraulically extended out sideways of the machine to provide good stability. Steep slope handling ability is good due to the wheels being either lifted or lowered to suite the slope profile. Wheels can be independently moved vertically or transversely which allows the machine to navigate over uneven terrain. When harvesting trees, stabiliser plates attached to each wheel can be lowered to the ground. The wheels would therefore be suspended in the air, which results in a stable machine when felling or processing. This is important for machine stability on steep slopes.

Figure 41. Kaiser S2 4X4 Cross excavator (www.kaiser.li). All information was obtained from www.kaiser.li.

Menzi Muck walking mobile harvester

Due to an innovative harvester chassis which can be adjusted to suite the terrain, an all-wheel drive traction system and a walking function, the Menzi Muck is claimed to operate comfortably at 100% slopes. As seen in **Figure 42**, all four wheels can be independently adjusted horizontally and vertically. The horizontal adjustment improves machine stability, while the vertical adjustment allows operation on uneven terrain and steep slopes. Hydraulically operated stabilisers are available as an option.

Figure 42. Menzi Muck harvester (www.menzimuck.com)

On very steep terrain, the harvester head grips a purpose built excavator foot. Wheel traction is supported by placing this foot on the ground and using it to push or pull the machine with the boom. All information was obtained from www.menzimuck.com.

Walking machines

Sakai *et al.* (1991) investigated a five-legged walking machine for steep slopes for use as a feller buncher. This machine, a model of a Menzi Muck, had two front stabiliser legs with pads, two rear legs with wheels and a boom for attachments and moving the machine. It was able to level itself by adjusting the length of the legs, and moved by alternating three and four-point ground contact with its legs. The machine was more effective operating straight up and down the slope compared to parallel to the contours. The machine achieved its objective of being able to fell on steep slopes with minimal soil impact, but it moved too slowly to achieve acceptable productivity. Further developments resulted in the Menzi Muck machine mentioned in the sections above, where use was made of a wheel on each of four legs.

The John Deere (Timberjack) Plustech walking concept harvester shown in **Figure 43** was developed in Sweden in 1994. Sensors in the machine's legs reacted automatically to soft, sloping, or uneven terrain, while a computer control system distributed weight and support equally to all six legs. The harvester walks over obstacles and the operator is able to adjust its ground clearance (between 20 and 120 cm) and height. It can walk in any direction (forward, reverse or sideways) and change direction while standing in one position. It has not entered production due to its movement being too slow to obtain the productivity necessary to achieve sufficiently low costs per cubic metre. However, it is a machine with very low soil impact and good steep slope handling properties.

Figure 43. John Deere walking harvester (www.JohnDeere.com)

Moran (no date), summarised some of the advantages of the John Deere walking machine:

- Spot contact with the ground, no continuous tracks left behind.
- Minimum risk of soil erosion on steep slopes.
- Optimum distribution of ground pressure.
- High, variable ground clearance.
- Good manoeuvrability on difficult terrain.
- Movement in all directions.
- Ability to turn on the spot.
- Excellent stability.

Tethering forwarders for extraction on steep terrain

As shown in **Figure 44**, tethered forwarders, sometimes referred to as cable forwarders, have winches with cables that are secured at the top of a steep section of slope. The harvester can descend up and down a slope in a controlled and safe way. However, the operator sits at an uncomfortable angle, a problem which can be overcome by placing a levelling mechanism under the seat.

Figure 44. Forwarder with winch

Research carried out by Bombosch *et al.* (2003) showed that using a tethered wheeled forwarder on 70% average slopes was possible, and no significant wheel slip was encountered. For the research, the winch that secured the forwarder needed to control the tension to up to 80 kN at all times. A snow grooming vehicle, the PistenBully 300 W Polar, was used for this, and was parked at the top of the slope. It had a 1 000 m rope which was attached to the rear tow bar of the forwarder. The research highlighted that to safely use this method, the following additional actions would be required:

- Placing the sensor controlled winch system onto the forwarder (if a standalone machine is not feasible)
- A safety security measure is needed for the forwarder in case the rope breaks. This could be a spike on the forwarder blade which is pushed into the ground.
- A camera system for reversing uphill.
- Using a tilting crane and levelling cab or seat.
- Very good planning is required with simulations of each extraction route.

The Ponsse Alpine Wisent, manufactured by Herzog Forsttechnik AG of Switzerland, has a hydraulic cylinder (see **Figure 45**) which lifts the front bogie so that steep embankments and obstacles can be navigated, and optimal traction can be obtained from all wheels of the front bogie. They also modify a Ponsse Buffalo by adding a winch (see **Figure 45**) to enable extraction on steep slopes where poor traction is encountered. The forwarder is called the Ponsse Alpine Buffalo. The winch allows the forwarder to extract up steeper areas than would normally occur, and also breaks it safely down steep slopes. The cable is attached to a suitable tree and is 300 m long. The operator selects the desired cable power, and then the electronic control unit ensures controlled movement up to a maximum speed of 5.5 km/hr. The result is a safer operation and less wheel slip which reduces soil damage and improves fuel consumption. Two cameras monitor the winch drum and the rear of the forwarder (which has xenon lights for night time work). Additional equipment that complements the forwarders steep slope handling properties include the Crane Tilt Herzog, which allows crane tilt of 53% and a titling mechanism in the operator seat (**Figure 45**) which allows the operator to remain level on slopes of up to 50%. Optional equipment includes the bogie lift mechanism mentioned above (www.herzog-forsttechnik.ch).

Figure 45. Herzog Forsttechnik equipment for steep slopes (www.herzog-forsttechnik.ch)

Tethering of excavators for pre-bunching for cable yarding

Amishev and Evanson (2010) studied two cable yarding contractors in New Zealand where excavators, secured by wire ropes and a winch, bunched either chainsaw or mechanically felled trees on steep terrain for grapple yarder extraction. One excavator was secured to a bulldozer that had the winch attached to it and would lower the excavator down the slope, while the other excavator had the winch mounted onto it and the end of the cable would be secured to a suitable anchor, and it would lower itself down the slope. The results showed that 33% more trees (or 17 m^3 per PMH) could be extracted per cycle compared to the scenario for unbunched trees. The excavators had no levelling capabilities, and the operators were secured using racing car-style full harness seats. One of the excavators had the track frame extended by 500 mm to the rear for more stability. The tracks had double grouser extensions for increased traction, and were chamfered (angled) at the ends. On slopes of less than 20%, the tethering system would not be used.

ATV’s

All-terrain vehicles (ATV’s) can be used for various tasks in forestry, including log transport. They have low pressure oversize tyres which enable them to operate on soft and uneven terrain. Four-wheeled ATV’s have become more popular than the three-wheeled versions, as they are more stable and have more traction. A four-stroke engine of at least 250 cc is recommended if heavy forestry work is to be performed, such as hauling logs.

ATV's have wide tyres with low inflation pressures, which allows them to mould to the terrain, providing good traction and ride quality. Large studs aligned in a "V" shape towards the centre provide good road holding capacity, but resists sideways movement. To improve hauling, weight can be added to the tyres by filling them with water, anti-freeze solution or lead powder. This also lowers the centre of gravity, thereby increasing stability, but may cause excessive rutting on soft soils. Cross-ply tyres should be used, and to minimise downtime caused by punctures, a puncture sealant could also be used.

For log hauling, disc brakes should be used to enable better heat dissipation. ATV's should not be used for winching in logs, as its frame was not designed for this. Winches are however useful when stuck in mud. Skid plates are required to protect the ATV under-carriage from stumps and rocks. Counterweights are also available for stability, especially when hauling large loads uphill. However, heavy bags could also be placed on the front of the ATV for a similar affect. Dual wheels can be placed on the rear axle to increase traction; however turning then becomes more difficult.

For more difficult terrain, an interesting innovation is the fitting of two additional wheels and band tracks to improve both flotation and traction. Other innovative products, such as the flexi-track shown in **Figure 46** produced by Leve, are also available.

Figure 46. Track system for ATV's (www.ecvv.com)

When extracting logs on difficult terrain, care must be taken as the ATV is light and can become unstable. A rule of thumb is that the trailer and load should not exceed the weight of the ATV and its driver. However, the owner's manual and precaution should always be considered to prevent accidents. Operating ATV's for timber extraction safely and productively requires special training. On rough terrain, a trailer with a bogie axle (see **Figure 47**) should be considered to allow the trailer to climb over obstacles. Various timber hauling options are available, and for general information, the reader should consult www.novajack.com.

Figure 47. ATV with log trailer with a bogie axle (www.novajack.com)

Unless otherwise indicated, the information above was sourced from Dunnigan *et al.* (1987).

Mini-tractors and forwarders

These mini-tractors are purpose built for forestry work. They have proper ROPS, a PTO, 3-point linkage and a towbar that allows multiple accessories to be used. They are easily transported between sites as they can often be towed by LDV's. Research has shown that these smaller tractors can compete with larger modified agricultural tractors when thinning small and less uniform trees. They have greater payload and terrain handling abilities than ATV's, as the wheels of the trailers are usually driven. The main traction force comes from the trailer itself, allowing for more control. The mini-tractors struggle on rough terrain and very soft soil, and it might be necessary to install a winch in case it becomes stuck. Many of these mini-tractors and forwarders can also use other attachments such as harvester heads.

Examples of these machines include the Vimek 630 Minimaster tractor, as shown in **Figure 48**. It is an eight-wheel drive mini-tractor with 40 cm of ground clearance. The underside is completely smooth which protects all vulnerable parts. It is powered by a Honda 620 cc engine, has wide profile tyres and has a high, low and reverse gear. The tractor weighs 524 kg. The driven trailer has a bogie oscillation of 25 cm and a loading capacity of 2 000 kg. The crane has 3.6 m of reach. Optional equipment includes wheel tracks, wheel chains, a radio controlled hydraulic winch and a chainsaw holder.

Figure 48. Vimek 630 minimaster (www.vimek.se)

An example of a mini-forwarder is the Vimek 608.2 shown in **Figure 49**. It has a payload of 4 500 kg. Equipped with an 18 kW Kubota engine, it has 40 cm of ground clearance, flotation tyres and a narrow width of only 1.9 m, which allows for easy navigation in thinning. The crane reach is 5.2 m. Optional extras include wheel chains, wheel tracks, a pneumatic chair, a dolly trailer, a radio controlled hydraulic winch and a weight scale system. Vimek also manufactures other mini-machines that can be used as harvesters or loaders.

Figure 49. Vimek 608.2 mini-forwarder (www.vimek.se)

The Terri 34 shown in **Figure 50** can be configured as a harvester or forwarder. It has a 1.5 m^2 load area, and is only 1.9 m wide. Each axle has three bogies which improves terrain handling and improves operator comfort. Track width is 490 mm and track length is 1.2 m, resulting in rear ground pressures of only 0.46 kg/cm^2. It is powered by a 45.5 kW Perkins engine and has a three-speed hydrostatic transmission. Crane reach is 5.7 m and it can carry a load of 3 600 kg.

Figure 50. Terri 34 forwarder/harvester (www.terri.se)

Using monorails in steep slope extraction

A monorail system was tested on very steep slopes in Japan (an example is shown in **Figure 51**). The aim of using the monorail was to reduce new road construction in a steep area. A four tonne capacity monorail was installed on a mountainous area, and this was used to transport a small excavator and small forwarder to the site. The excavator was used to construct forwarder trails on a hillside with 70% slopes. When extraction was complete, the bucket was exchanged for a grapple to accumulate and load logs. Trees were manually felled and cross-cut, and then the forwarder would transport the logs approximately 200 m to the monorail. The monorail then transported the logs about 300 m to a roadside landing. The monorail had a maximum possible gradient of 100%. Production of 28 m^3 per day was achieved (Boswell, 2008).

Figure 51. Monorail (www.thinktheearth.com)

Chute extraction

The South African Ground Based Harvesting Handbook (GBHH) (2010) describes chutes as "an inclined channel system in which timber is transported downhill". Half pipe (open chutes) and round pipe chutes occur. Chutes are a labour intensive system and used to extract logs down steep slopes using gravity (FAO, 1996). Slopes of at least 15% to 20% are required to operate chutes. Once the chute slope angle exceeds 30%, a braking system is normally used where logs reach the landing. The upper slope limit indicated in most literature for chutes is 45%; however this applies to the chute gradient itself. On slopes above 45%, the chutes can be installed diagonally to the slope, as long as they can be stabilised. Therefore the actual slope gradient straight up and down the slope can be much more. The GBHH (2010) provides an upper slope limit of 90%. Chutes are also suitable for use in thinning. Compared to other ground-based systems, chutes cause minimal ground disturbance on these steep slopes (Dewar, 1994).

Chutes can be used to effectively harvest small inaccessible areas with lower stocking (**Figure 52**). This prevents having to move an expensive cable yarding system to these areas. Chutes have been commonly used in the past in South African harvesting; however, they have largely disappeared due to various reasons. These include a lack of knowledge on how to operate them, lack of expertise in their manufacture, and operational planning that is more difficult than one would expect. However, their disappearance has been to the detriment of our abilities to harvest steep slopes and relatively rough terrain. Even though chutes may not be a mainstream system, their very low capital costs makes it possible to purchase and store them, and only use under the conditions where they are suitable. In this situation chutes would be used to compliment an existing harvesting system, where it would be too expensive to bring in an additional system to harvest the small steep areas. Chutes can also reduce some of the safety risks associated with manual extraction on steep slopes. This document will not go into any additional information on chutes, as they are well described in the FESA Chute Operating Manual (1994) which can be accessed at http://www.icfr.ukzn.ac.za/collaboration/forest-engineering-southern-africa/fesa-publications/

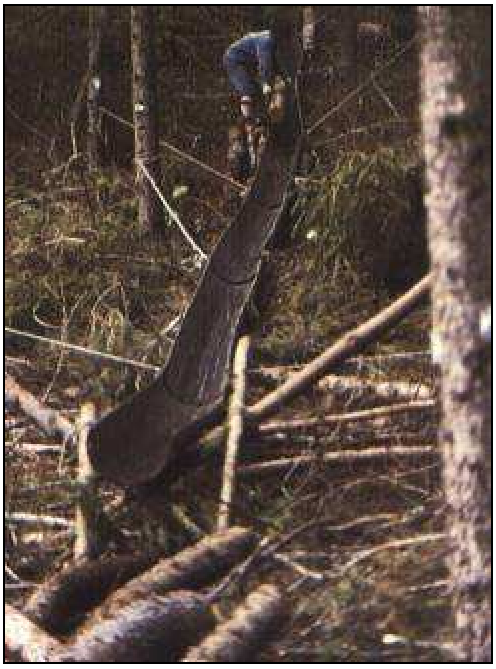


Figure 52. Chute extraction (www.fao.org)

Animal extraction

An extraction option used in the past and in some forests or plantations today is the animal extraction system. Animals are still used to effectively extract logs on steep slopes due to their ability to operate across slopes in steeper areas. Garland (1997) indicated that horses (**Figure 53**) are able to extract on short, steep slopes of over 50%, and downhill extraction is preferred. Animal extraction usually has very low soil disturbance. Parker and Bowers (2006) stated that horses should only operate on gentle slopes, with less than 5% slopes on downhill preferred. These limitations seem too conservative, as horses commonly operate on steeper terrain.

Figure 53. Horse extraction

Small-scale winches

Various types of small winches can be used to extract timber from difficult terrain. However, these winches are usually only applicable to small-scale operations, or isolated pockets of timber that cannot be harvested with other systems. These winches can be powered by a variety of small engines. An attachment is even possible for a chainsaw, as shown in **Figure 54**. The Lewis Winch is able to pull 1 800 kg in a straight line and 3,600 kg if the Lewis Winch snatch block is used. Using a 5 mm diameter cable, a 50 m long cable can be used.

Figure 54. The Lewis Winch chainsaw winch kit (www.lewiswinch.com)

Corduroy

This technique is used when extracting over very soft ground. Logs are placed perpendicular to the extraction route so that they form a mat for the machine to drive on. Often, harvesting slash is placed on top of the logs to help keep them in position. Due to the large contact area, the logs increase the bearing strength of the soil and allow machine movement that would not normally be possible. Short sections of temporary roads can also be constructed using corduroy, as the soil impact is very low and once the logs are removed, the site rehabilitates itself very quickly.

Operator experience and training

As indicated numerous times, having machines with exceptional terrain handling capabilities is pointless unless the operators are skilled and competent to operate under these conditions. Both formal and informal training are critical components (**Figure 55**). Industry needs to develop standards whereby a certain minimum training level is required before an operator can use a specific machine on certain terrain. However, this is only the starting point, and operators need continual on-site training, and must work on their own capabilities. Steep slope harvesting competence is gradually built up over time. Operators should never be made to operate outside of their competence boundaries, regardless of handbook guidelines or manufacturer recommendations (AFAG, 2006).

Figure 55. Harvester/Forwarder simulator (www.deere.com)

Multi-skilling of machine operators usually results in more efficient operations on steeper slopes. For example, in cut-to-length operations consisting of a harvester and forwarder, if the harvester operator has driven a forwarder, he/she will be more sensitive regarding the placement of extraction routes and the placement and presentation of logs. This arguably becomes even more important when using feller bunchers and skidders. New operators should first be placed on the extraction equipment before the felling equipment. This maintains better control of the operation during the learning period and gives the operator an appreciation of the difficulties in accessing incorrectly placed extraction routes and timber.

Cable skidders are commonly used on difficult terrain in South Africa. Chokerman are often of the lowest paid workers in harvesting operations in South Africa. This is contrary to many other countries where the chokerman can be paid more than the skidder operator. This is because the chokerman issues all instructions to the skidder operator when in the compartment, and is responsible for the efficiency of the entire operation. The travelling and dechoking are consistent time elements of the work cycle (for a given distance, terrain and payload), but the productivity of the choking element depends heavily on the skill, experience and motivation of the choking team. For example, if due to the way the tree is laying, it is not possible to debranch it on the lower side, the chokerman chokes the tree with the hook on the underside to twist the tree during breakout so that the branches are on the upper side of the tree for easier debranching at the landing. For cable skidder productivity to increase in South Africa, more attention needs to be placed on the training of cable skidding chokermen, especially on steep areas, and their profile needs to be raised within the harvesting team, with possibly even the team leader being one of the chokermen.

Harvest planning activities

The FAO Model Code of Harvesting Practice (1996) lists four ingredients for successful and sustainable harvesting practices. These are comprehensive harvest planning, effective implementation and control of harvesting operations, thorough harvesting assessment and communication of results to the planning team and to harvesting personnel, and the development of a competent and properly motivated workforce. These ingredients are even more important when harvesting on difficult terrain.

Harvest plans help achieve objectives such as reducing harvesting costs, minimising environmental and other impacts, improving productivity, and provide flexibility for changing circumstances (FAO, 1996). Harvesting plans are usually classified into strategic, tactical and operational plans. Often, an annual plan of operations (APO) is also included, although it is in reality the first year of the tactical plan, but planned in more detail and phased over the year. Planning is the most important tool that a forester has to implement safe, environmentally acceptable and low cost systems. Most foresters will acknowledge that their oldest compartments are the ones that are on their steepest (or most difficult) terrain. This is indicative of either not having the correct systems to harvest these areas, or the harvesting costs are prohibitive. Throughout the interviews and surveys conducted for this project, planning was consistently raised as the most important activity for a harvesting forester, and also as the skill or discipline area that foresters lack the most.

The various FESA handbooks explain the differences between the different planning levels. Therefore, this section will explain each type of plan with regard to its relevance to difficult terrain harvesting.

Strategic plans

The strategic plan should identify major problem areas that could affect harvesting operations. These could include rock outcrops and wet or sensitive soils. The general categories of harvesting systems applicable to the plantation area should be identified, for example the percentage ground based and cable yarding systems required. Road locations should be considered to ensure that longer term changes can be considered for the road network to improve both harvesting and timber transport efficiencies and machine selection.

Because difficult terrain areas are usually expensive to harvest, some companies take the strategic decision to extend rotation lengths on these sites. This enables the trees to grow larger to try and offset some of the harvesting costs, and try to obtain a higher proportion of higher value products from the larger dimension trees.

Tactical plans

Tactical planning involves the assessment of market demand, timber availability and cost of processing the timber. The tactical plan considers a three to five year period. It most importantly includes the selection of suitable equipment. Harvesting operations on steeper slopes are more costly than on flat terrain due to more expensive machines being used and lower productivity compared to easier terrain. Machine costings are necessary to quantify the costs, and accurate cost assumption information is essential. For example, many suppliers tend to supply generic costs for the fuel consumption of a given machine, but the fuel consumption on difficult terrain increases. The potential machine owner needs to ensure that they source accurate information. Planning needs to ensure that equipment is well utilised to ensure the lowest harvesting costs (Staaf and Wiksten, 1984). When operating on steep slopes, planning is essential because of the high safety risks and significant environmental impacts that may occur on the site. Therefore the descriptive and functional terrain characteristics must be integrated and suitable systems must be applied to the steep sloped areas. Ground-based harvesting should not be used to the detriment of the overall weighted harvesting cost per tonne. If cable yarding is only left with isolated patches of timber on extreme terrain, the operation will be very expensive. Therefore, tactical planning needs to maintain the balance to achieve the lowest overall weighted cost.

