Machinery and Equipment in Harvesting

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Abstract

Forest harvesting is one of the most important and cost-intensive operations in forest management. The different process steps of harvesting operations are felling, delimbing, debarking, bucking, off-road transport of the wood, and loading. Specifically in tropical countries, the resources, equipment, and machines that can be used are manifold and can be composed in complex systems. The climate conditions, soil properties, and human resources have to be considered in the choice of the equipment or machine used in each single process step of harvesting operations. Many tropical countries are even today facing a lack of financial resources for using their forests in a competitive and sustainable way. Harvesting in native tropical forests faces the following problems: trees of big dimension, low volume per ha, diversified assortments in species, length and diameter, sensitive soils where no mechanical or chemical corrections are possible, many environmental restrictions, and difficult access. The financial situation, technical know-how, and machine availability have impact on the volume and assortments that can be produced in harvesting operations. Logging companies with better financial background are able to mechanize many harvesting processes and increase productivity and working safety this way. They are able to create a net of forest roads to facilitate forest operations and to use adequate machines and equipment that allow also to extract big and heavy logs of high value. Smallholders or communities on the other hand are still relying on simple tools and equipment, animal-assisted skidding, and manual or motor-manual work in wood harvesting operations. In general they face strict limitations concerning the size of the trees that can be felled and the logs that can be skidded. In tropical forest plantations, the conditions found are quite different. In general only one or two species are planted, the stands are homogeneous in height and diameter, dimensions of the trees are smaller, the forest is planned and provides good access, and high volumes per hectare are harvested in clear-cut systems. All these utilization conditions are favorable to a higher degree of mechanization, since the economic returns are higher and faster in short rotation plantations. Smaller properties as well as industrial plantation owner work with adapted agricultural tractors or specific forestry machines, which allow high productivity with acceptable environmental impact. The present chapter gives an overview on the existing methods, equipment, and machines that are available for harvesting operations in tropical countries. It focuses on the description of the use and suitability of the equipment for the different process steps of harvesting operations. The permanent technical innovation in the sector makes it difficult to present always the technical specification of the newest existing machines on the markets. Detailed information about chainsaws, harvester, forwarder, skidder, feller buncher, loader, and additional tools available for harvesting operations should always be evaluated in the respective country for the specific working conditions.

Keywords

Forest Machinery • Harvesting Equipment • Wood Harvesting • Logging • Felling • Wood Hauling • Loading • Mechanized harvesting • Wood Processing

Introduction

Wood harvesting consists of a complex chain of processes linked to each other. Depending on the forest type and structure, wood utilization, legal and environmental restrictions, availability of technical equipment, and financial resources, the combination of machinery and equipment may vary significantly (Machado 2014). In tropical regions, the forests may be used by single persons, local communities, or medium- or big-sized enterprises, each group with specific needs and interests in the raw material provided by the ecosystem. It must be distinguished between native and planted forests, both requiring different approaches in wood harvesting, planning, and execution (Rummer 2011).

The harvesting equipment needed for feeding a small-scale charcoal production of a local community living in a native forest may be different from a pulp and paper company managing 100,000 ha of eucalypt plantation. The present chapter is focused on the presentation of the existing equipment and machinery, from well-proved manual equipment until the most modern machinery used in fully mechanized systems. Which machine or equipment combination is the most appropriated is depending on the above-cited criteria (Salmeron 1980).

Forest harvesting refers to cutting and delivering trees in the form of merchantable assortments (Rigolo and Baptista 2011). The whole process covers several steps which can be performed in a variety of ways combining different methodologies.

A rough classification of harvesting operations can be done as follows:

- Manual and animal assisted
- Motor manual
- Partially mechanized
- Fully mechanized

Within the classification described above, harvesting has to be separated into the following steps:

- Felling
- Delimbing
- Debarking
- Bucking
- Hauling
- Piling and loading

Besides the main operations felling and hauling, delimbing and bucking are of a major importance. **Delimbing** is the process of cutting the branches from the trees. In many wood utilization, the so-called crown slash remains in the forest and provides valuable organic matter in a decomposition process. Especially in tropical forests with poor soils, nutrient cycling plays an important role in the sustainability of soil fertility. Delimbing also facilitates the **bucking** of the stems into commercial length. In general assortments are formed that are directly linked to the further use of the wood. The cut-to-length process is important for all kind of transport processes, being off and on the road. It significantly influences productivity of the whole harvesting process and the subsequent utilizations of the wood. Finally, some wood utilization requires the removal of the bark (**debarking**), already in the forest or at the mill yard.

Where the bark is removed is not only a technical question but also an environmental one. Like the crown slash, bark plays an important role at nutrient cycling of the ecosystems. On the other hand, the removal of bark in many cases is difficult and time consuming and therefore expensive, if it is done in a nonindustrial process. Bark often is used as a source for bioenergy in wood industry or for gardening purposes, so that a central debarking makes sense. Finally, **hauling** has to be mentioned as the process step of harvesting, which is most influenced by the infrastructural framework of a harvesting operation (Hubbard et al. 1998).

Forest roads, waterways, slope of the terrain, assortments, and vegetation have influences on the overall costs for this operation (Böhm 2008). Mainly the average hauling distance determines productivity and final costs of the overall harvesting operation. Therefore special attention has to be paid to this process. All processes described above can be done in a manual, semi-mechanized, or mechanized way during the harvesting operations, requiring special equipment, according to the necessities of the user (Baumann 2008).

Felling, Delimbing, Debarking, and Bucking

The first step of the harvesting operation consists in the felling of the trees and the preparing of the assortments that have to be transported to the forest road. For some wood utilization, it is useful and economic to do all the processing in the forest; in other cases, it might be recommendable to concentrate the manipulation of the wood in central log yards. However, the tools used in such operations may vary from completely manual work up to fully mechanized systems (Machado 2014). The most advanced technologies already work with robotics (Billingsley et al. 2007).

Manual Equipment for Felling, Delimbing, Debarking, and Bucking

Originally most of the steps of tree harvesting were done manually. Axes, one- or two-man-operated handsaws, machete, or other instruments with cutting knives were used for felling, delimbing, bucking, or debarking. Today hand tools are only used in some minor cases for cutting smaller trees for personal use or by indigenous communities. As soon as commercial aspects become of interest, hand tools do not show a competitive productivity to provide merchantable assortments for the markets.

Fig. 1 Manual felling operation with a two-man saw in Africa. Source: Leif Nutto

For **manual felling** in a tropical forest managed by smaller communities, mainly for personal needs, the use of hand tools is still common. For felling smaller trees, mainly machete or axes are used. Axes are also applied for felling bigger trees. In general a simple scaffold of wood is built to avoid the large buttresses found in larger tropical trees (Machado 2014). Then five to six persons climb up and start the felling of the tree with axes, often taking several days for that process. For bigger trees, also saws are used, mainly two-man saws that allow cutting of bigger trees in a more economic way (Fig. 1).

Manual delimbing or cutting off the branches is done with axes too. In most cases only the straight stem is used, leaving all the crown slash in the forest. For these operations the same cutting knives (axes, machete, slasher) are used. In Europe and North America, special shaped axes and slasher for delimbing were developed in the past centuries, but with the upcoming of chainsaws, the construction and commercialization of the tools were stopped. Today the main difference found in axes is if the blade is for cutting or splitting of the wood.

Manual debarking in the forest today is done for several reasons, as there are:

- No use of the bark in the processing mill, like it is often the case in pulp and paper industry (except for bioenergy)
- Importance of nutrient cycling (especially phosphor) at specific sites
- Reduction of transport weight of the wood
- Phytosanitary reasons (mainly fighting of bark beetle)

In most wood utilizations, the removal of bark can be done more economically in an industrial process with drum, chain, or knife debarkers. In former times, innumerous different shaped hand tools were developed for manual debarking, which rarely are applied in tropical forests. In general, it is extremely difficult to remove the thick and short-fibered bark of tropical broad-leaved trees coming from these ecosystems (Fig. 2).