Machine and system selection

Terrain areas affecting machine selection are identified during tactical planning. These include slope, ground roughness, ground conditions, and erosion and compaction areas. Like terrain areas are grouped together to enable machine and system requirements to be determined. Detailed maps at the correct scale are required to ensure that the terrain is well understood over the duration of the tactical planning period. More difficult terrain should have larger map scales. Good maps reduce harvesting planning errors and reduce harvesting costs in difficult terrain (FAO, 1996). Improper planning at the tactical level will result in machines and systems being selected that are not suitable to the terrain. The result is poor productivity, excessive machine downtime, increased costs, safety risks and possible site damage. Once machines have been purchased, local management has to live with the operational implications until the machines have reached the end of their useful lives.

The maximum slope, and amount of area covered by the maximum slope, is the most important slope value to know. If a small section of a compartment has steep area, it does not necessarily mean that a different system will be selected, but different operating techniques may be employed. Some of these techniques include factors such as directional felling on short, steep slopes, and then reaching for these trees from the side, or extracting straight down the slope. However, once steep areas extend

beyond isolated patches, the machine selection becomes important (MacDonald, 1999).
In the selection of a harvesting system, one must note that each machine type is suited to various terrain conditions. This is governed by the basic features on the machine and it must be utilized within its capacity range. If the machine is operated within its appropriate working limits; safety risks, environmental degradation and other adverse effects are minimized (MacDonald, 1999). Foresters responsible for equipment selection must understand the basic features of the equipment, its range of operating techniques, the influence of site conditions and any external requirements imposed (MacDonald, 1999). Machine selection must be very specific, and not be limited to a generic name for a machine. For example, identifying that a grapple skidder is required is only the first step. The most important aspect is ensuring that grapple skidder has all the correct specifications, options and features that will enable it to operate efficiently and safely on difficult terrain. These include tyres choices, engine capacity and grapple type and size.

Foresters and contractors sometimes tend to hesitate to ask for advice regarding machine selection. If the optimal equipment configuration is to be obtained, the necessary technical expertise must be consulted, whether this be from a company forest engineering expert, machine supplier, experienced contractor or consultant. This should not be an office meeting, but an infield visit to representative compartments of the tactical plan.

Annexure A provides examples of systems that can be used on steep slopes, including the slope limitations of the systems, making provision for uphill and downhill extraction.

Phasing of harvesting operations

Scheduling of the harvesting plan is of crucial importance when the harvesting operation has to be conducted on steep slopes in order to achieve good economic results.. Sensitive and soft soils must be considered in the tactical plan. Instead of planning for an alternative, more expensive system, one might be able to phase the harvesting for a season when little damage will occur, or the ground is not as soft. Slippery soils can be overcome by good planning, or even considering using other techniques such as slash mats. However, these issues cannot be decided once one is about to commence harvesting, they need to be well planned during tactical planning.

Machine obsolescence

An additional problem for cost effective operations that consistently produce the correct volumes of timber when required, is when machine life is extended beyond the obsolescence period. The reasons for the non-replacement of machines are varies, but the result is usually a contractor or forester who is unable to meet production targets due to constant mechanical breakdowns. Many cable skidders and cable yarders fall into this category. Another constant problem is the unrealistic life expectations of agricultural tractors operating infield.

Contractors and contracts

Where contractors are used, it might be necessary to stipulate in the contracts the detailed machine specifications required in order to harvest the difficult terrain encountered (Owende *et al.*, 2002). Contractors also need to be given contracts of sufficient length to be able to depreciate the specialised machinery required for difficult terrain. This will require contracts of at least three years, but preferably at least five years. When using specialised machines, the contractor or company purchasing the equipment must also have the economies of scale to ensure that they can have their own skilled mechanical backup (or on-site/very close to the site dedicated backup from the supplier) and spare parts, and they can be sourced at reasonable prices. When using highly mechanised systems on difficult terrain, the contractor needs to have very good technical skills for maintaining machines, and this should be one of the aspects included on the scorecard for contractor selection. Machines operating on challenging terrain tend to have higher maintenance requirements. Low mechanical availability can bankrupt a contractor quicker than poor productivity.

Road infrastructure and landings

The literature has indicated that tracked machines are the most capable steep slope ground-based equipment. However, often road access is poor in steep areas, and even when roads occur they may be narrow and windy. Low-bed trucks may not be capable of accessing these areas, resulting in the machine “walking” excessive distances from one compartment to another. This needs to be considered during tactical planning as it could affect equipment selection.

The location of landing sites is of particular importance in steep terrain. Landing sites need to be identified as part of the tactical planning processes. Once the potential landing areas are known, then road network upgrades and changes, and extraction dynamics can be considered. Often steep terrain harvesting is made even more difficult and expensive by roads not being upgraded (or built) or maintained, or landings not being prepared prior to harvesting (especially with narrow roads). Roads can also cause a bottleneck with trees and logs blocking roads and trucks not being able to pass each other to access timber and transport it to the market. Using excavator loaders to stack logs higher on roads, landings or depots on steep slopes can reduce space requirements considerably.

Harvesting pockets of timber

It might be necessary to make use of a specialised team to harvest the pockets of timber left behind after harvesting has taken place. This should be well planned and controlled, and the volumes and areas required identified during tactical planning. The danger of using these specialised teams is that the mainstream harvesting teams tend to start creaming the easier terrain and leaving larger areas than necessary for the specialised team. However, if well controlled, specialised teams with equipment that is suited to the difficult terrain areas being harvested can reduce the number of pockets of timber, with associated benefits such as reduced temporary unplanted areas, improved safety of operations, reduced environmental impact and hopefully lower costs.

Operational plans

Spending time on operational harvest planning for complex terrain is cost effective (Boswell, 1998). The main advantage is increased efficiency of equipment. The hourly costs for planning are considerably lower than machine hourly costs and therefore the consequences of inefficient plans are expensive. This is particularly true on steep slopes, where more time is required at the compartment making sure that the dynamics of the entire compartment are understood before system operation decisions are made. Each compartment should be considered a project and managed accordingly.

Site machine matching

During the implementation of the harvesting plan, certain assessments have to be undertaken before the harvesting operation commences. The plan considers the terrain, topography and soils whereby an infield site assessment is carried out in order to match the suitable ground based machine according to ground roughness, condition and slope (Health and safety executive, 2006).

Information gathering

Difficult terrain cannot usually just be evaluated from the roads; substantial walking is required. Planning tools such as maps (even Google Earth) and GIS are now integral to reducing the total time spent on planning, but without reducing its accuracy. Good maps reduce planning times as options can be considered on paper without wasting excessive time infield. Maps with contour intervals not exceeding 5m are best for accurate planning on steep slopes.

Risk assessments

Operational planning activities include risk assessments. These risk assessments are more important on difficult terrain, and more planning effort will be required. According to AFAG (2006), choosing which machine to work on the site, the operator and how to supervise the work and allow for changing conditions are of the most important aspects to consider. The entire operation needs to be considered and not just single machines. Therefore, more people need to be involved in the planning process, and during the operation they all need to be in contact with other. Even though the terrain may be classified as difficult, each site will still be different, and this needs to be considered in the planning. Each person operating on difficult terrain should have had the necessary training according to the machine being operated and the terrain type.

The British Columbia Forest Safety Council (2011) has produced a steep slope resource package for identifying risks. The package consists of four parts:

- **Part 1 – The steep slope hazard assessment tool**. This tool evaluates site-specific hazards and develops a steep slope plan to reduce the risks.
- **Part 2 – Steep slope planning and operational responsibilities**. This describes the planning and administrative responsibilities of owners, employers and employees of harvesting operations.

- **Part 3 – General and machine-specific best practice**. Procedures and practices that should be incorporated into management systems are included.
- **Part 4 – Support Documents**. This contains all support forms and practical information.

Companies interested in a more formal and structured (and resource intensive!) approach to managing safety risks on steep slopes should consult the website included in the reference list.

Planning tools

As technology progresses, vehicle movement can be tracked and controlled using GPS and map data. This will assist the operator to identify sensitive and problematic soils which could not be identified otherwise. This technology could also be used to prevent machines from entering terrain areas that are beyond their abilities or where they could cause damage. New problematic terrain identified during operating could also be logged in real time (Owende et al, 2002). However, using map data assumes that the map data is sufficiently accurate and does not allow for the skill levels of different operators.

Stakeholder interaction

On difficult terrain, a site visit with all contractors, equipment operators, supervisors and foresters is necessary to ensure that all are able to analyse working conditions and cooperate sufficiently according to an agreed plan (Kosicki, 2003). Planned, regular reviews of the plan may be necessary, and frequent visits are required from the responsible harvesting forester. Operators should not be allowed to deviate from plans without necessary permission from the approved person. Records of all site meetings and plan changes should be made (AFAG, 2006). When managing operations on difficult terrain, there is no substitute for spending time at the operations (infield, not on the road or landing).

Operational detail

Felling direction is particularly important on difficult terrain as it affects the safety and operational efficiency of the extraction equipment more than on easier terrain. When using feller bunchers on difficult terrain, bunch size is also very important for optimisation of the extraction equipment. Bunch sizes that are too large cannot be extracted over the difficult terrain, while bundle sizes that are too small result in further compromising the efficiency of extraction equipment which already cannot achieve the productivity levels possible on easier terrain.

When felling with chainsaws on steep slopes, felling should commence on the down-slope side of the compartment and move up the slope while the face of the standing trees lies along the contour. This is because trees on steep slopes tend to lean downhill, and felling them in an opposite direction can be difficult and dangerous. Also, trees tend to slide down the slope and could stop against standing timber (MacDonald, 1999). However, McKenzie and Garrett (1994) prefer uphill felling on steep slopes because fewer breakages occur, even if it requires special techniques that cost more. Their justification is that research has shown that the extra costs are negated by the increased stem utilisation.

Extraction routes should go straight up and down slopes as far as possible. Exceptions to this might be for skidders extracting downhill on erodible soils, where the extraction routes should be slightly angled to allow water to dissipate into the vegetation and not increase in speed and volume as it moves down the slope. On rounded hills, wedge shaped patterns need to followed. This will result in wider extraction route spacing at the bottom of the slope, and extraction routes possibly leading into one another towards the top. Teams that mark trees for row thinning for forwarder extraction need to be well trained and experienced to ensure that the marked “rows” are straight up and down the slope.

Kosicki (2003) highlighted than in order to obtain the lowest costs from grapple skidder operations on steeper slopes, careful operational planning of the compartment and all harvesting phases is necessary. On moderately steep slopes, the skidding direction is not that critical, but downhill skidding is still recommended (Kosicki, 2003). On steep slopes, a return-trail pattern is used where turning the machine on a steep slope is dangerous. A dedicated travel empty route is planned to the top of the slope. The machine then travels straight down the slope along a planned route, picking up timber along the way.

During operational planning, very difficult terrain should be harvested during the day shift. Operators naturally have better vision and are usually more attentive during this shift (MacDonald, 1999). Weyerhauser implemented a safety rule in their Canadian operations that stipulated that a rubber-tyred skidder cannot be used on slopes greater than 30% for a distance of 30 m or more, unless the contractor has a detailed plan (Boswell, 1998). This steep slope addendum to their standard harvesting plans is two pages long and it needs to be signed by the contractor before each felling block.

Productivity expectations on steep slopes should not be the same as on flatter areas. For example, Stampfer (1999) showed that the productivity of the Konigstiger steep terrain harvester reduced from 25 m^3 per PMH to 18 m^3 per PMH when the slope increased from 25% to 50%. This translates directly into higher costs per m^3. Productivity information for ground based equipment is lacking for steep terrain harvesting, especially the newer mechanised technology which has recently been introduced into the country. Companies will have to invest in obtaining this information, and the best way to do it will be through collaborative funding of machine and system work studies. To make the funds invested stretch further, modelling of different conditions will need to take place.

Contingency plans

Should weather conditions deteriorate to the point that machines have trouble operating without causing site damage or causing safety risks, the system needs to either stop operating or find an alternative compartment. During operational planning, contingency planning should make provision for this, especially when harvesting during the wet season on steep slopes with ground based equipment. An alternative is to limit the damage to a more resilient area of the compartment where rehabilitation can take place.

Conclusions

Difficult terrain harvesting is possible if the applicable technology is fully considered and utilised. An acceptable machine for the future is one that must be able to negotiate difficult terrain and work safely with fewer disturbances on the ground or environment.

Brink (2001), highlighted that future harvesting machines will continue to improve their ability to reduce ground impacts. Remote controlled harvesting machines and high speed cable extraction systems would be manufactured in order to promote safety and making work more attractive to workers. Bayne and Parker (2012) indicated that robotics may be able to be used to improve productivity and safety, and reduce costs on difficult terrain. However, there was concern expressed in the New Zealand study scenario regarding the effects on employment in rural areas and the ability of the robotics to operate on very difficult terrain. However, it was accepted that the use of robotics is inevitable, and prototypes are already being used.

MacDonald (1999) indicated that during FERIC interviews, it was evident that operator attitude had a greater impact on soil disturbance than the equipment itself. This highlights that good operator training, motivation, management and supervision are unavoidable when harvesting on difficult terrain. The most technologically advanced equipment will perform no better than standard equipment if the operator is not adequately trained and motivated to use it. The operator also needs to take ownership of the machine if it is to be kept in a condition to operate effectively on difficult terrain. The most experienced and competent operators should be used on very steep slopes (Crawford, 2010). The operator needs to be comfortable on steep slopes, and should not be expected to operate above his or her personal limits, regardless of what guidebooks and machine manufacturers say.

Finally, when deciding on machines and their difficult terrain capabilities, the starting point is to talk to contractors and companies that are already using such systems. This can be backed up by attending equipment demonstrations, speaking to manufacturers, and reading research articles and harvesting handbooks. Criticism is often levelled at younger foresters that they have no hands on experience of managing harvesting teams. Although this is no fault of their own, it might be necessary to address this, especially with the systems used on difficult terrain. If inexperienced foresters are expected to manage these operations, it will be important to make sure that they are supervised by a suitably experienced mentor.

Harvesting difficult terrain, especially steep slopes, will require systems that have lower productivity and higher costs per cubic metre (Sarles and Luppold, 1986). Also, as terrain becomes increasingly difficult, so the productivity of a given system reduces further, and costs naturally increase. Companies and contractors will always strive to be innovative and should carry out good planning activities on difficult terrain, but the reality is that the systems will still be more expensive than those used on easier terrain. It is therefore unrealistic to expect the same productivity and harvesting costs from a given ground-based system operating on easy and difficult terrain. However, through good machine and system selection and planning, the reductions in productivity and the cost increases can be minimised. This is what forestry managers should be striving to achieve.

To exacerbate the difficult terrain problem, often the steeper areas also have more marginal soils, which result in harvesting of smaller trees. This can be overcome by reducing the stocking and increasing rotation ages. Difficult areas suffer greater access restrictions during wet weather, and usually have higher safety risks. There is usually hesitation amongst harvesting crews to operate in these areas, and therefore management needs to be disciplined regarding good planning and making sure that difficult terrain areas are harvested as per the planning schedule. Failure to do this will result in an excess of over-aged trees on difficult terrain, with the consequence of a spike in the harvesting costs. Another consequence is leaving pockets of trees behind that become a nightmare for harvesting foresters of the future, and create establishment challenges for silvicultural foresters. Good planning and operational discipline needs to be maintained at all times.

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Annexure A: Harvesting systems and methods commonly encountered in South Africa and other plantation forestry conditions.

There are three main harvesting methods in use namely full tree, tree length and cut-to-length methods. The method is determined by the form the felled tree arrives at the road side, landing or depot. A harvesting system refers to the chain of actions used to fell, extract and process the trees. The systems are further described as being manual, semi-mechanised or mechanised in nature. Lastly the systems are defined as being ground, cable or aerial based according to the method of extraction chosen.

The limiting factor with regard to the steepness of the terrain that the systems can be applied to is usually determined by the method of primary transport (extraction). If processing is done infield the processing method may also pose as a slope limiting factor. However the operator can normally alter his work method to ensure uphill harvesting and infield processing is done. Felling and processing machines are generally capable of handling steeper slopes when working uphill as compared to downhill.

The maximum slope class ranges indicated below are based on extraction. Traction aids are assumed to be fitted to equipment if needed. All slope limits are obtained from the South African Ground Based Harvesting Handbook as adjusted by the results of the NMMU/FESA steep slope harvesting survey.

Full tree and tree length:

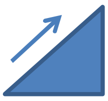
Full tree and tree length systems are systems where optimisation activities are carried out at roadside or a landing. With tree length systems the trees are debranched and topped infield. The full tree method on the other hand requires that the felled tree be brought to the landing with all of its branches intact.

System 1: Semi-mechanised tree length method: (Max slope: 30 – 40% Uphill / 35 – 50% Downhill)

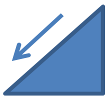
Felling and de-branching is done motor-manually using chainsaws, the felled, topped and debranched trees are then extracted to roadside with skidders or landing where the tree is optimised and processed motor-manually with chainsaws.

Motor-manual felling is not limited by slope however according to the South African Ground Based Harvesting Handbook motor-manual processing should be limited to gradients of less than 60%. Since skidders are used for extraction the maximum slope that the system can be applied to for ground based harvesting is 40% uphill and 45% downhill if cable skidders are used, or 40% uphill and 50% downhill if 6x6 grapple skidders are utilised for extracting the timber. If 4x4 grapple skidders are used the maximum slopes that can be safely negotiated is reduced to 30% uphill and 35% downhill respectively.

System 1: Semi-mechanised tree length method: Uphill extraction (Max slope 30 – 40%)

	Stand	Extraction route	Roadside landing	Slope limit
Motor-manual felling debranching				Felling: any slope Debranching: up to 60% up and down slope
Skidder				4x4 Grapple skidder up to 30% uphill Cable skidder up to 40% uphill 6x6 Grapple skidder up to 40% uphill
Motor-manual processing				Processing: up to 60% up and down slope

System 1: Semi-mechanised tree length method: Downhill extraction (Max slope 35 – 50%)

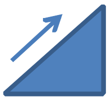
	Stand	Extraction route	Roadside landing	Slope limit
Motor-manual felling debranching				Felling: any slope Debranching: up to 60% up and down slope
Skidder				4x4 Grapple skidder up to 35% downhill Cable skidder up to 45% downhill 6x6 Grapple skidder up to 50% downhill
Motor-manual processing				Processing: up to 60% up and down slope

System 2: Semi-mechanised full tree method: (Max slope: 30 – 40% Uphill / 35 – 50% Downhill)

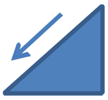
Felling is done motor manually using chainsaws no infield de-branching takes place. The felled trees are then extracted to roadside with skidders or landing where the tree is optimised and processed motor manually with chainsaws.

Once again the slope limiting equipment in the chain will be the skidders, as with the tree length method described above the range of application will be between 30% and 40% for uphill extraction and 35% and 50% for downhill skidding. Depending on the type of skidder utilised.

System 2: Semi-mechanised full tree method: Uphill extraction (Max slope 30 – 40%)

	Stand	Extraction route	Roadside landing	Slope limit
Motor-manual felling				No limit
Skidder				4x4 Grapple skidder up to 30% uphill Cable skidder up to 40% uphill 6x6 Grapple skidder up to 40% uphill
Motor-manual processing				Processing: up to 60% up and down slope

System 2: Semi-mechanised full tree method: Downhill extraction (Max slope 35 – 50%)

	Stand	Extraction route	Roadside landing	Slope limit
Motor-manual felling				No limit
Skidder				4x4 Grapple skidder up to 35% downhill Cable skidder up to 45% downhill 6x6 Grapple skidder up to 50% downhill
Motor-manual processing				Processing: up to 60% up and down slope

System 3: Fully mechanised full tree method 1: (Max slope: 30 – 40% Uphill / 35 – 50% Downhill)

Felling is done using a feller buncher and then extracted to road side or landing by skidders (usually a grapple skidder) where it is processed mechanically using a machine with a processing head. Levelling feller bunchers are capable of working on very steep terrain therefore the grapple skidders that are normally used in this system are the limiting link. The terrain suited to this system will therefore have a maximum gradient of between 35 and 50% when extracting downhill. If conditions require uphill skidding the slope limit is reduced to between 30% and 40%. In South Africa grapple skidders are mostly of the 4x4 type having a 30% uphill and 35% downhill slope limit.

System 3: Fully mechanised full tree method 1: Uphill extraction (Max slope 30 – 40%)

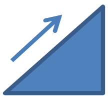
	Stand	Extraction route	Roadside landing	Slope limit
Feller buncher				Wheeled: - Levelling up to 40% uphill and 30% downhill - Non-levelling up to 35% uphill and 20% downhill Tracked: - Levelling up to 60% uphill and 35% downhill - Non-levelling up to 40% uphill and 25% downhill
Skidder				4x4 Grapple skidder up to 30% uphill Cable skidder up to 40% uphill 6x6 Grapple skidder up to 40% uphill
Processor				Wheeled: - Levelling up to 45% uphill and 30% downhill - Non-levelling up to 35% uphill and 20% downhill Tracked: - Levelling up to 60% uphill and 35% downhill - Non-levelling up to 40% uphill and 25% downhill

System 3: Fully mechanised full tree method 1: Downhill extraction (Max slope 35 – 50%)

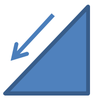
	Stand	Extraction route	Roadside landing	Slope limit
Feller buncher				Wheeled: - Levelling up to 40% uphill and 30% downhill - Non-levelling up to 35% uphill and 20% downhill Tracked: - Levelling up to 60% uphill and 35% downhill - Non-levelling up to 40% uphill and 25% downhill
Skidder				4x4 Grapple skidder up to 35% downhill Cable skidder up to 45% downhill 6x6 Grapple skidder up to 50% downhill
Processor				Wheeled: - Levelling up to 45% uphill and 30% downhill - Non-levelling up to 35% uphill and 20% downhill Tracked: - Levelling up to 60% uphill and 35% downhill - Non-levelling up to 40% uphill and 25% downhill

System 4: Fully mechanised full tree method 2: (Max slope: 30 – 40% Uphill / 35 – 50% Downhill)

Felling is done using a feller buncher and then extracted to road side or landing by skidders (usually a grapple skidder) where it is processed mechanically using a chain flail delimber debarker (CFDD). The slope limits are the same as described for the systems above. The CFDD is normally used at a landing and therefore does not limit the slope.