Fig. 2 Manual debarking with ax and different-shaped hand tools for manual debarking. Source: Leif Nutto

Furthermore debarking is not necessary for the main utilizations of the wood coming from native forests. In saw and veneer mills, the separation of the bark from the wood can be done in a more economical way, and the energetic use of wood as firewood or for charcoal production does not require debarking. Wood from industrial plantations on the other hand today is debarked with processing heads of machines or with industrial debarkers at the mill. Manual debarking therefore is of minor importance.

As already mentioned above, the main objective of a harvesting operation is to provide merchantable assortments to the wood industry. Manual *bucking* or *cut to length* plays an important role in the harvesting process. Crosscuts can be done with axes, machetes, slasher, or saws. Today it is only applied in tropical countries for local communities and smallholders to supply themselves with fuelwood for charcoal production or firewood. In general wood of smaller diameter like crown slash or smaller trees is used for this purpose. In former times, also bigger trees were crosscut with axes or saws, being the ax the more robust tool and easier to sharp, a big advantage for dealing with the extremely hard wood, often rich in silica and therefore of high abrasion for the tools. The assortments bucked manually today are about the length of 1–2 m (Fig. 3).

Fig. 3 Piling manually bucked assortments in a pine plantation. Source: Tigercat

Fig. 4 Motor-manual felling with chainsaw in the Amazon region. Source: Grammel. Source: Grammel

Equipment for Motor-Manual Felling, Delimbing, Debarking, and Bucking

Already before 1900, the first motor saw was used in European forestry, and since then, **motor-manual felling** has replaced manual tools. Disregarding some minor wood utilization of individual households or smaller indigenous communities, chainsaws today are found in any country of the world and are the minimum standard required for productive felling operations. In tropical countries, specifically in native forests, it became an indispensable tool for people living in forest regions. Chainsaws in the society today are associated with deforestation of tropical forests. As any tool invented by humans, not the tool itself but the irresponsible use is the reason for massive forest destruction. Motor saws improved productivity of felling operations in an exponential way (Fig. 4).

Motor-manual delimbing is the process of cutting branches of felled trees. While in deciduous trees and large conifers, this term is used, for smaller logs with a straight stem (often plantation-grown trees), also the term "snedding" is used. Motor-manual delimbing may be considered as the standard procedure for

Fig. 5 Manual and motor-manual delimbing and bucking in a eucalypt plantation. Source: Jorge Malinovski

Fig. 6 Motor-manual debarking of logs with a tool mounted on a chainsaw. Source: Jorge Malinovski

removing branches from all bigger trees felled in harvesting operations. Another type of motor-manual delimbing is the use of a chainsaw with extension. This type of motor-manual tool allows a highly ergonomic work with smaller trees felled, performing the operation in upright position and far away from the cutting part of the tool. It is used for cutting branches after motor-manual felling in forest plantations with steep terrain, where no mechanized operations are possible (Fig. 5).

As already stated, this procedure should be performed in a mechanized or industrial way wherever possible, because of its time-consuming and low productive nature. For **motor-manual debarking** exist some tools, mainly as additional head for chainsaws, that may assist debarking where necessary. They are practically cutter heads or rotating knives moved by the motor saw engine. The costs are between 500 and 700 US$ per unit; the productivity depends on tree species, diameter, and bark type (Fig. 6).

Motor-manual bucking is the cut-to-length process in a harvesting operation. To make a crosscut in trees of big dimensions, like they occur in tropical rainforests, should not be underestimated. There is a high risk that the chainsaw gets stuck during the operation if the stem is not laying perfectly plain on the underground or if it is under any kind of tension. Since heavy large trees can hardly be moved manually, it is important to train the chainsaw operators to perform the cut in the best way possible.

After measuring the distance from the last crosscut precisely to provide the correct length of the stem for further processing, the stem should be carefully checked for any tension caused by uneven underground. It is recommendable to cut the crown first, before doing the further crosscuts. In general the crown lifts the stem from the ground or causes other tensions in it. If necessary, the use of wedges is recommendable, which allows performing the final cut from underneath the stem or above, depending on the type of tension detected. The time needed for the delimbing, cutting off the crown, or bucking should be taken into account for the calculation of the daily productivity of the chainsaw operator.

Machines for Felling, Delimbing, and Debarking

In homogeneous and even aged forests with trees of smaller diameter and terrain where wheel- or track-based machines can operate, mechanized felling may be the best choice in terms of costs and productivity. Mechanized felling means the use of machines with special "felling heads" that allow the cutting of trees (Sant'anna 2008). The felling heads can be equipped with scissors, chainsaws, or saw disks.

There can be observed a strong trend toward mechanized felling all over the world (Malinovski et al. 2006). Firstly, the productivity is much higher, and secondly, safety aspects become more and more important. The main factors influencing the decision of using a mechanized system are:

- Tree diameter
- Stand density, structure, and homogeneity
- Slope of the terrain
- Availability of skilled machine operators
- Availability of appropriate felling systems

For improving efficiency of mechanized felling, the felling layout has to be planned carefully. Trees have to be felled in a direction that facilitates subsequent activities such as delimbing, debarking, crosscutting, or hauling operations (Forest and Rangelands 2011e). Typical tools for tree felling are the heads. The heads can be mounted on several track- or wheel-based machines with general utilization or designed for specific forestry activities (Freitas 2005) (Fig. 7).

Mechanized felling has several advantages compared to motor-manual tree cutting (Alves and Ferreira 1998). The most important and worth to mention are:

- High productivity
- Higher safety and comfort standards for the operator

		
Head with hydraulic chainsaw	*Head with hydraulic shears*	*Head with disc*

Fig. 7 Heads for fully mechanized felling operations. Source: Huldins / Tigercat

- Higher performance of subsequent activities, since a pre-concentration of the wood is possible
- Less losses of wood, since the felling cut can be made close to the soil level
- Possible to work at night (24 h) with spotlight equipment and without climate influence (air conditioned)
- More constant productivity, less turnover

On the other hand, there must also be mentioned the disadvantages:

- Limited maximum diameter of the trees to be felled: main reason for restriction in use in tropical native forests
- High investment costs
- Demand for highly qualified maintenance and spare part logistics
- Soil damages, like compaction and erosion
- Limited use in mountainous and rocky terrain
- Less demand for unskilled labor force, causing social impact
- Difficulties in finding skilled machine operators

The productivity of these machines under the above-described conditions, mainly found in forest plantations, is much higher than of a chainsaw operator (Nordfjel et al. 2010). Another important issue to consider is the reduced risk of injury for operators and the low ergonomic impact compared to a chainsaw operator.

Harvester

Harvester consists of a basic machine, a crane, and a processing head. The use of these machines in general is multifunctional and allows to perform several processing steps with one machine only. The first step is to grab the tree subject to felling (Bramucci and Seixas 2002). The cranes have a reaching distance

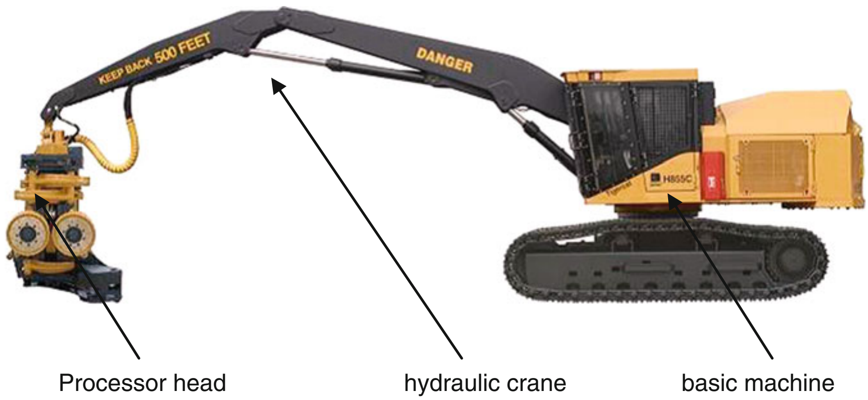


Fig. 8 Basic machine with tracks equipped with a harvester head for multiple processing. Source: Tigercat

between 7 and 12 m, depending on the size of the basic machine. Once grabbed the tree at its base with the processing head, the cutting process is activated. With the help of the head and the crane, the felling can be directed to any direction. After cutting some, heads also are able to debark, delimb, and crosscut the tree in the stem length of the assortments to be produced (Amablin 1991) (Fig. 8).