<table>
<tr><th colspan="5">System 4: Fully mechanised full tree method 2: Uphill extraction (Max slope 30 – 40%)</th></tr>
<tr><th></th><th>Stand</th><th>Extraction route</th><th>Roadside landing</th><th>Slope limit</th></tr>
<tr><td>Feller buncher</td><td colspan="2"></td><td></td><td>Wheeled:
- Levelling up to 40% uphill and 30% downhill
- Non-levelling up to 35% uphill and 20% downhill
Tracked:
- Levelling up to 60% uphill and 35% downhill
- Non-levelling up to 40% uphill and 25% downhill</td></tr>
<tr><td>Skidder</td><td></td><td colspan="2"></td><td>4x4 Grapple skidder up to 30% uphill
Cable skidder up to 40% uphill
6x6 Grapple skidder up to 40% uphill</td></tr>
<tr><td>Chain Flail Delimber Debarker</td><td colspan="2"></td><td></td><td>Up to 5% however processing only done at landing therefore does not affect the system slope limit.</td></tr>
</table>

System 4: Fully mechanised full tree method 2: Downhill extraction (Max slope 35 – 50%)

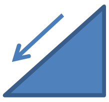
	Stand	Extraction route	Roadside landing	Slope limit
Feller buncher				Wheeled: - Levelling up to 40% uphill and 30% downhill - Non-levelling up to 35% uphill and 20% downhill Tracked: - Levelling up to 60% uphill and 35% downhill - Non-levelling up to 40% uphill and 25% downhill
Skidder				4x4 Grapple skidder up to 35% downhill Cable skidder up to 45% downhill 6x6 Grapple skidder up to 50% downhill
Chain Flail Delimber Debarker				Up to 5% however processing only done at landing therefore does not affect the system slope limit.

System 5: Fully mechanised full tree method 3: (Max slope: 30 – 40% Uphill / 35 – 50% Downhill)

Felling is done using a feller buncher and then extracted to road side or landing by skidders (usually a grapple skidder) where it is processed mechanically using a chain flail delimber debarker chipper (CFDDC). CFDDC's are used on a landing and is therefore not slope limiting. The maximum skidding slope limits are the same as described in the systems above.

System 5: Fully mechanised full tree method 3: Uphill extraction (Max slope 30 – 40%)

	Stand	Extraction route	Roadside landing	Slope limit
Feller buncher				Wheeled: - Levelling up to 40% uphill and 30% downhill - Non-levelling up to 35% uphill and 20% downhill Tracked: - Levelling up to 60% uphill and 35% downhill - Non-levelling up to 40% uphill and 25% downhill
Skidder				4x4 Grapple skidder up to 30% uphill Cable skidder up to 40% uphill 6x6 Grapple skidder up to 40% uphill
Chain Flail Delimber Debarker Chipper				Up to 5% however processing only done at landing therefore does not affect the system slope limit.

System 5: Fully mechanised full tree method 3: Downhill extraction (Max slope 35 – 50%)				
	Stand	Extraction route	Roadside landing	Slope limit
Feller buncher				Wheeled: - Levelling up to 40% uphill and 30% downhill - Non-levelling up to 35% uphill and 20% downhill Tracked: - Levelling up to 60% uphill and 35% downhill - Non-levelling up to 40% uphill and 25% downhill
Skidder				4x4 Grapple skidder up to 35% downhill Cable skidder up to 45% downhill 6x6 Grapple skidder up to 50% downhill
Chain Flail Delimber Debarker Chipper				Up to 5% however processing only done at landing therefore does not affect the system slope limit.

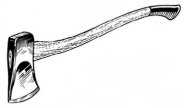
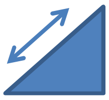
Cut- to –length (CTL) systems:

With CLT systems the processing is done infield and the logs extracted to the landing, as opposed to full tree and tree length systems where the trees optimised at roadside.

System 1: Manual CTL method: (Max slope 20%)

Felling, crosscutting and delimbing are done motor-manually using chainsaws, delimbing can also be done manually using axes or similar tools depending on branch thickness. Debarking and stacking is done manually. The logs are extracted via a tractor with a trailer.

Felling and processing are not slope limiting since manual processing can be done at slopes of up to 60%. Agricultural tractors are very sensitive to slope especially if used for forwarding with a trailer. Tractor with trailer extraction is limited to 20% up or down slope.

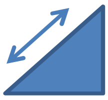
System 1: Manual CTL method: (Max slope 20%)				
	Stand	Extraction route	Roadside landing	Slope limit
Motor-manual felling				Any slope
Manual processing				Up to 60% uphill and downhill
Tractor with trailer				Up to 20% uphill and downhill

System 2: Semi-mechanised CTL method 1: (Max slope 20%)

Felling, crosscutting and delimbing are done motor-manually using chainsaws, debarking is done mechanically and the logs are extracted using a tractor with a trailer.

Since the agricultural tractor trailer combination is the limiting agent the slope range of the system is limited to a maximum of 20% either uphill or downhill.

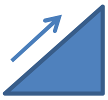
System 2: Semi-mechanised CTL method 1: (Max slope 20%)

		Extraction route	Roadside landing	Slope limit
Motor-manual felling, debranching and crosscutting				Felling: any slope Processing: up to 60% up and down slope
Mechanical debarking				Wheeled: - Levelling up to 40% uphill and 35% downhill - Non-levelling up to 35% uphill and 20% downhill Tracked: - Levelling up to 55% uphill and 35% downhill - Non-levelling up to 40% uphill and 25% downhill
Tractor with trailer				Up to 20% uphill and downhill

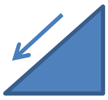
System 3: Semi-mechanised CTL method 2: (Max slope 25 - 60% Uphill / 35 - 60% Downhill)

Felling, crosscutting and delimbing are done motor-manually using chainsaws, debarking is done mechanically and the logs are extracted using a forwarder.

Motor-manual felling and processing can be done safely on slopes of up to 60%, while forwarders are capable of working downhill on slopes of 35% and 25 % uphill for four wheeled forwarders. The larger eight wheel drive forwarders are capable of handling slopes of 45% uphill and 50% downhill. If forwarders are fitted with a synchronised traction aid winch system they can work on slopes exceeding 60% depending on underfoot conditions.

<table>
<tr><th colspan="5">System 3: Semi-mechanised CTL method 2: Uphill extraction (Max slope 25 - 60%)</th></tr>
<tr><th></th><th>Stand</th><th>Extraction route</th><th>Roadside landing</th><th>Slope limit</th></tr>
<tr><td>Motor-manual felling, debranching and crosscutting</td><td> </td><td></td><td></td><td>Felling: any slope
Processing: up to 60% up and down slope</td></tr>
<tr><td>Mechanical debarking</td><td colspan="2"> </td><td></td><td>Wheeled:
- Levelling up to 40% uphill and 35% downhill
- Non-levelling up to 35% uphill and 20% downhill
Tracked:
- Levelling up to 55% uphill and 35% downhill
- Non-levelling up to 40% uphill and 25% downhill</td></tr>
<tr><td>Forwarder</td><td></td><td colspan="2"></td><td>Four wheel forwarder: up to 25% uphill
Six wheel forwarders: up to 35% uphill
Eight wheel forwarders: up to 40% uphill
Fitted with winch: up to 60% uphill</td></tr>
</table>

System 3: Semi-mechanised CTL method 2: Downhill extraction (Max slope 35 - 60%)

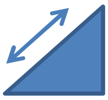
	Stand	Extraction route	Roadside landing	Slope limit
Motor-manual felling, debranching and crosscutting				Felling: any slope Processing: up to 60% up and down slope
Mechanical debarking				Wheeled: - Levelling up to 40% uphill and 35% downhill - Non-levelling up to 35% uphill and 20% downhill Tracked: - Levelling up to 55% uphill and 35% downhill - Non-levelling up to 40% uphill and 25% downhill
Forwarder				Four wheel forwarder: up to 35% downhill Six wheel forwarders: up to 45% downhill Eight wheel forwarders: up to 50% downhill Fitted with winch: up to 60% downhill

System 4: Semi-mechanised CTL method 3: (Max slope 20%)

Only felling is done motor-manually the rest of the processing activities i.e. crosscutting, debranching and debarking are all mechanised activities. The logs are extracted using an agricultural tractor with a trailer.

Agricultural tractor trailer extraction can only be used on slopes of up to 20% making it the slope limiting factor for the system.

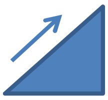
System 4: Semi-mechanised CTL method 3: (Max slope 20%)

	Stand	Extraction route	Roadside landing	Slope limit
Motor-manual felling				Any slope
Mechanical processing				Wheeled: - Levelling up to 40% uphill and 35% downhill - Non-levelling up to 35% uphill and 20% downhill Tracked: - Levelling up to 55% uphill and 35% downhill - Non-levelling up to 40% uphill and 25% downhill
Tractor with trailer				Up to 20% uphill and downhill

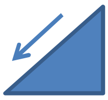
System 5: Semi-mechanised CTL method 4: (Max slope 25 - 60% Uphill / 35 - 60% Downhill)

Felling is done motor-manually using chainsaws, crosscutting; delimbing and debarking are done mechanically. The processed logs are transported with a forwarder.

Forwarders can be utilised on slopes with a maximum gradient of between 25 and 45% uphill or 35% and 50% working downhill. If forwarders are fitted with a synchronised traction aid winch system they can work on slopes exceeding 60%.

System 5: Semi-mechanised CTL method 4: Uphill extraction (Max slope 25 - 60%)				
	Stand	Extraction route	Roadside landing	Slope limit
Motor-manual felling				Up to 60%
Mechanical processing				Wheeled: - Levelling up to 40% uphill and 35% downhill - Non-levelling up to 35% uphill and 20% downhill Tracked: - Levelling up to 55% uphill and 35% downhill - Non-levelling up to 40% uphill and 25% downhill
Forwarder				Four wheel forwarder: up to 25% uphill Six wheel forwarders: up to 35% uphill Eight wheel forwarders: up to 40% uphill Fitted with winch: up to 60% uphill

System 5: Semi-mechanised CTL method 4: Downhill extraction (Max slope 35 - 60%)

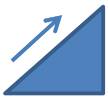
	Stand	Extraction route	Roadside landing	Slope limit
Motor-manual felling				Up to 60%
Mechanical processing				Wheeled: - Levelling up to 40% uphill and 35% downhill - Non-levelling up to 35% uphill and 20% downhill Tracked: - Levelling up to 55% uphill and 35% downhill - Non-levelling up to 40% uphill and 25% downhill
Forwarder				Four wheel forwarder: up to 35% downhill Six wheel forwarders: up to 45% downhill Eight wheel forwarders: up to 50% downhill Fitted with winch: up to 60% downhill

System 6: Mechanised CTL method: (Max slope 25 - 60% Uphill / 35 - 60% Downhill)

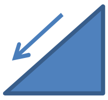
Felling, crosscutting, debarking and delimbing are done by a mechanical harvester with extraction done by using a forwarder.

Wheeled harvesters are capable of working uphill on slopes of up to 35% for non-levelling models and 45% for levelling machines; their tracked counterparts are capable of up to 40% for non-levelling and 55% for levelling machines. If harvesting is to be done downhill the slope limits drop to 20% for non-levelling and 35 for levelling wheeled harvesters. Non-levelling tracked harvesters can cope with slopes of up to 25% and levelling tracked harvesters 35% when working downhill. Synchronised traction aid winches can be fitted to wheeled harvesters that will increase their capability to 60%. Forwarders can be utilised on slopes with a maximum gradient of between 35% and 50% when extracting downhill or between 25% and 45% uphill. If fitted with a synchronised traction aid winch system they can work on slopes exceeding 60%.

System 6: Mechanised CTL method: Uphill extraction (Max slope 25 - 60%)

	Stand	Extraction route	Roadside landing	Slope limit
Harvester				Wheeled: - Levelling up to 40% uphill and 35% downhill - Non-levelling up to 35% uphill and 20% downhill Tracked: - Levelling up to 55% uphill and 35% downhill - Non-levelling up to 40% uphill and 25% downhill
Forwarder				Four wheel forwarder: up to 25% uphill Six wheel forwarders: up to 35% uphill Eight wheel forwarders: up to 40% uphill Fitted with winch: up to 60% uphill

System 6: Mechanised CTL method: Downhill extraction (Max slope 35 - 60%)

	Stand	Extraction route	Roadside landing	Slope limit
Harvester				Wheeled: - Levelling up to 40% uphill and 35% downhill - Non-levelling up to 35% uphill and 20% downhill Tracked: - Levelling up to 55% uphill and 35% downhill - Non-levelling up to 40% uphill and 25% downhill
Forwarder				Four wheel forwarder: up to 35% downhill Six wheel forwarders: up to 45% downhill Eight wheel forwarders: up to 50% downhill Fitted with winch: up to 60% downhill

Annexure B: Steep slope harvesting survey

102 experts were selected due to their knowledge of difficult terrain harvesting. They were invited to participate in the second NMMU FESA Steep Slope Harvesting Survey. 20 of these individuals submitted their contributions before the posted deadline. Three of the invited experts declined to participate in the survey indicating that the scope of the survey fell outside of their field of expertise. There was also a small group of experts that were unable to participate due to technical difficulties with their servers blocking the survey. The person responsible for the survey was involved in a serious motorcycle accident and was unable to work on the project for a period of three months. This meant that the document format issues could not be resolved before the due date of the survey and also that follow-up in terms of why and to obtain a larger percentage of people on the list participating was not possible. Nevertheless the 20 individuals that took part in the survey are highly respected experts from around the globe.

The survey consisted of 50 multiple choice questions based on the slope handling capability of the harvesting equipment indicated in the South African Ground Based Harvesting Handbook published by FESA in 2010 (GBHH). The questions were formulated based on the slope limitations assigned by the GBHH, which was found to be the most up-to-date reference for slope handling ability of harvesting equipment after an extensive literature review.

Respondents were asked to submit a response of “Unsure” if they felt a question fell outside of their field of expertise. An “Other” option was also included for each question, allowing experts to give their own opinion if none of the supplied answers were adequate.

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Feller Buncher

		Wheeled				Tracked			
		Non-Levelling		Levelling		Non-Levelling		Levelling	
		GBHH	SSHS	GBHH	SSHS	GBHH	SSHS	GBHH	SSHS
Slope (%)	Uphill	35	30	40	40	40	40	60	60
	Downhill	20	20	30	30	25	25	35	40

Harvester

		6 or 8 Wheeled				Tracked			
		Non-Levelling		Levelling		Non-Levelling		Levelling	
		GBHH	SSHS	GBHH	SSHS	GBHH	SSHS	GBHH	SSHS
Slope (%)	Uphill	35	35	45	45	40	40	60	55
	Downhill	20	20	30	35	25	25	35	35

Forwarders

		4 X 4		6 X 6		8 X 8	
		GBHH	SSHS	GBHH	SSHS	GBHH	SSHS
Slope (%)	Uphill	25	25	35	35	45	45
	Downhill	35	35	45	45	50	50

Skidding

		Agricultural Tractor		Cable Skidder		4 X 4 Grapple Skidder		6 X 6 Grapple Skidder		Clambunk Skidder		Tracked Skidder	
		GBHH	SSHS	GBHH	SSHS	GBHH	SSHS	GBHH	SSHS	GBHH	SSHS	GBHH	SSHS
Slope (%)	Uphill	25	25	40	40	30	30	45	40	35	35	50	45
	Downhill	35	35	45	45	35	35	55	50	40	40	55	50

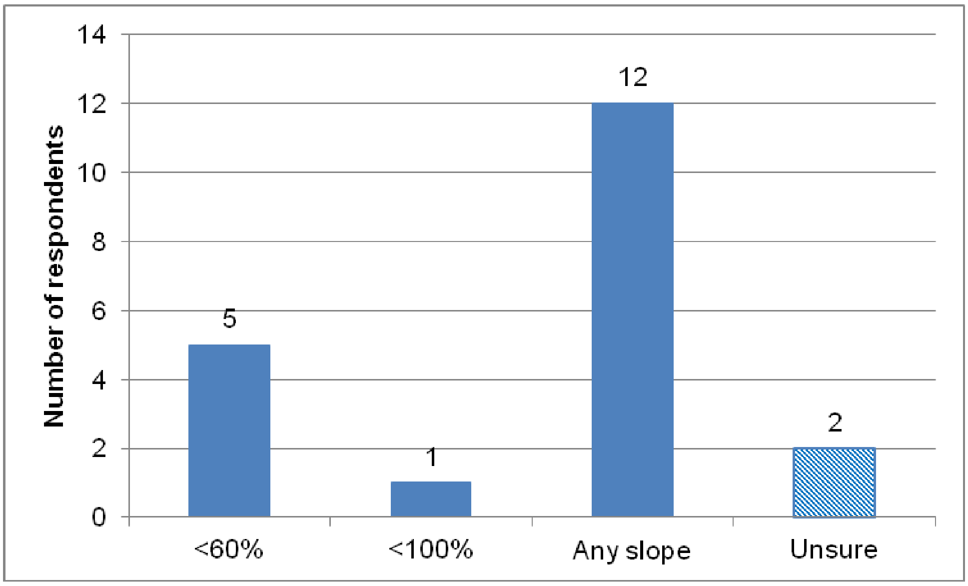
Other Extraction

		Manual		Chutes		Animal		Agricultural Tractor Trailer		Articulated dump truck (ADT)		Shovel logger			
												Non-Levelling		Levelling	
		GBHH	SSHS	GBHH	SSHS	GBHH	SSHS	GBHH	SSHS	GBHH	SSHS	GBHH	SSHS	GBHH	SSHS
Slope (%)	Uphill	10	10	N/A	N/A	15	15	20	20	20	20	35	35	55	55
	Downhill	ANY	ANY	90	90	35	35	20	20	25	25	25	25	45	45

Question 1: Can motor-manual felling be carried out on any slope?

Twelve of the respondents agreed that it is possible for motor-manual felling to be carried out on any slope class. Five felt that motor-manual felling activities should be limited to slopes of less than 60%. Two respondents were unsure and one indicated that motor-manual felling can safely be done on slopes of up to 100%.

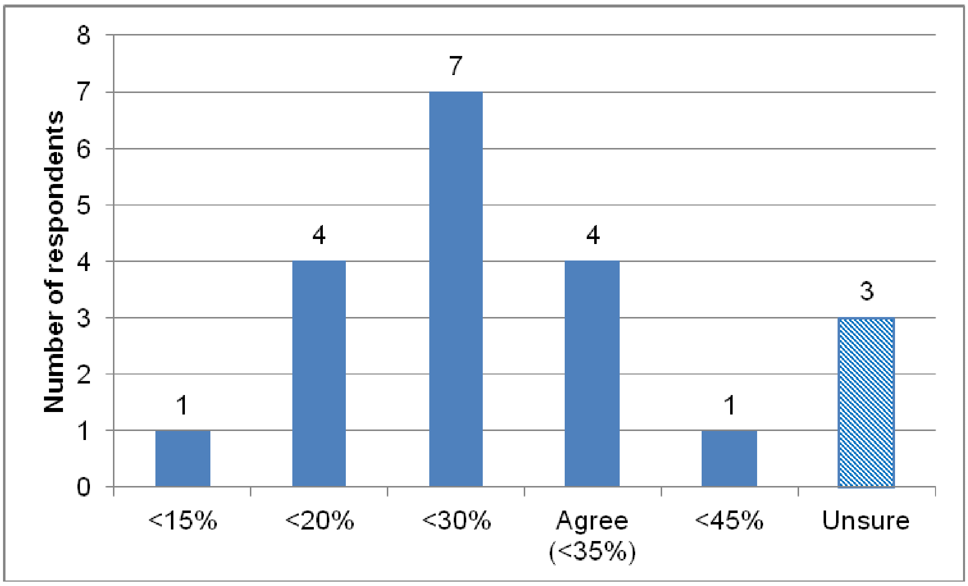
The majority of experts therefore indicated that it is safe to fell motor-manually on any slope gradient.



Question 2: Non-levelling wheeled Feller Bunchers can operate on slopes of less than 35% working UPHILL.

Four of the respondents agreed with the less than 35% slope limit; however 12 indicated that non-levelling Feller Bunchers should be operated on lesser slopes. Of the 12; four limited slope handling capability to slopes less than 20%, seven other respondents indicated that only slopes less than 30% can be negotiated safely and one indicated that the slope gradient should be less than 15%. Three respondents were unsure of the slope handling capabilities of non-levelling Feller Bunchers. Only one indicated that the 35% slope limit may be extended to slopes of less than 45%.

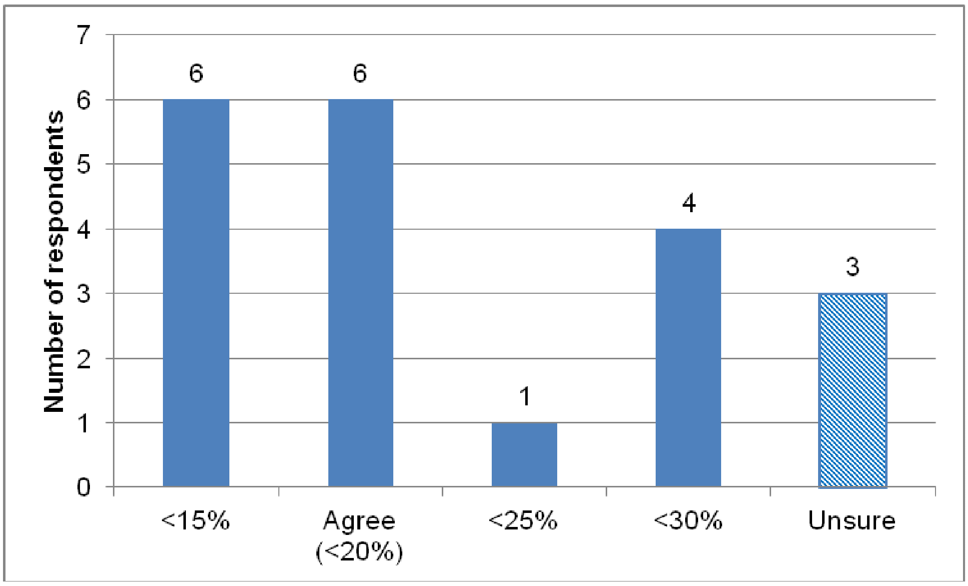
The survey result suggests that the slope limit indicated in the GBHH is too high and should be lowered to slopes of less than 30%.



Question 3: Non-levelling wheeled Feller Bunchers can operate on slopes of less than 20% working DOWNHILL.

Six of the respondents agreed with the statement that non-levelling Feller Bunchers are capable of working on slopes less than 20% downhill. Six indicated that the slope should be limited to less than 15% while working downhill. A total of five respondent felt that a slope of 20% downhill is too low; one indicated a slope of less than 25% and four preferred a slope of less than 30%. Three of the respondents were unsure of the downhill capability of non-levelling Feller Bunchers.

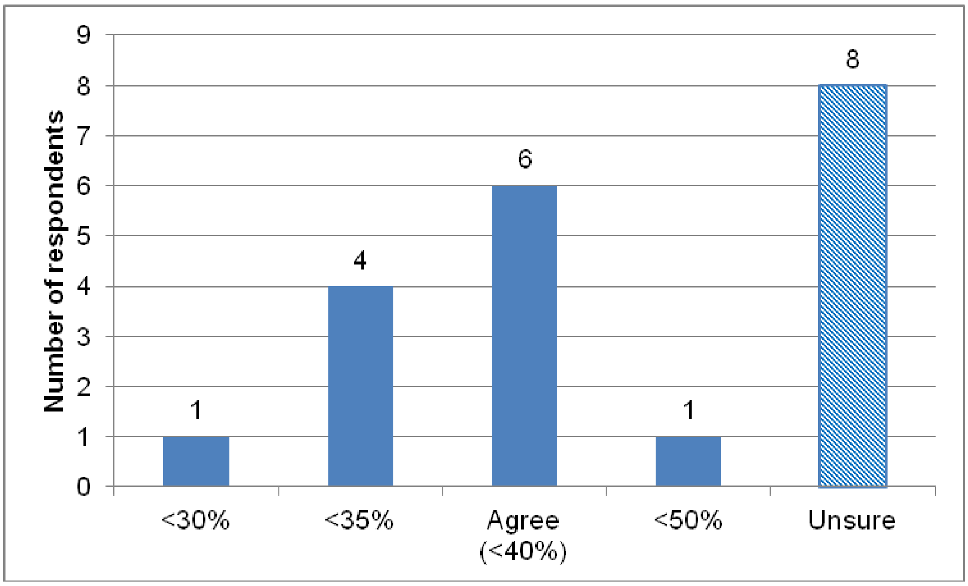
The survey results confirmed the slope limit as suggested by the GBHH.



Question 4: Levelling wheeled Feller Bunchers can operate on slopes of less than 40% working UPHILL.

Six of the respondents agreed with the assessment that wheeled levelling Feller Bunchers can operate on slopes of 40% or less. Five other respondents argued that the capability is less than the stated 40% slope limit, with four indicating a safe operating slope as being 35% or less and one indicated a slope class of 30% or less. One person indicated a safe operating slope limit of less than 50%. The other eight respondents were unsure.

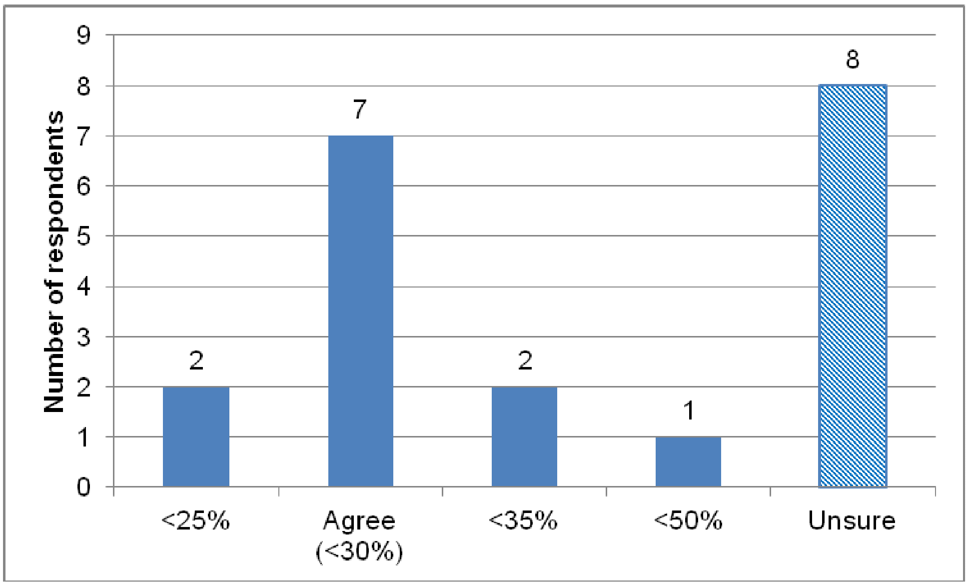
Levelling wheeled Feller Bunchers are very uncommon machines; which explains the high number of unsure responses from the respondents for question four and five. The survey results confirmed the less than 40% slope limit as indicated by the GBHH.



Question 5: Levelling wheeled Feller Bunchers can operate on slopes of less than 30% working DOWNHILL.

Seven of the respondents indicated that they agreed with the less than 30% slope limit assigned to levelling heeled Feller Bunchers that are operating downhill. Two felt that the limit should be lowered to 25% while two more indicated that the maximum slope should be 35%. One person chose the less than 50% option and the remaining eight were unsure.

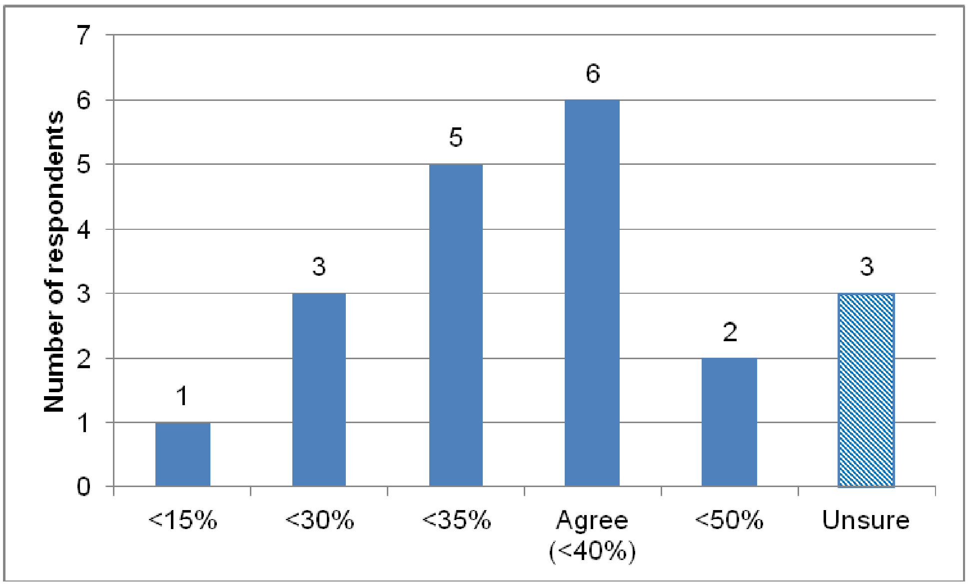
The survey result strongly agreed with the GBHH that slopes of less than 30% is the appropriate safe operating limit for Levelling wheeled Feller benchers working downhill.



Question 6: Non-levelling tracked Feller Bunchers can operate on slopes of less than 40% working UPHILL.

Six of the respondents agreed with the less than 40% assessment but nine others indicated a lower slope limit. One respondent indicated a slope of less than 15%, three indicated a slope class of less than 30% and five chose the less than 35% slope limitation. Two respondents indicated that 40% uphill is too low and preferred a slope of less than 50%, three were unsure.

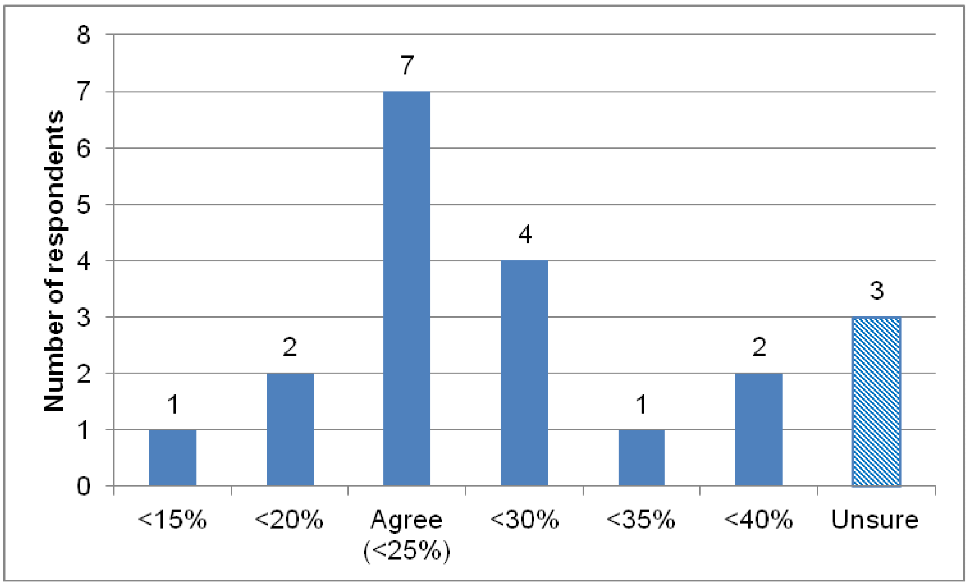
The GBHH slope limit of less than 40% was confirmed by the survey results.



Question 7: Non-levelling tracked Feller Bunchers can operate on slopes of less than 25% working DOWNHILL.

Seven of the respondent agreed with the statement. Among the respondents that indicated a lower slope limit, one indicated a slope of 15% or less, two chose a slope of 20% or less. Four felt that a limit of less than 30% is more appropriate, one indicated less than 35% and two indicated that the non-levelling Feller Bunchers can negotiate slopes of up to 40%. Three respondents were unsure of the slope handling ability.

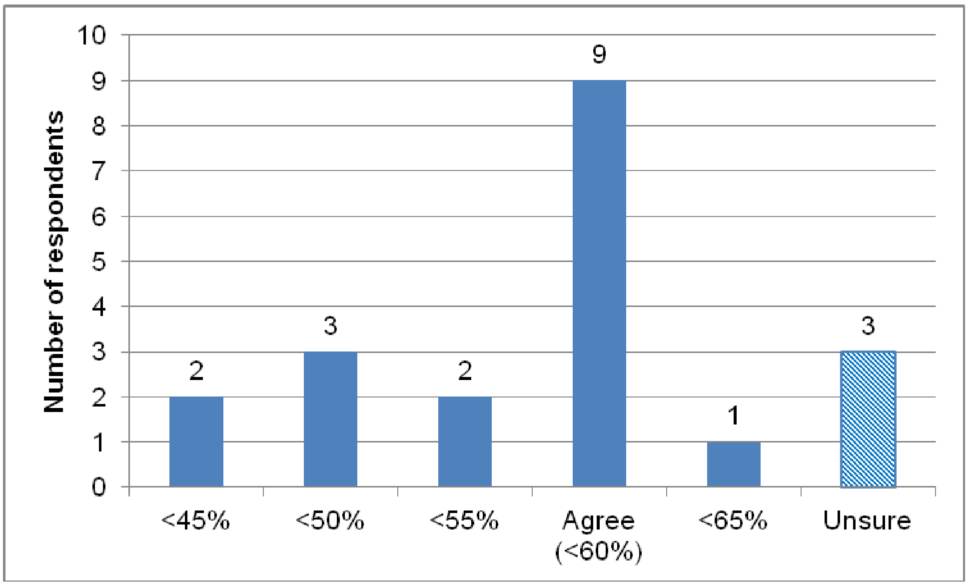
The survey results indicate that the less than 25% slope limit is correct with the possibility to increase the limit to slopes of less than 30%.



Question 8: Levelling tracked Feller Bunchers can operate on slopes of less than 60% working UPHILL.

Nine of the respondents agreed that levelling tracked Feller Bunchers can operate on slopes of up to 60%, one raised the limit to less than 65%. Two indicated a slope of less than 45%, three selected a slope of less than 50% and two a slope of up to 55%. The remaining three were unsure.

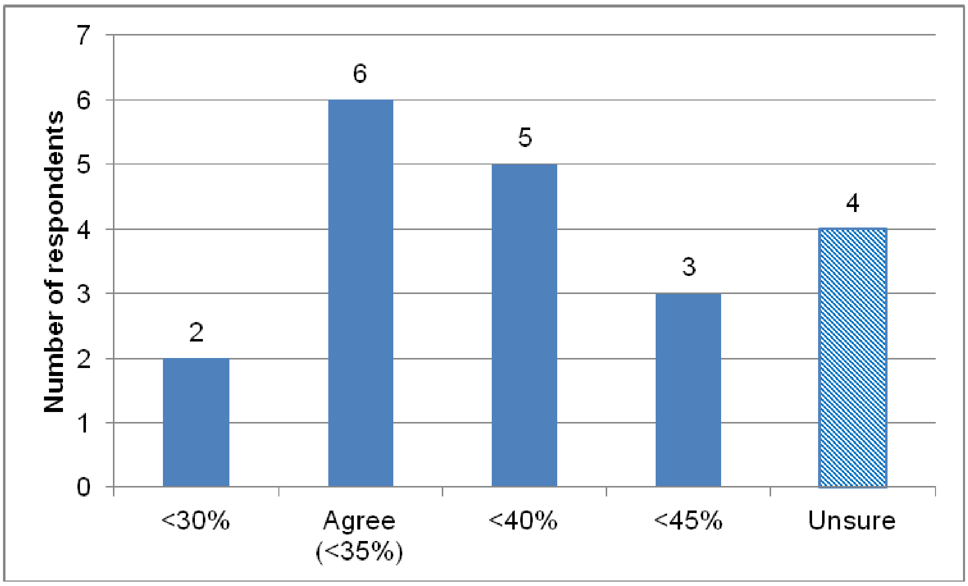
A clear majority of respondents agreed with the limit set by the GBHH.



Question 9: Levelling tracked Feller Bunchers can operate on slopes of less than 35% working DOWNHILL.

Six of the experts agreed with the less than 35% slope limit. Two lowered the limit to less than 30%, while five indicated a higher slope limit of up to 40%. Three experts raised the limit to 50% while working downhill. The remaining four were unsure.

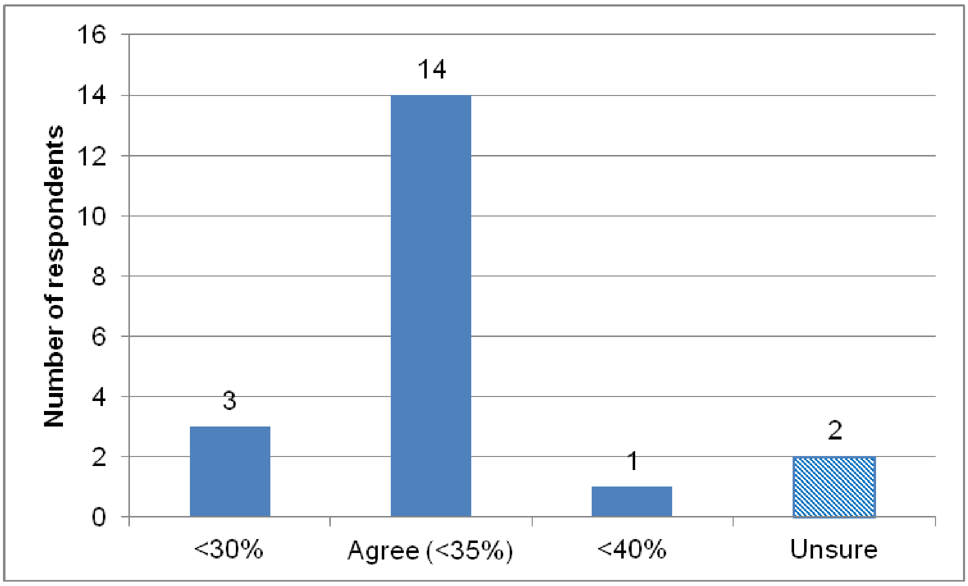
The results of the survey indicated that the slope limit should be increased to a gradient of less than 40% from the current less than 35%.



Question 10: Non-levelling 6 and 8 wheeled Harvesters can operate on slopes less than 35% working UPHILL.

Fourteen of the respondents indicated that they agreed while three others indicated that the limit should be less than 30% and one felt that the slope limit should be raised to 40%. Two of the respondents were unsure.

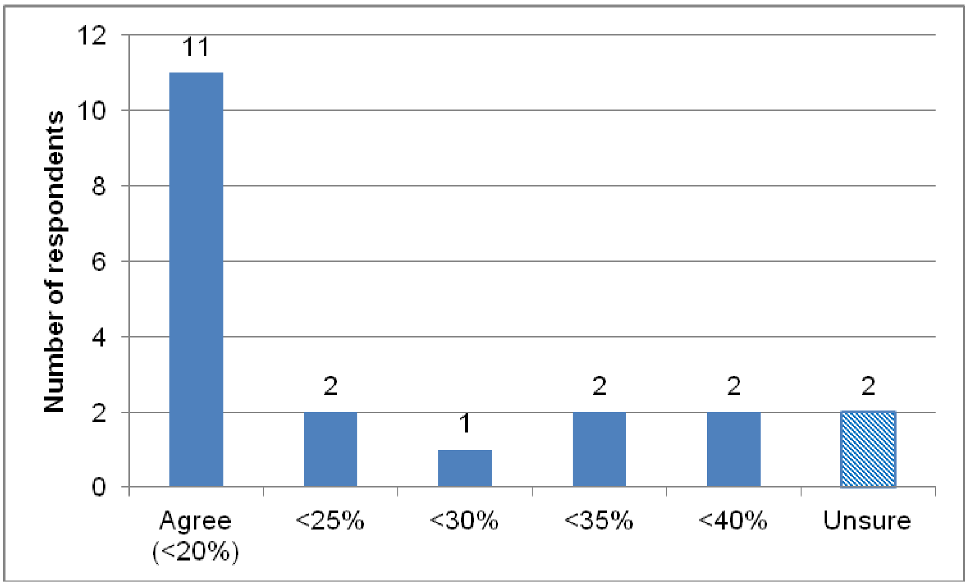
The less than 35% slope limit indicated in the GBHH was confirmed by the survey results.



Question 11: Non-levelling 6 and 8 wheeled Harvesters can operate on slopes less than 20% working DOWNHILL.

Eleven respondents agreed with the 20% downhill slope limit. Seven of them indicated that the limit should be raised; two suggested a new limit of less than 25%. One indicated less than 30%, two persons chose the less than 35% and 40% slope classes respectively. Only two were unsure of the downhill capability of non-Levelling Harvesters.

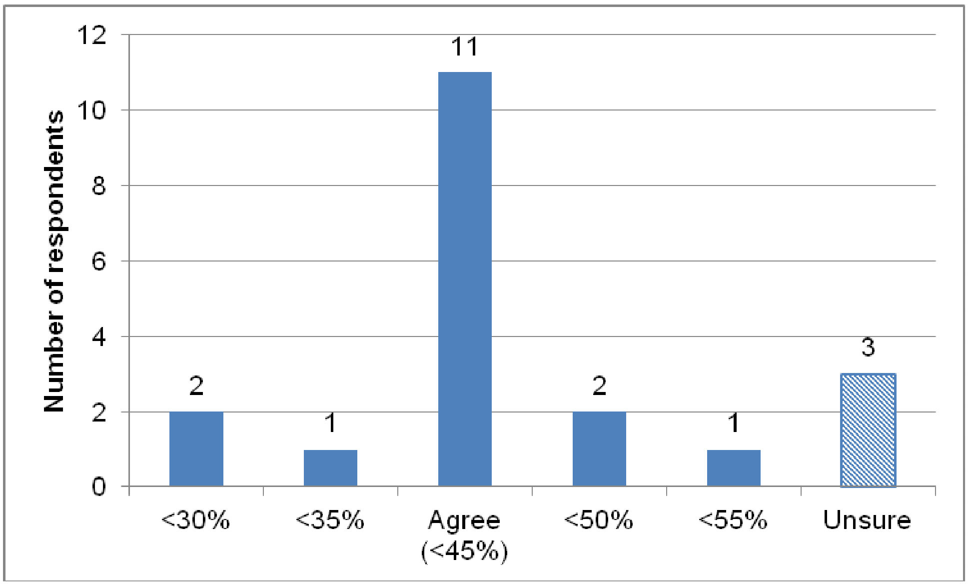
The survey results clearly indicated that the GBHH's indicated slope limit of less than 20% is correct.



Question 12: Levelling 6 and 8 wheeled Harvesters can operate on slopes less than 45% working UPHILL.

Eleven respondents agreed that wheeled harvesters are capable of operating on slopes of less than 45%, two were of the opinion that the slope should be limited to 30% and one suggested a slope limit of less than 35%. There were also three respondents that indicated slopes exceeding 45% are possible, two of these placed the limit at 50% and the third chose a slope of less than 55%. Three of the respondents were unsure.

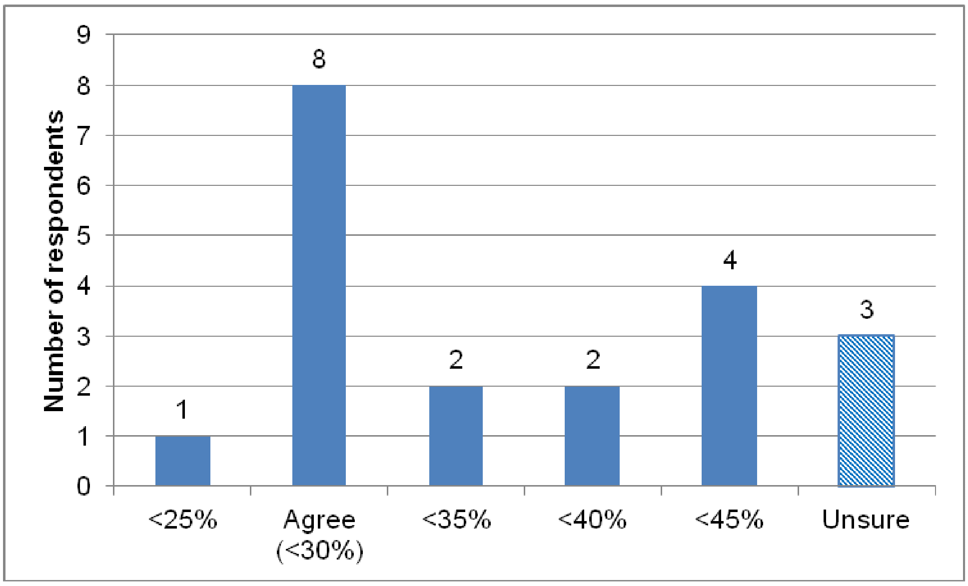
The majority of the experts agreed with the current slope limit as set by the GBHH.



Question 13: Levelling 6 and 8 wheeled Harvesters can operate on slopes less than 30% working DOWNHILL.

Of the 20 respondents 8 were of the opinion that slopes of less than 30% are the correct option for the safe operation of levelling wheeled harvesters. Only one felt that the slope should be reduced to less than 25% while five others indicated higher slope classes. The less than 35% and less than 40% options were selected by two respondents each. Four selected the less than 45% option and the remaining three respondents were unsure.

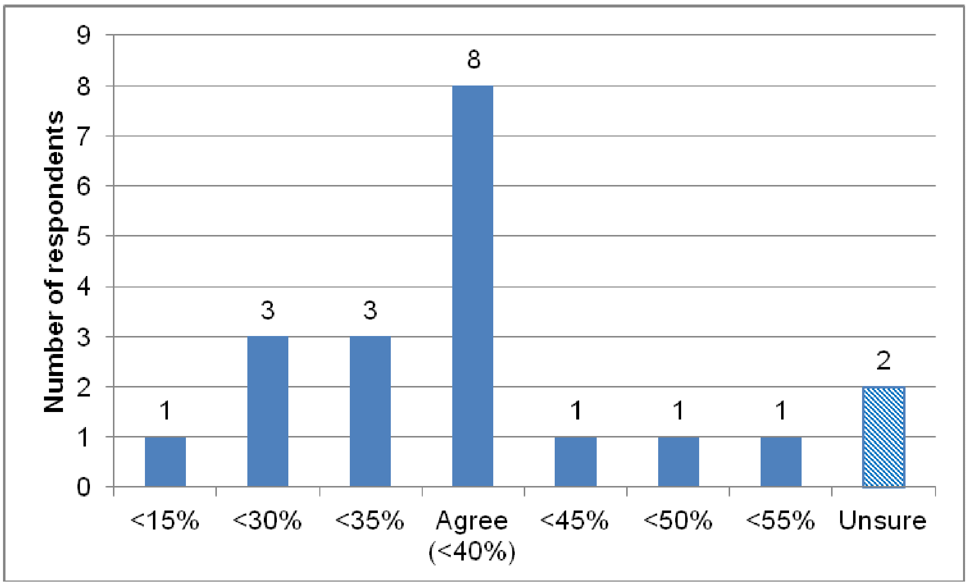
Although eight of the respondents agreed with slope class assigned by the GBHH; the general trend indicated that the slope should be increased to gradients of less than 35%.



Question 14: Non-levelling tracked Harvesters can operate on slopes less than 40% working UPHILL.

Eight respondents agreed with statement and three were of the opinion that non-levelling tracked harvesters are capable of working on slopes greater than specified. One participant each selected the less than 45, 50 and 55% slope classes. Seven felt that the limiting slope should be lowered, of the seven; the less than 30 and 35% classes attracted three votes each. One was of the opinion that the machines should work on slopes of less than 15% only and the remaining two respondents were unsure.

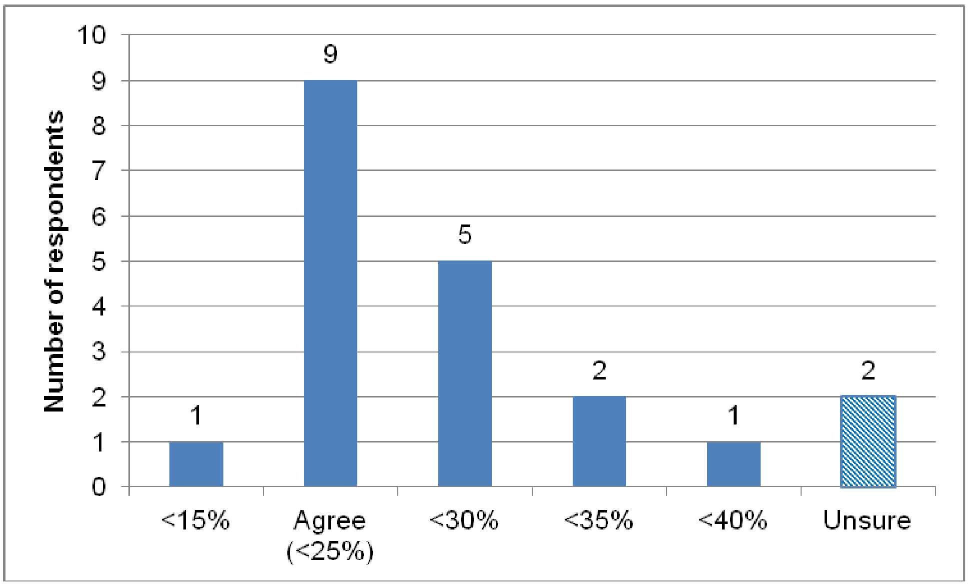
The survey results confirmed the current less than 40% slope limit of the GBHH.



Question 15: Non-levelling tracked Harvesters can operate on slopes less than 25% working DOWNHILL.

Nine persons agreed that non-levelling tracked harvesters should operate on slopes of less than 25%. Only one person indicated that the slope limit should be less, stating that the limit should be less than 15%. Five felt that the safe operating limit could be increased to slopes of less than 30%, while two more suggested a slope of less than 35% and a single participant felt that it should be less than 40%. Two respondents were unsure.

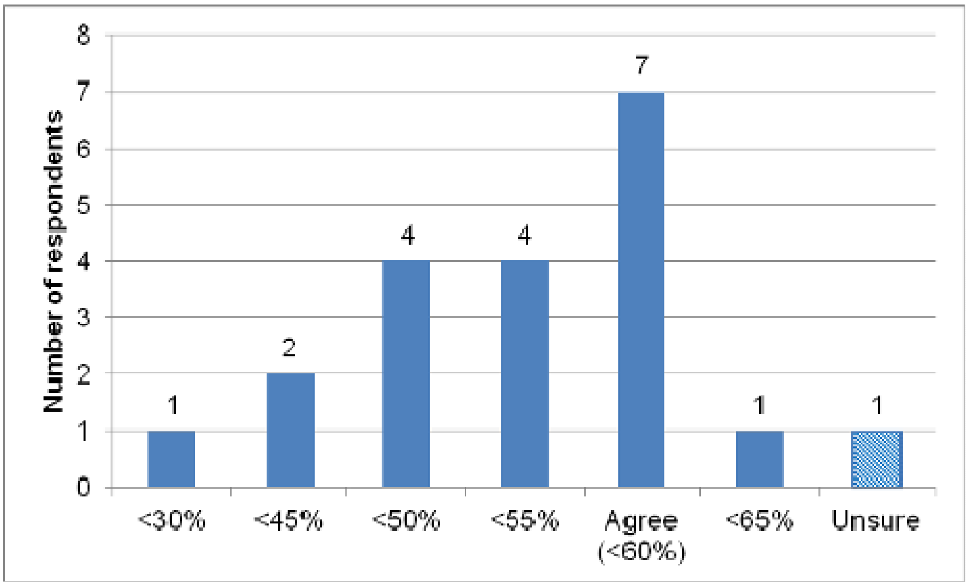
The survey results indicated that it might be possible to increase the slope limit to slopes of less than 30%. However it was decided to keep the limit at slopes of 25% or less as recommended by the GBHH.



Question 16: Levelling tracked Harvesters can operate on slopes less than 60% working UPHILL.

Seven of the 20 respondents in the survey agreed with the less than 60% slope assessment. Only one person indicated that the limitation should be raised to less than 65%. Eleven respondents were of the opinion that the slope handling capability of levelling tracked harvesters are lower, the less than 50 and 55% classes drew four votes each, less than 45% was selected by two respondents and the less than 30% got the support of one individual. Only one person was unsure.

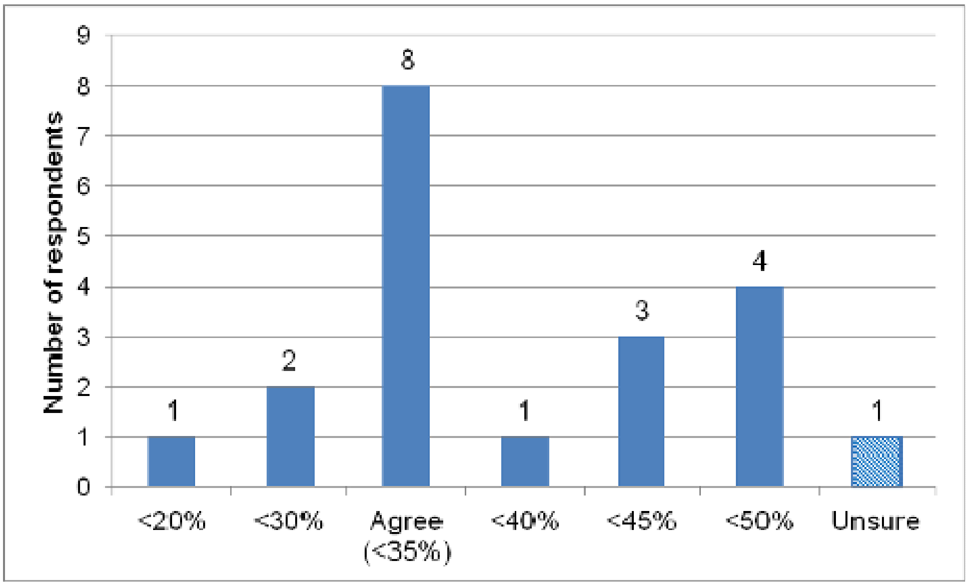
It was decided that the safe operating slope limit should be lowered to gradients of less than 55%. In the end the decision could have gone either way due to the large number of respondents that agreed with the original less than 60% slope assessment.



Question 17: Levelling tracked Harvesters can operate on slopes less than 35% working DOWNHILL.

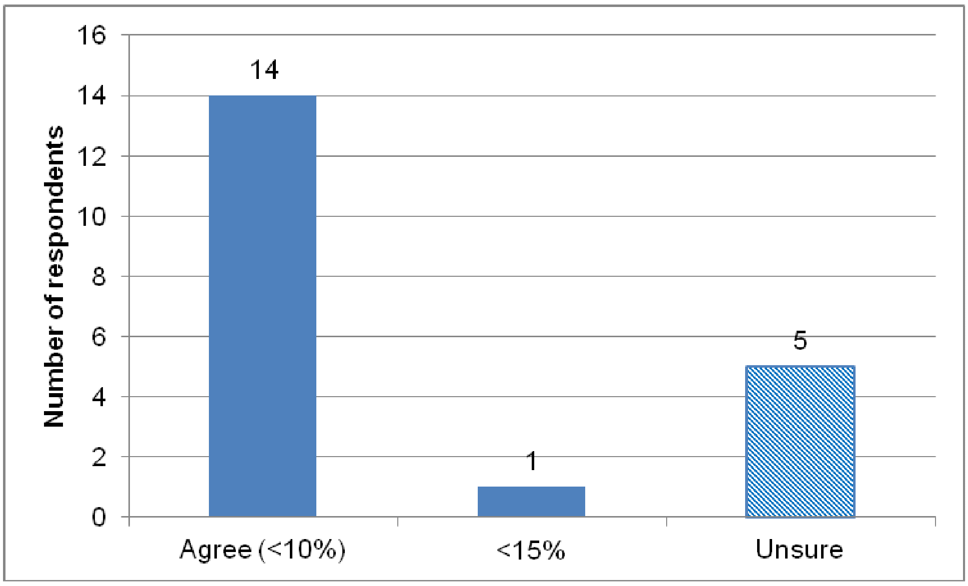
Eight persons agreed that less than 35% slope is a safe operating range for levelling tracked harvesters when working downhill. Three felt that the stated slope range was over optimistic and that it should be lowered. Two suggested a slope limit of less than 30% and one elected the less than 20% option. A further eight persons indicated that the current slope limit is to low and that it should be raised. One of them suggested a new limit of less than 40%, while three suggested less than 45% and four less than 50%. Only one person indicated that he was unsure.

Although it was plausible to raise the slope limit to slopes of less than 40%; the cluster of eight respondents agreeing with the original limit of less than 35% indicated that it should remain unchanged.



Question 18: Manual extraction is limited to slopes less than 10% when extracting UPHILL. Fourteen persons agreed with statement and one felt that manual extraction can be carried out on slopes of less than 15%. The remaining five respondents were unsure.

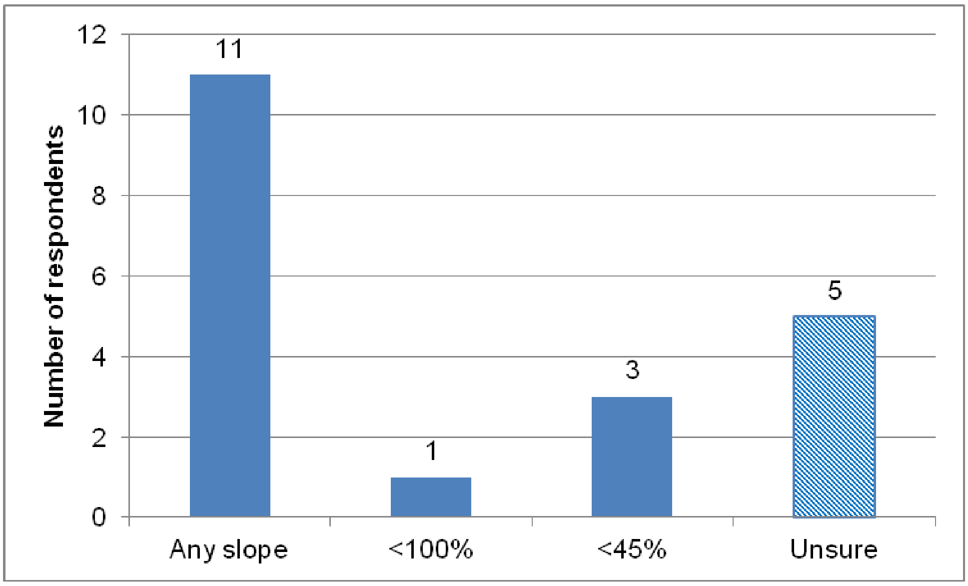
The survey results clearly indicated that the slope limit should remain unchanged.



Question 19: Manual DOWNHILL can be done on any slope.

Eleven respondents agreed that manual extraction can be done on any slope. One indicated that it should be limited to slopes less than 100% and three more suggested that the limit be lowered to slopes of less than 45%, the remaining five persons were unsure.

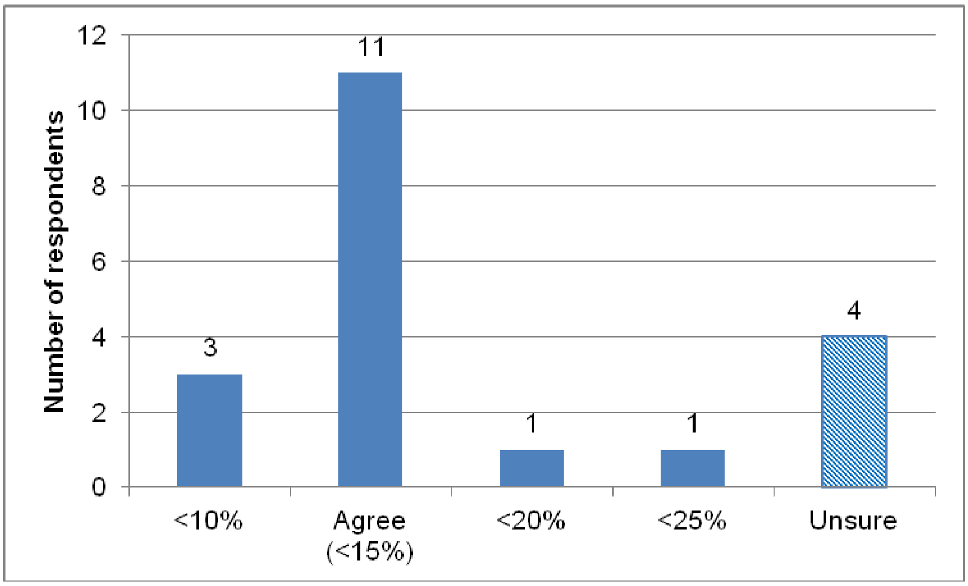
The results indicated that the assessment of the GBHH was correct and that the slope limit should remain unchanged.



Question 20: UPHILL animal extraction is limited to slopes less than 15%.

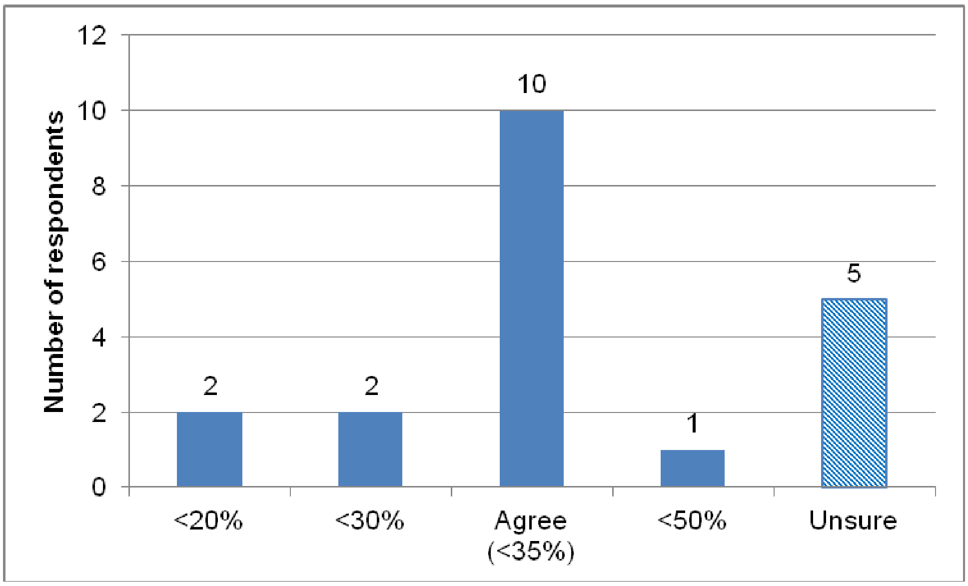
Eleven of the experts agreed that slopes should be less than 15% for uphill animal extraction. Three felt that the limit should be lowered to less than 10%, while two others suggested that it be raised to less than 20% and 25% respectively. Four of the respondents were unsure.

The survey results indicated that the less than 15% slope limit assigned to uphill animal extraction was correct.



Question 21: DOWNHILL animal extraction can be done on slopes less than 35%.
Half of the respondents believed that downhill animal extraction can be conducted on slopes less than 35%. Four indicated that the slope limit should be lower; two each choosing the less than 20 and 30% slope options respectively. Only one was of the opinion that the stated limit was to low and should be raised to slopes of less than 50%. The remaining five persons were unsure.

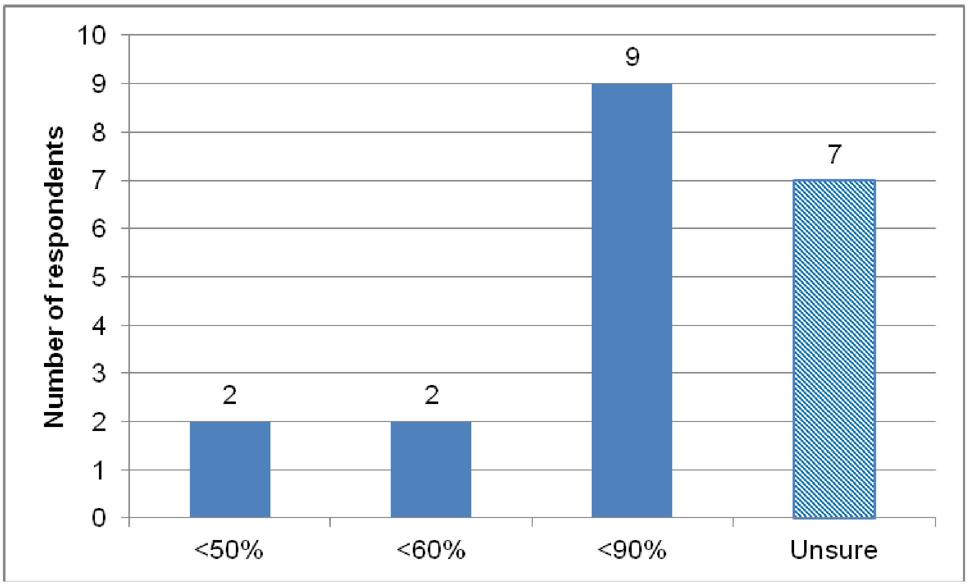
The survey results confirmed the current slope limit.



Question 22: Chutes can be utilised on slopes of less than 90%.

Eight of the respondent agreed with the statement. Four, however, disagreed of which two persons indicating that the slope limit should be less than 60% and the other two less than 50%. The remaining seven indicated that they were unsure.

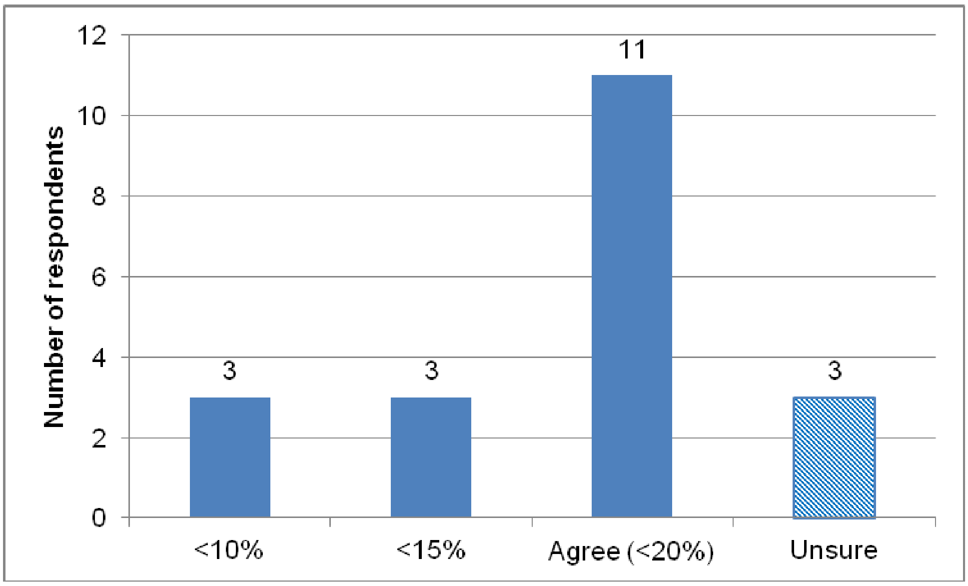
The majority of the respondents indicated that the slope limit should remain unchanged.



Question 23: Agricultural tractor trailer extraction can be used on slopes of less than 20% UPHILL.

Eleven of the respondents agreed and six indicated that the slope limit was too high. Three of the six preferred a slope class of less than 15% and the remaining three opted for the less than 10% option. Three respondents were unsure.

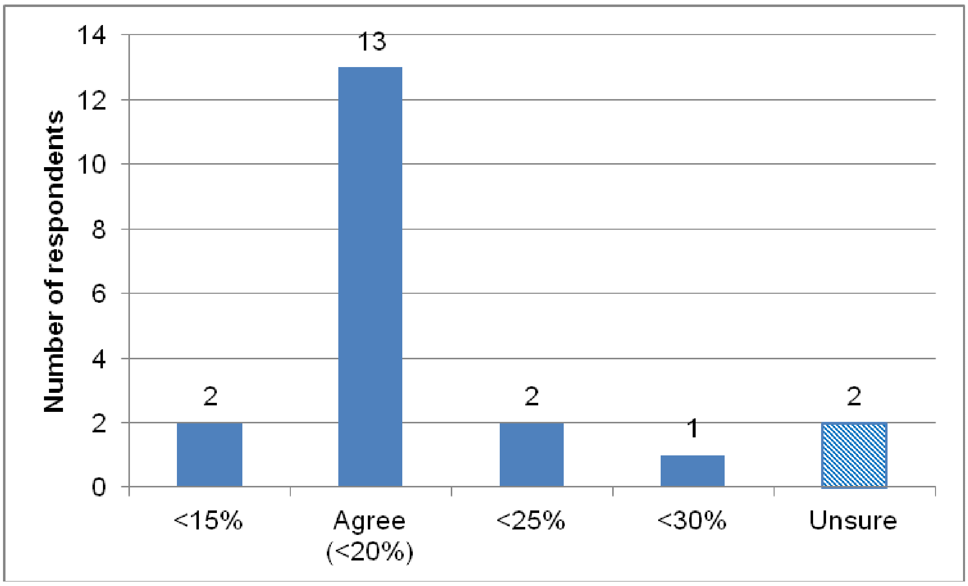
The survey results confirmed that the current slope limit is correct



Question 24: Agricultural tractor trailer extraction can be used on slopes of less than 20% DOWNHILL.

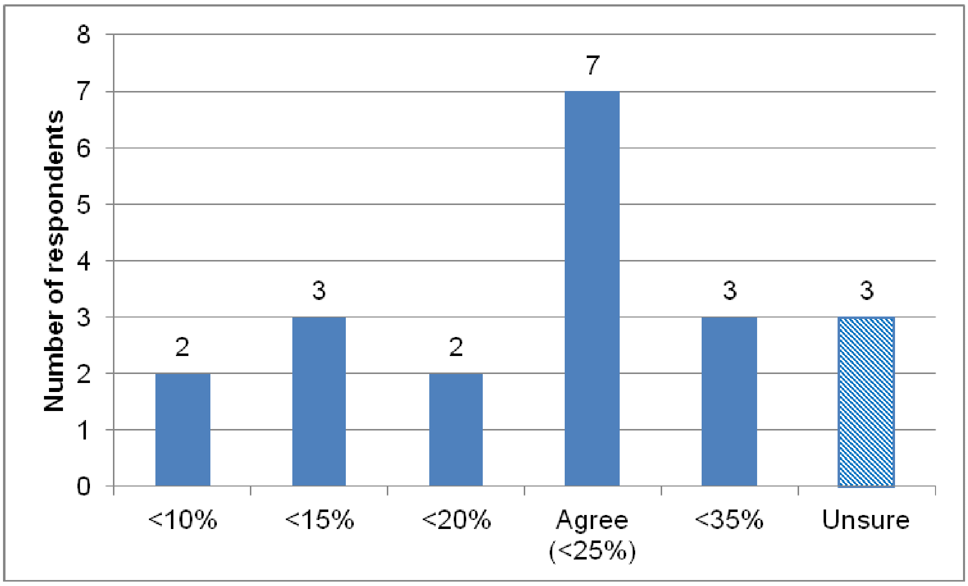
Thirteen of the respondents agreed with the stated slope range, two indicated that a lesser slope class of less than 15% is more preferable. Three indicated that the slope limit should be higher two of them chose the less than 25% class and one the less than 30% option. The other two indicated that they were unsure.

The survey results clearly indicated that the slope limit of less than 20% as indicated by the GBHH is the correct limit.



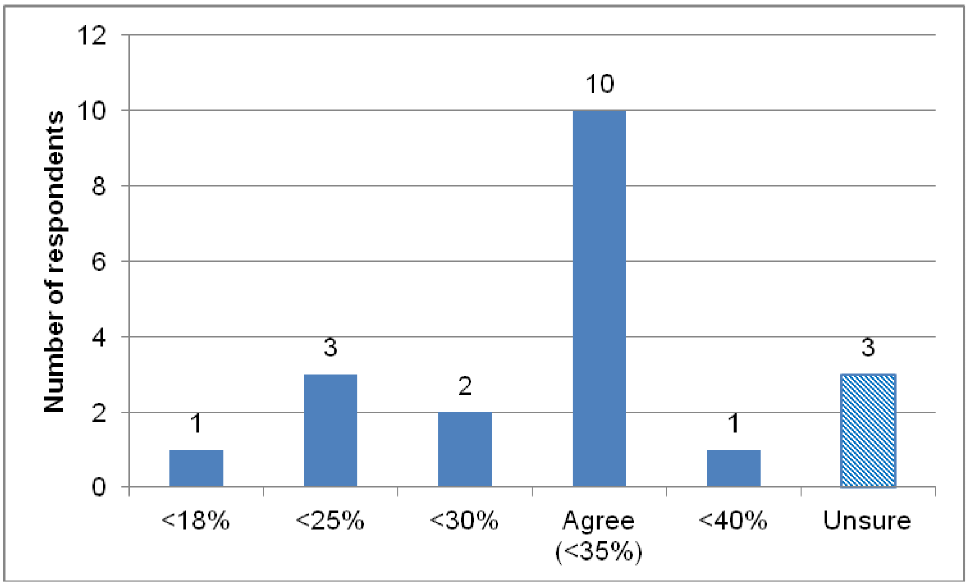
Question 25: Agricultural tractor skidding can be used on slopes of less than 25% UPHILL. Seven of the experts agreed and seven of those whom disagreed indicated that the actual capability is lower than stated. Of the seven two chose less than 10%, three chose less than 15% and the remaining two less than 20%. Three felt that agricultural tractor skidders are capable of handling slopes of less than 35%, three were unsure.

The survey confirmed that the current limit should remain unchanged.



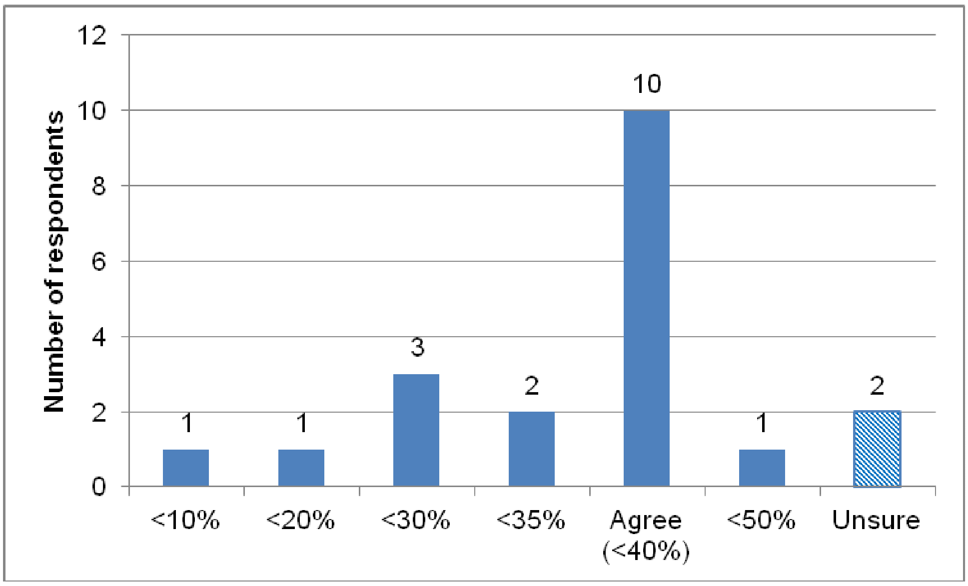
Question 26: Agricultural tractor skidding can be used on slopes of less than 35% DOWNHILL. Ten respondents agreed and seven chose options lower than the stated less than 35% slope class. One believed the slope limit should be less than 18%, three less than 25% and two less than 30%. One chose the less than 40% option and the remaining three were unsure.

The survey results clearly indicated that most of the respondents agreed with the current slope limit and that is should remain unchanged.



Question 27: Cable skidding can be done on slopes of less than 40% UPHILL.
Ten respondents agreed, only one participant felt that a greater slope class is possible choosing the less than 50% slope category. Seven others chose lesser slope categories; one chose the less than 10% slope, one less than 20%, three less than 30% and two settled on the less than 35% slope class. The other two respondents were unsure.

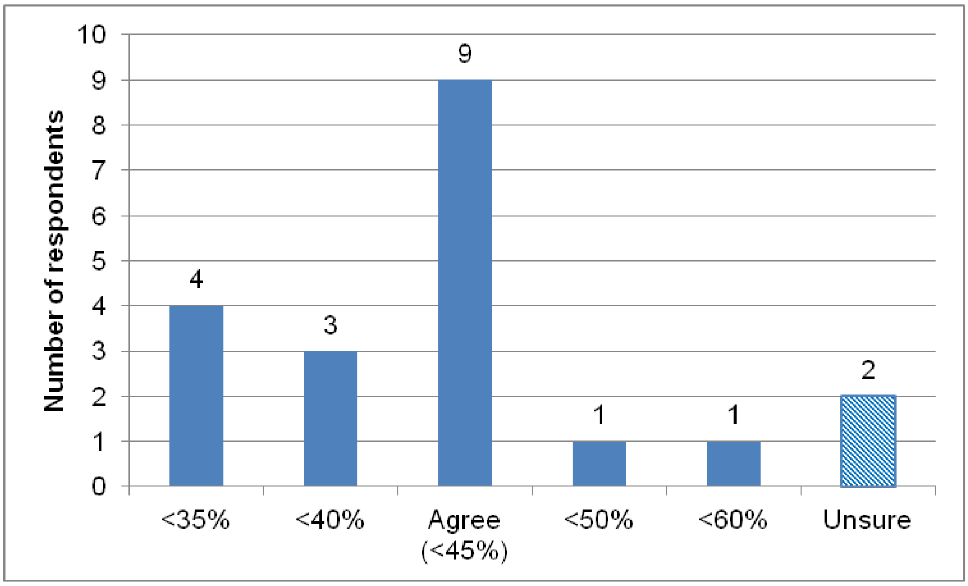
The survey results indicated that the respondents mostly agreed with the current uphill limit of less than 40%.



Question 28: Cable skidding can be done on slopes of less than 45% DOWNHILL.

Nine of the twenty respondent agreed, four indicated that cable skidding should only be done on slopes of less than 35%, three less than 40% and one preferred the less than 50% slope class. One person indicated that slopes of up to 60% can be handled when skidding downhill, while the remaining two were unsure.

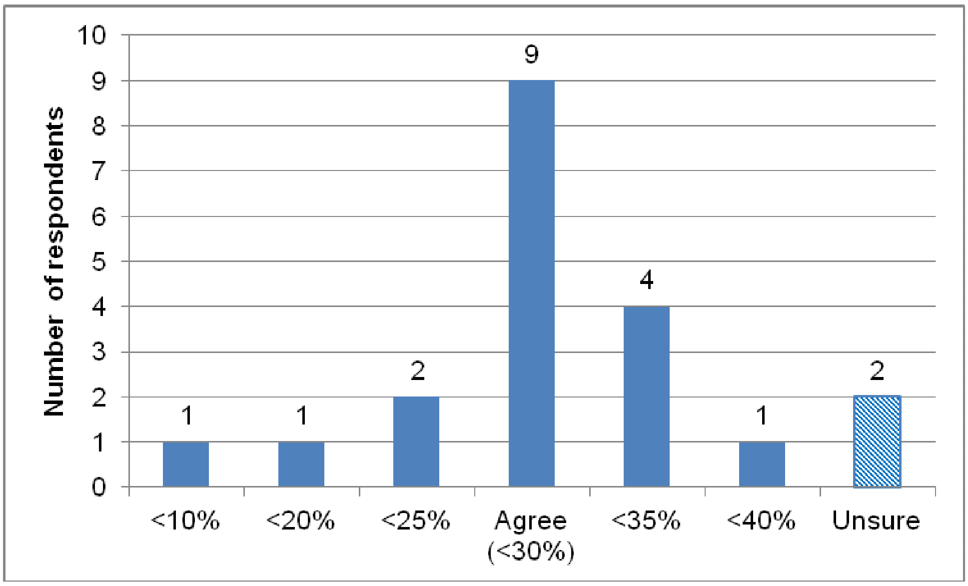
The survey results indicated that the slope limit should remain unchanged.



Question 29: Grapple skidding (4x4) can be done on slopes of less than 30% UPHILL.

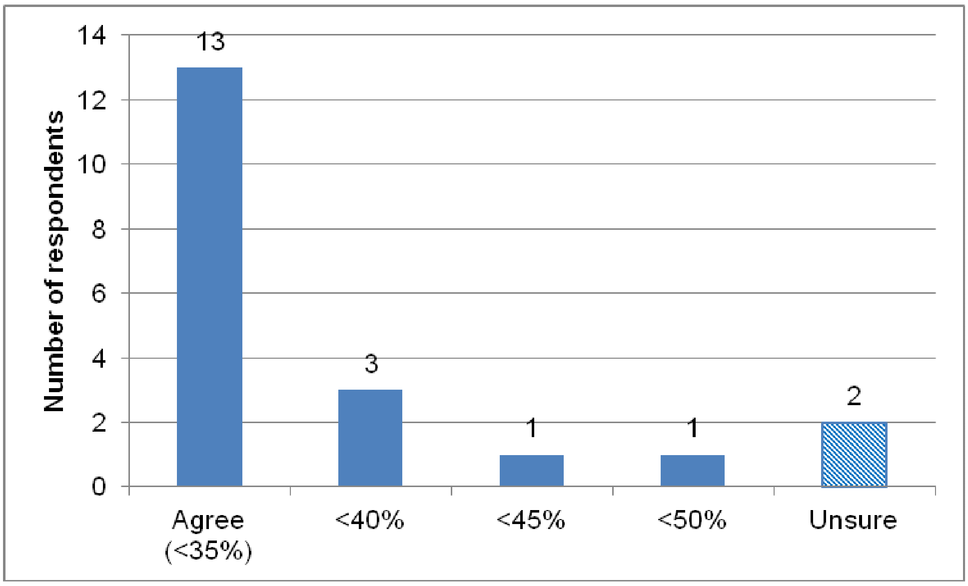
Nine persons agreed with the statement, one stated that the slope should be limited to less than 10%, one chose less than 20% and two less than 25%. Four of the respondents were of the opinion that the slope could be raised to a class of less than 35%, one more person indicated to less than 40%. Two of the respondents were unsure.

The survey results confirmed the current slope limit set by the GBHH.



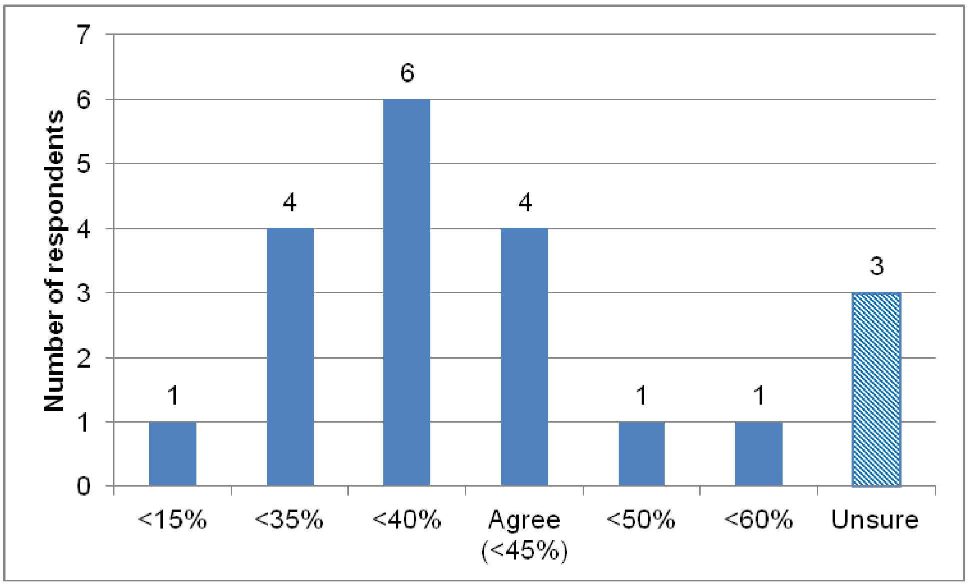
Question 30: DOWNHILL Grapple skidding (4x4) can be done on slopes of less than 35%. Thirteen of the experts agreed that the Downhill grapple skidding should be limited to slopes less than 35%. No one chose slopes with a smaller gradient, but three chose the less than 40% option. The less than 45% and 50% classes also had one suggestion each. The other two respondents were unsure of the downhill slope handling ability of 4x4 grapple skidders.

A clear majority of the respondents agreed with the current slope limit of less than 35% downhill.



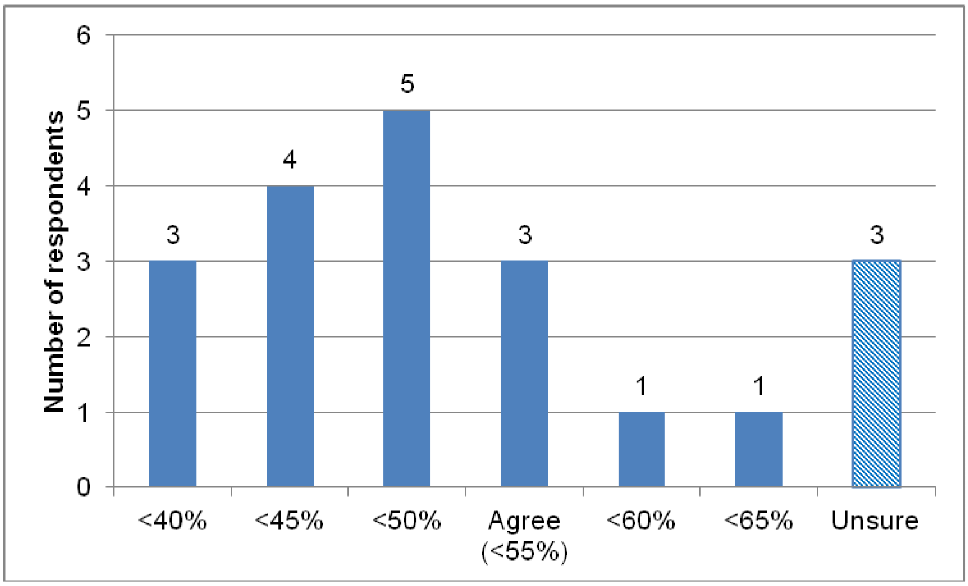
Question 31: UPHILL 6x6 Grapple skidding can be safely done on slopes of less than 45%.
Only four of the respondents agreed with the uphill slope handling capability of less than 45% allocated to 6x6 grapple skidders. The majority (11) felt that the slope should be lower. Six of the 11 opted for the less than 40% slope value, one selected less than 15% and the other four felt that the slope limit should be less than 35%. Two indicated that the slope could be higher one opting for less than 50% and the other less than 60%. Three were unsure.

Based on the results of the survey it is suggested that the current slope limit be lowered to slopes of less than 40%.



Question 32: DOWNHILL 6x6 Grapple skidding can be done on slopes of less than 55%.
Three respondents agreed and 12 opted for slope options with lesser gradients. Five of the 12 chose the less than 50% option, four less than 45% and three less than 40%. The two respondents that indicated a greater slope limit chose the less than 60, and 65% options respectively. Three were unsure.

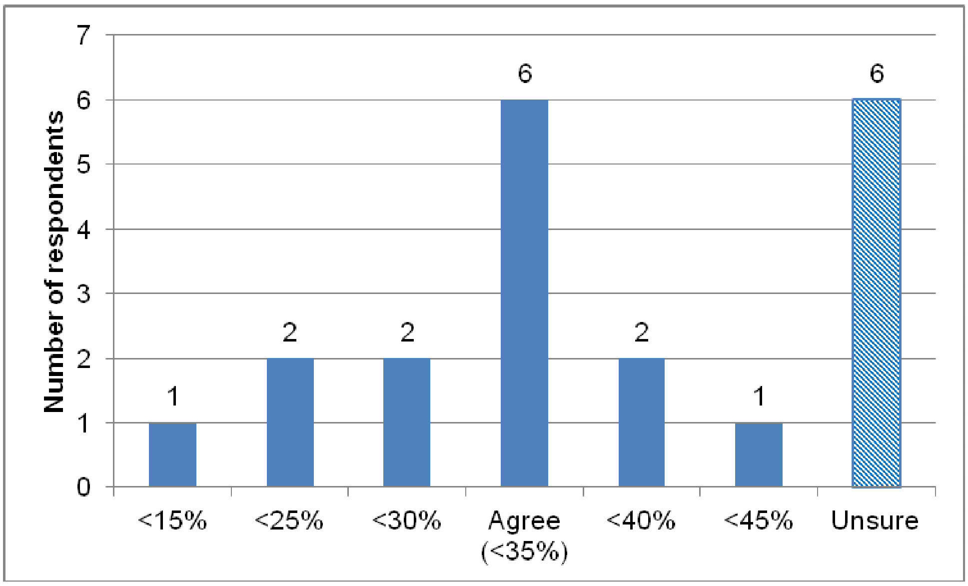
The survey indicated that the current slope limit as suggested by the GBHH should be lowered to slopes of less than 50%.



Question 33: Clambunk skidding is limited to slopes of 35% when extracting UPHILL.

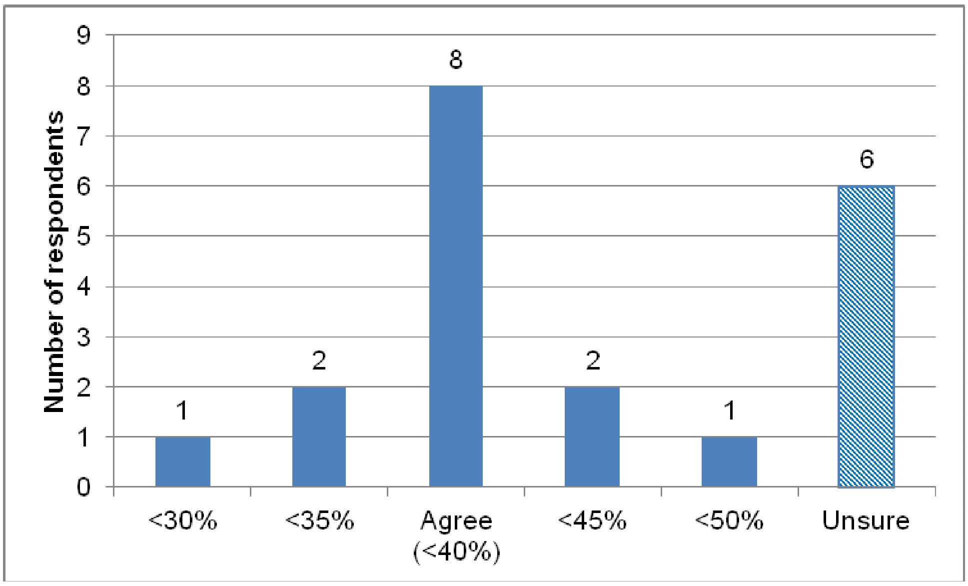
Six persons agreed with the statement and five where of the opinion that the slope limit should be lower. Of these five one indicated that the slope should be less than 15%, two less than 25% and the other two selected less than 30%. Three person selected slope classes greater than the stated 35% slope, with two opting for less than 40% and one less than 45%. Six of the respondents were unsure.

The survey results indicated that the current slope limit is correct and should remain unchanged.



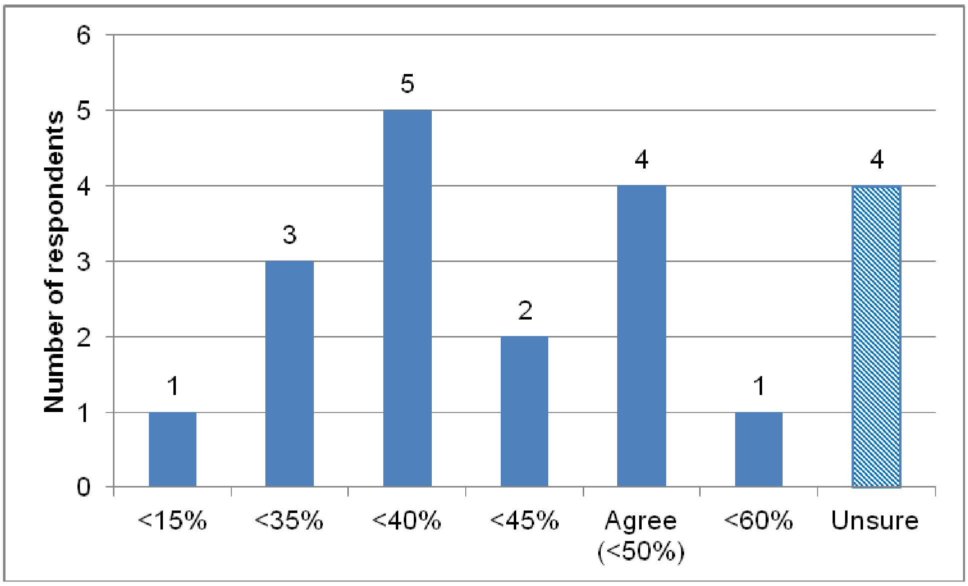
Question 34: Clambunk skidders can work on slopes of less than 40% DOWNHILL.
Eight persons agreed with this statement. One respondent felt that the ideal slope class is less than 30%, two less than 35%, two less than 45% and one chose less than 50%. The remaining six were unsure.

The majority of the respondents indicated that they agreed with the current slope limit.



Question 35: Tracked skidders are capable of extracting on slopes less than 50% UPHILL.
Four of the respondent agreed with the statement, 11 indicated that the slope should be smaller. Out of the 11, one chose a slope limit of less than 15%, three less than 35%, five less than 40% and two selected slopes of less than 45%. One person indicated that tracked skidders are capable of working on slopes of less than 60% uphill and the remaining four were unsure.

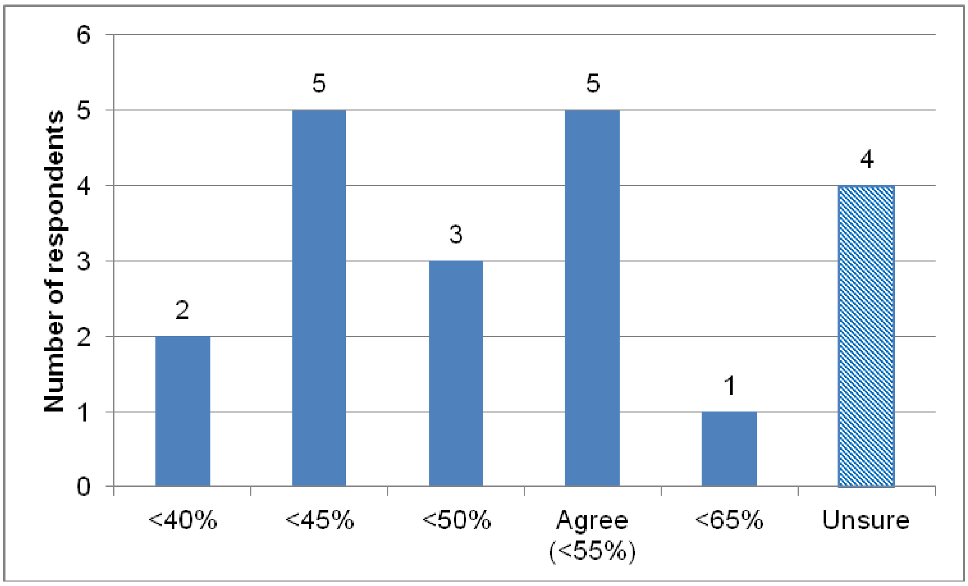
There was a strong indication from the survey results that the current slope limit should be decreased. It is therefore suggested that the slope limit be decreased to slopes of less than 45%. It could be argued that the slope should be reduced to slopes of less than 40% however in the end a limit of 45% was chosen as the appropriate slope limit.



Question 36: Tracked skidders can operate on slopes less than 55% DOWNHILL.

Five persons agreed and four were unsure of the downhill capability of tracked skidders. Two respondents believed that downhill operations should be limited to slopes of 40% or less, five chose less than 45% and three indicated that the ideal slope should be 50% or less. One participant chose a slope of less than 65%.

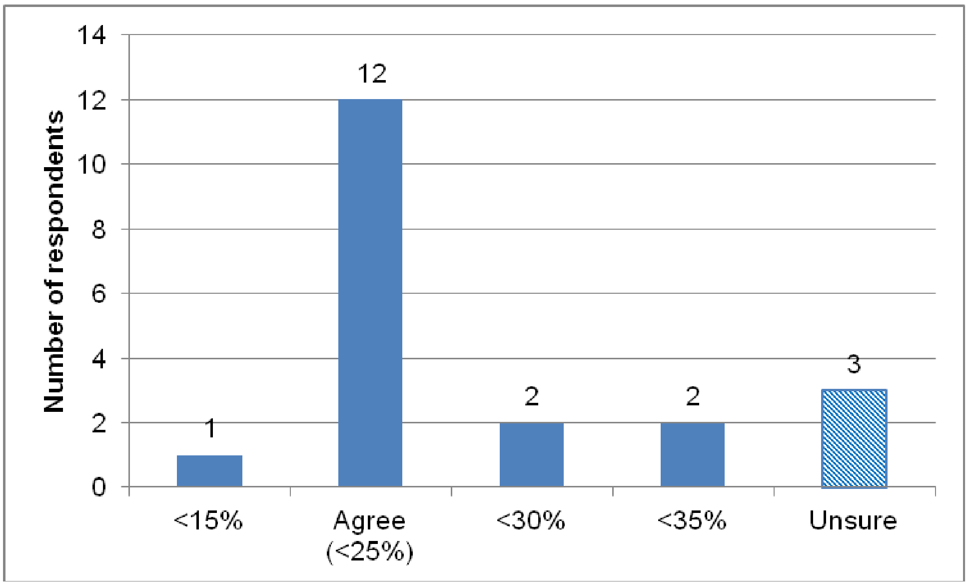
It might be argued that the slope limit should be kept at less than 55% but it was decided that the limit should be lowered to slopes of less than 50%. The decision was based on the fact that the majority of the respondents were of the opinion that the current slope limit is too high.



Question 37: 4x4 Forwarders can be utilised on slopes of less than 25% when extracting UPHILL.

Twelve respondents agreed with the statement. Four respondents felt that the 4x4 forwarders are capable of greater slope handling than stated. Two of them indicated slopes of less than 30% and two less than 35%. One person chose a slope class of 15% or less. The remaining three were unsure.

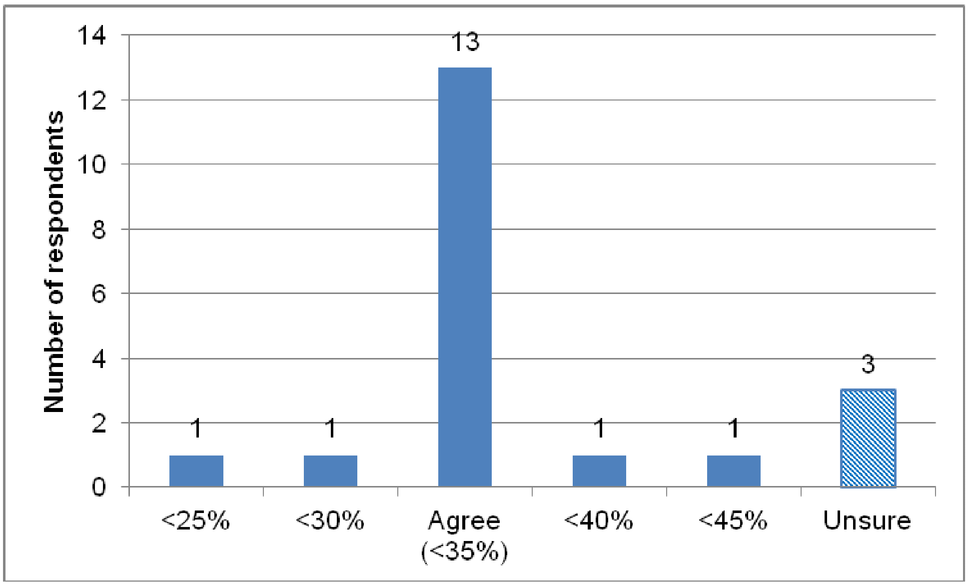
The respondents clearly indicated that the current slope limit is correct and should remain unaltered.



Question 38: 4x4 Forwarders are capable of DOWNHILL extraction on slopes of less than 35%.

Thirteen of the 20 respondents in the survey agreed with the stated slope handling ability. Three were unsure and the less than 25, 30, 40 and 45% classes each had one person opting for them respectively.

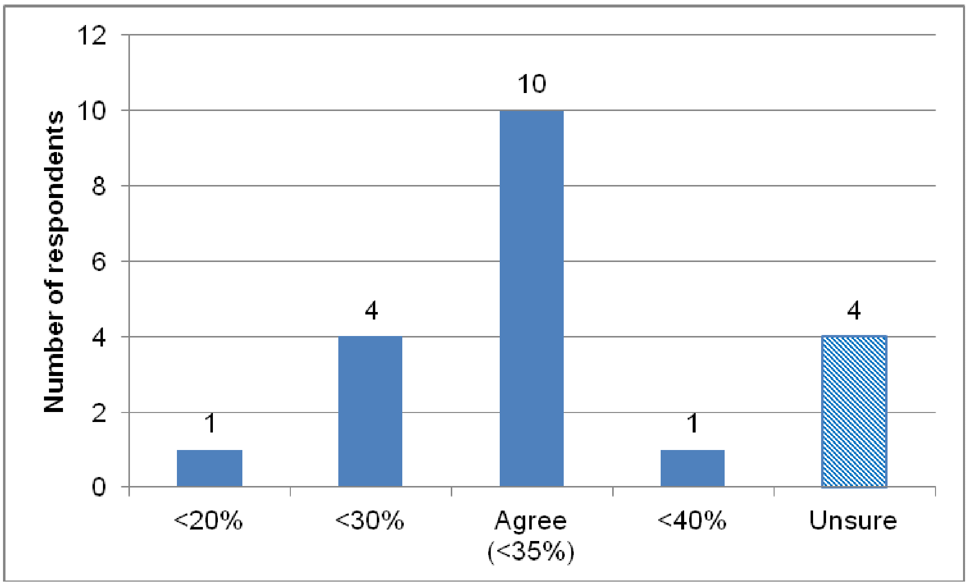
The survey results clearly indicate that the slope limit should remain unchanged.



Question 39: 6x6 Forwarders have a slope limit of less than 35% when working UPHILL.

Ten respondents agreed with the less than 35% uphill slope limit for 6x6 forwarders. One limited the slope to less than 20%, four to less than 30% and one increased the limit to less than 40%. There were four of the respondents that were unsure.

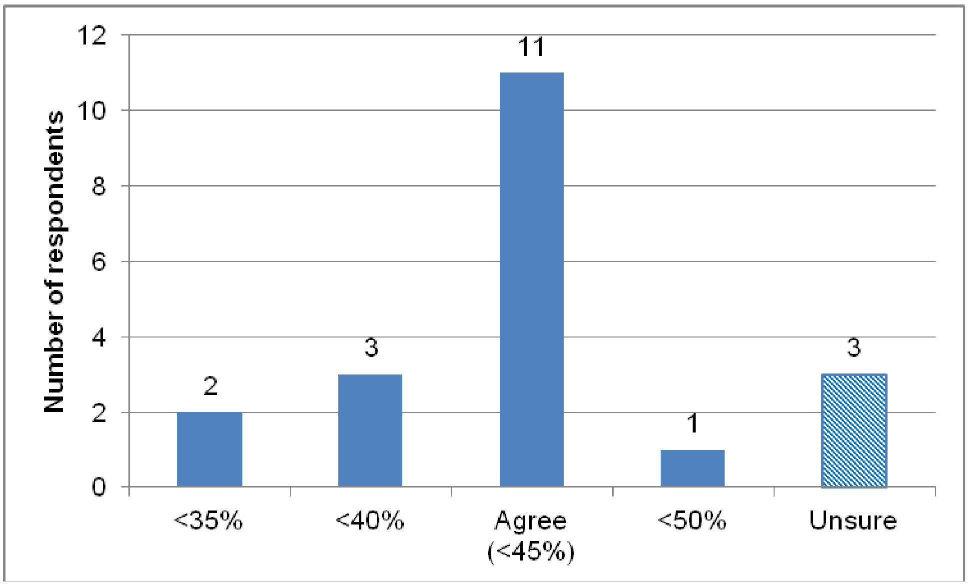
It is suggested that the current slope should not be changed since it was confirmed as correct by the majority of the respondents participating in the survey.



Question 40: 6x6 Forwarders work on slopes less than 45% DOWNHILL.

Eleven respondents agreed, three were unsure of 6x6 forwarder capabilities in downhill operations. One raised the limit to slopes with gradients of less than 50%. Two respondents chose the less than 35% option and three preferred the slopes to be less than 40%.

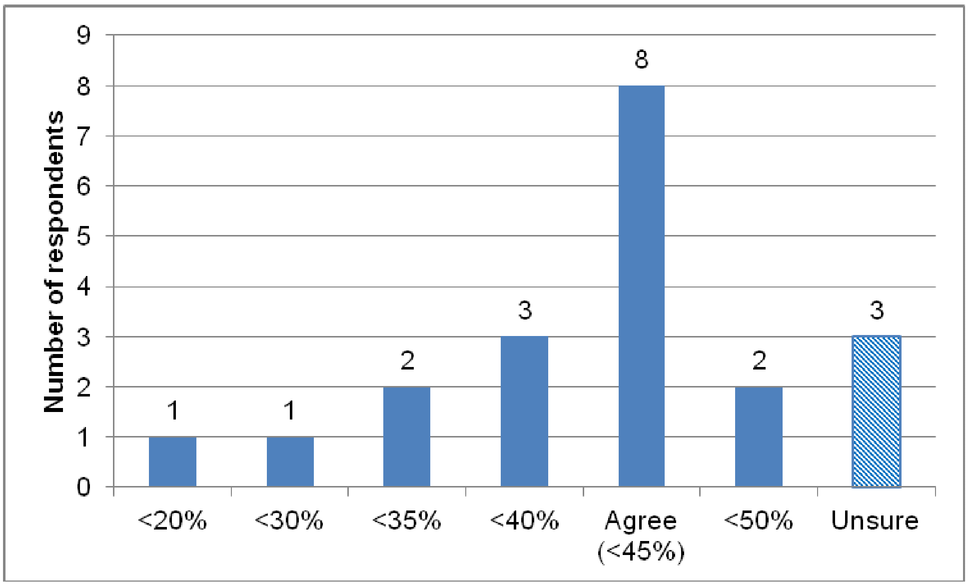
The survey confirmed the current slope limit as suggested by the GBHH.



Question 41: 8x8 forwarders are capable of handling slopes of less than 45% UPHILL.

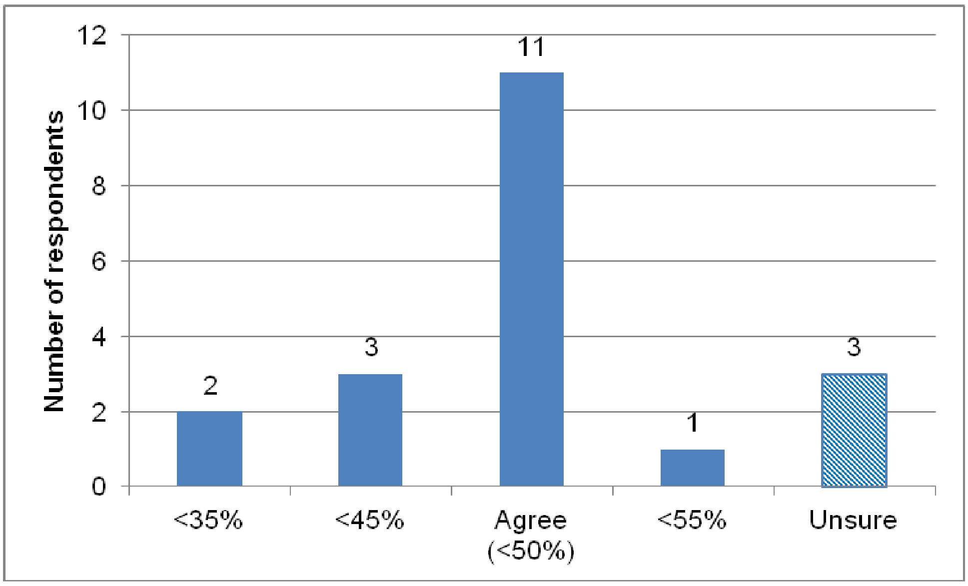
Eight respondents agreed with the stated slope limitation. One respondent felt that it should be less than 30%, two less than 35%, three less than 40% and two were of the opinion that the limit should be raised to less than 50%. One respondent indicated that the slope should not exceed 20% and the remaining three were unsure.

The survey results confirmed the current slope limit.



Question 42: 8x8 forwarders are capable of handling slopes of less than 50% DOWNHILL.
Eleven of the 20 submitted answers confirmed the statement. Five others indicated that the slope limit should be lower; with two respondents selecting the less than 35% option and three less than 45%. One respondent raised the slope to 55% or less and three others were unsure.

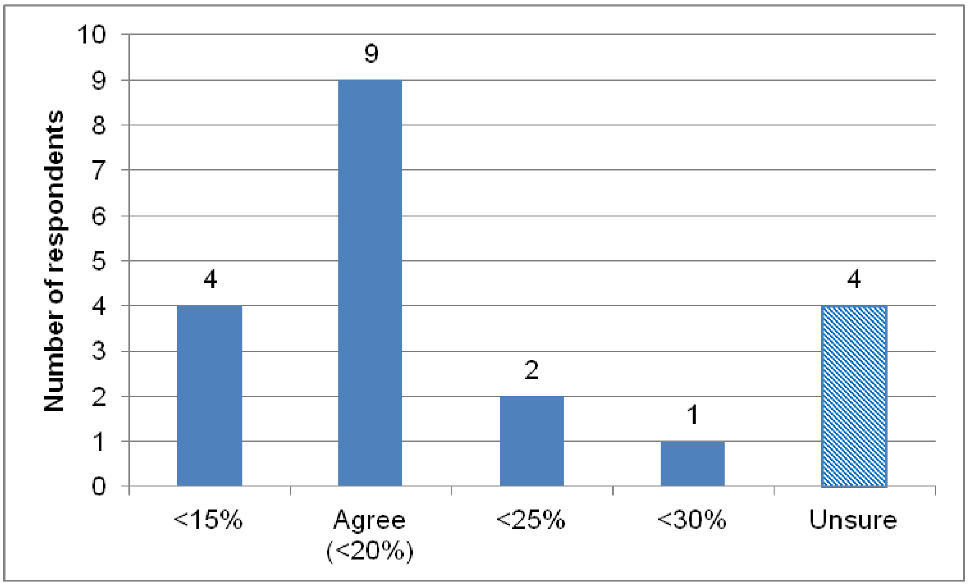
A clear majority confirmed the current slope limit.



Question 43: Articulated dump trucks have the ability to work on slopes of less than 20% UPHILL.

Nine persons agreed and four felt that slopes of less than 15% are more suitable. Two indicated that ADT's are capable of slopes less than 25% and one less than 30% when operating uphill. Four of the 20 respondents were unsure.

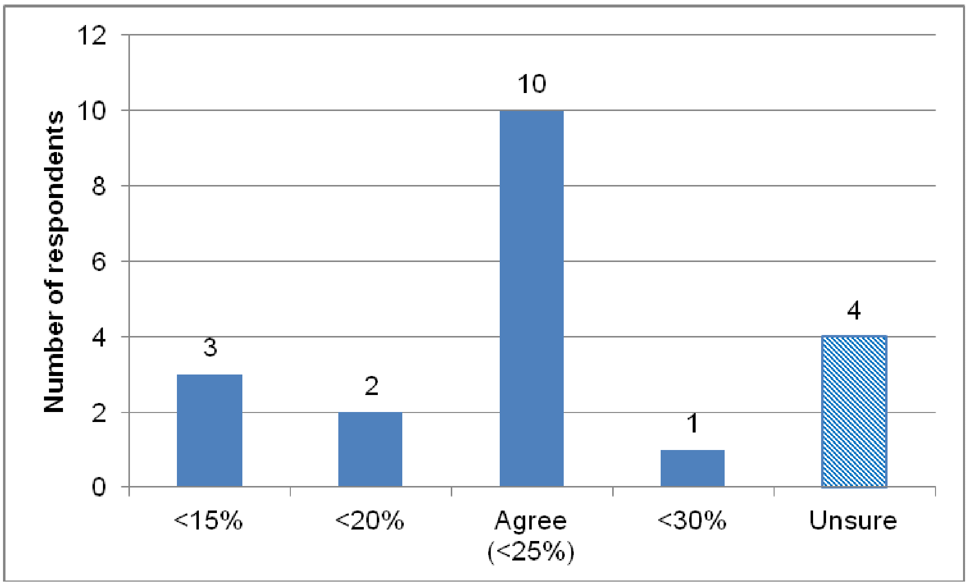
The current slope limit indicated in the GBHH was confirmed by the survey results.



Question 44: Articulated dump trucks have the ability to work on slopes of less than 25% DOWNHILL.

Halve of the 20 respondents agreed, three expressed the opinion that ADT's are better suited to slopes of less than 15% downhill, two less than 20% and one 30% or less. Four of the respondents were unsure.

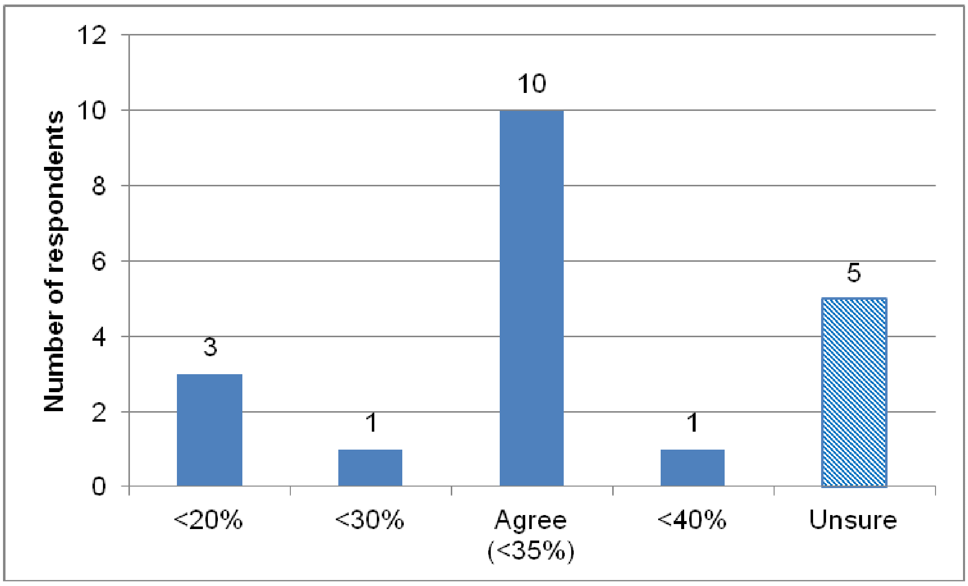
Most of the survey respondents agreed with that the current slope limit should remain unchanged.



Question 45: Non-levelling shovel loggers can work on slopes less than 35% UPHILL.

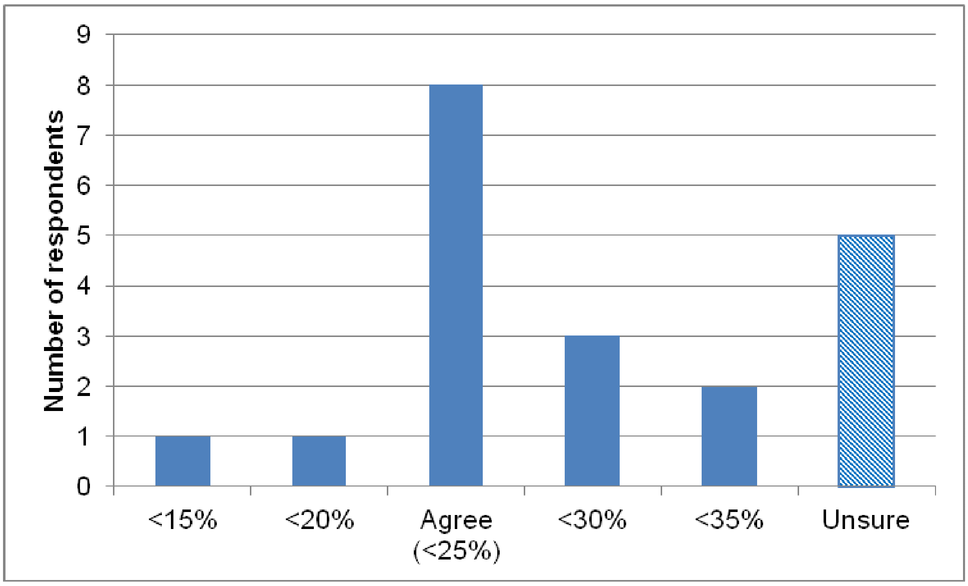
Ten respondents agreed, five were unsure, three chose the less than 20% slope option, one less than 30% and one slopes less than 40%.

The survey results confirmed the current slope limit set by the GBHH.



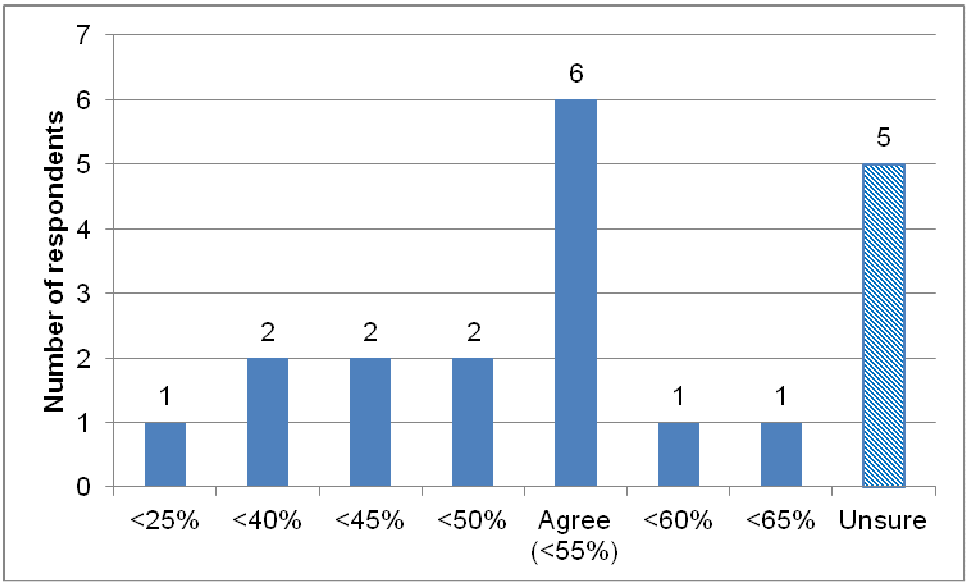
Question 46: Non-levelling shovel loggers can work on slopes less than 25% DOWNHILL.
Eight persons agreed that non-levelling shovel loggers should not work on slopes exceeding 25% when working downhill. One person selected the less than 15% slope option, one less than 20%, while three increased the slope to less than 30% and two less than 35%. Five of the persons submitting answers were unsure.

The survey results strongly supported the current slope limit.



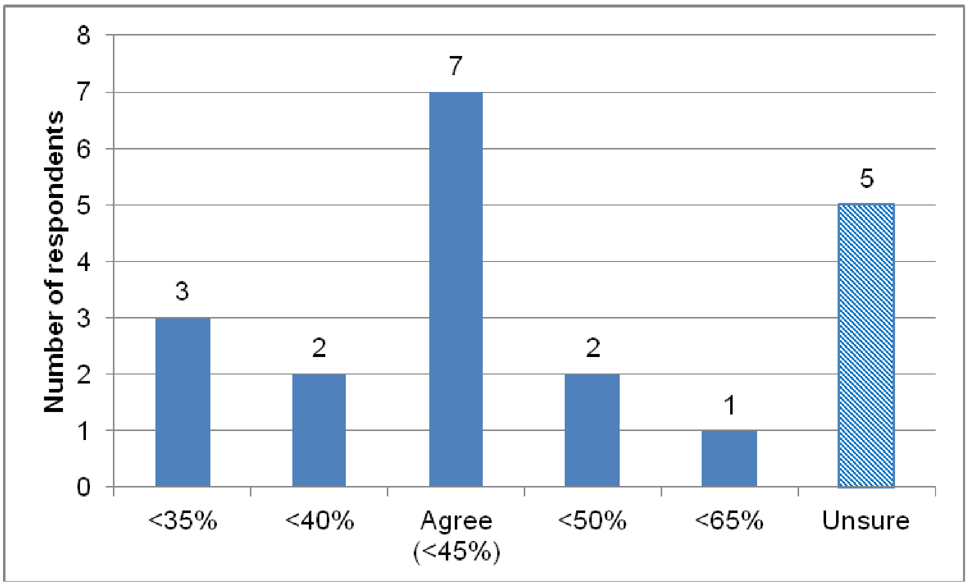
Question 47: Levelling shovel loggers can work on slopes of less than 55% UPHILL.
Six of the experts agreed with the current slope limit, five were unsure and two individuals indicated that levelling shovel loggers are capable of operating on slopes of less than 60 and 65% respectively on uphill operations. One individual lowered the slope limit to less than 25%. The less than 40, 45, and 50% slope classes attracted two votes each.

Although seven respondents indicated lesser slopes the survey results suggests that the current slope limit is correct and should therefore remain unchanged.



Question 48: Levelling shovel loggers can work on slopes less than 45% DOWNHILL.
Seven respondents agreed with this statement, five opted for lesser slope limits and three raised the current limit. Of those who recommended lesser slopes; three chose slopes of less than 35% and two less than 40%. Two respondents selected the less than 50% slope class and one the less than 65% slope class. Five of them were unsure.

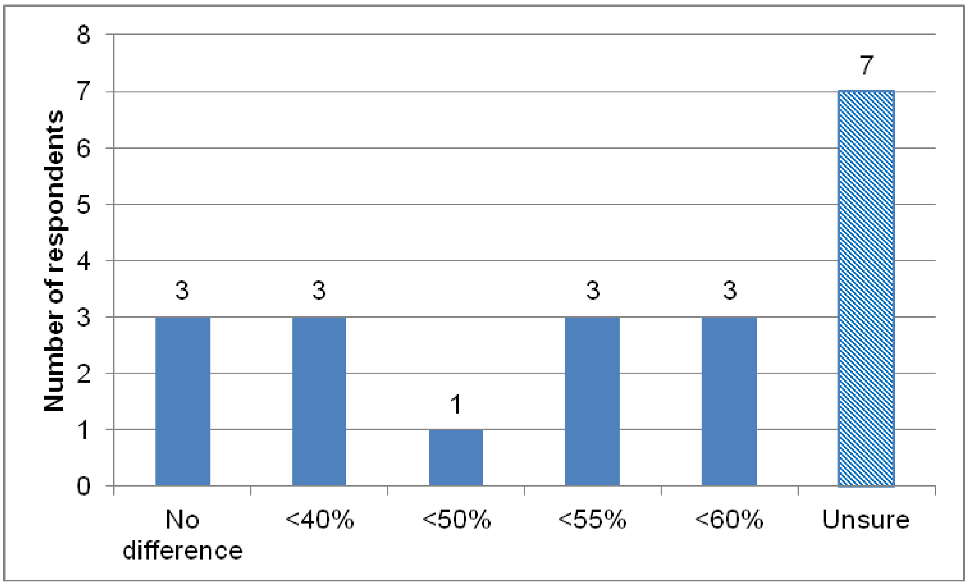
The survey results confirmed the current slope limit as indicated by the GBHH.



Question 49: Fitting a winch or cable anchoring device to any generic machine will increase its slope handling ability to:

Seven of the respondents were unsure and three were of the opinion that there will be no difference from the standard machine capability. Three persons indicated that it increases the machines slope handling capability to less than 40%, while one chose less than 50%, three less than 55% and the remaining three less than 60%.

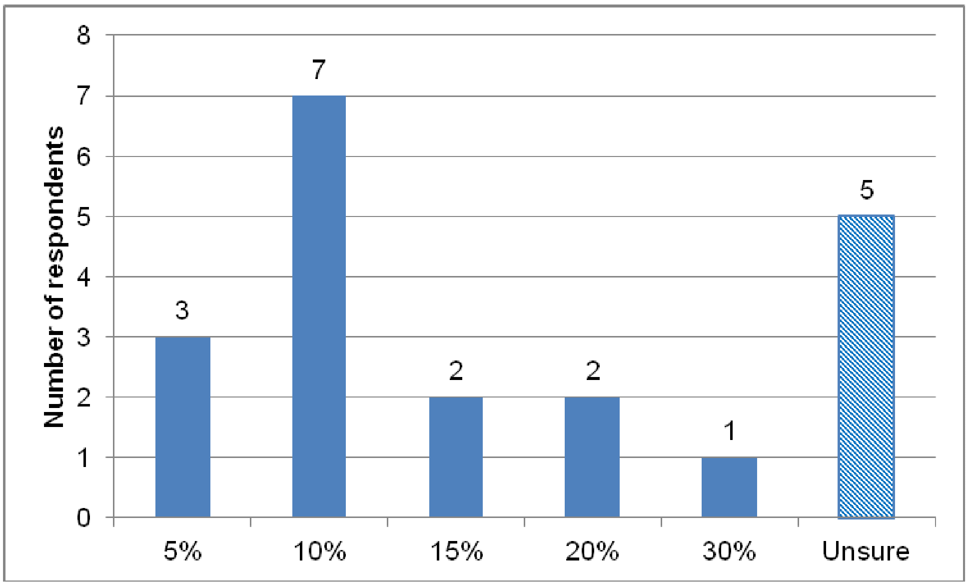
The survey results indicated that fitting a winch or cable anchoring device to a machine operating on steep slopes, increases its slope handling capability to slopes of less than 50%.



Question 50: On average the use of bandtracks and wheel chains will ADD …..% to the slope handling capability of wheeled machines:

Five of the 20 respondents were unsure of the effect of these traction aids on wheeled machines. Three where of the opinion that it adds 5% to the slope handling capability, seven chose 10%, two 15%, two 20% and one believed that it could increase the slope limit by 30%.

The survey results indicated that the use of bandtracks and wheel chains generally adds up to 10% to the slope handling ability of wheeled machines.



Number of respondents
0
1
2
3
4
5
6
7
8
3
7
2
2
1
5
5%
10%
15%
20%
30%
Unsure