Even if the main objective of the harvester initially was felling the trees, today it is often used to process a full tree at the forest road or at landing zones. In such cases, the objective is only delimbing and bucking and in some cases also debarking, for producing different merchantable assortments of wood and biomass. In this case the machine unit works as a "processor" (Bramucci 2001).

The processing heads today are completely computerized and software driven. The operator only determines the operations to be performed, and the head operates automatically after the program is activated. The head consists of grabbing arms to hold the tree during the cutting process and to direct it to fall to the wanted side. The cut can be done by a saw, a cutting knife, or a disk, being the first option in the form of a hydraulic chainsaw, the most commonly applied option (Fig. 9).

The next processing step consists of delimbing and, if the head is equipped with such a unit, also of debarking (McEwan 2007). The feed rollers transport the stem through the processing head where special knives cut off the branches (and also take off the bark, if such a unit is integrated). During the feeding, a small unit is taking the distance the stem passed through the head and gives the signal to the cutting unit where to perform the crosscuts. Over the position of the grabbing arms, the head also is able to measure the stem diameter. The software can be adjusted in a way that crosscuts are made after length and/or minimum diameters required for the assortments.

Today harvesters became extremely fast in processing trees with high precision and pre-concentrate the assortments for further forwarding or skidding. The productivity of course depends on single tree volume, species, assortment, terrain and upon the performance of the operator (Linhares et al. 2012; Purfürst 2009). Another

Fig. 9 Wheel harvester (*top*) and track harvester (*bottom*). Source: Gustavo Castro

important factor for the productivity of the machine is the form of the silvicultural operation. In clear-cuts, the machines show a significantly higher productivity than in thinnings.

The machine fells the trees, prepares the assortments by bucking, pre-concentrates the stems for forwarding, and gathers the crown slash in the line of movement. This way, the forwarding is more efficient, and soil compaction is reduced by the crown material in the lines where the machines move (Fig. 10).

Besides the single tree processing heads, there are also multi-tree-processing heads available. Depending on the quality of the wood, such heads might be of much higher productivity than the single ones. The difference is in the grabbing unit, where the arms of the machines are able to handle more than one stem at a time, improving productivity of the machine between 20 and 35 % (Fig. 11). The machine cuts the trees, prepare the assortments by bucking, pre-concentrates the stems for forwarding and gather the crown slash in the line of movement. This way the forwarding is more efficient and soil compaction is reduced by the crown

Fig. 10 Three-wheeler as basic machine for felling operations. Source: Leif Nutto

Fig. 11 Big-sized multiprocessing harvester heads (*left*) and a small-sized head for multiprocessing (*right*). Source: John Deere

material in the lines where the machines move. Beside the single tree processing heads there are also multi-tree-processing heads available. Depending on the quality of the wood, such heads might be of much higher productivity than the single ones. The difference is in the grabbing unit, where the arms of the machines are able to handle more than one stem at a time, improving productivity of the machine between 20 and 35 %.

The main reasons for developing tree harvesting machines were:

- Reduced labor force necessary
- Improved working conditions and ergonomy (safety and comfort)
- Reduced production costs

Some of the advantages are:

- Better use of the material wood by improving recovery rate
- Less soil compaction than with conventional (agricultural) machines

- Less problems in felling and bucking trees
- Improved quality and homogeneity of the assortments

Some disadvantages are:

- High initial investment necessary
- Well-trained machine operators necessary
- Higher harvesting costs than cutting trees with a feller buncher system

Feller Buncher

One of the first felling machines used in practice was the feller buncher, a tool which could cut and pre-concentrate trees (Forest and Rangelands 2011c). Mainly applied in North America, the machine is gaining importance in forest plantations with the objective of full-tree utilization, specifically for energy wood production. Today the heads of the tools are designed for accumulated felling and equipped with shears or disks for cutting the tree in the form of directional felling. The heads with disks can be divided in tools with intermittent or continuous rotation.

Besides track-based machines, also wheel-based options are available at the market. For smaller-sized trees in thinning operations, even a three-wheeler version is available, showing extreme good handling on small spots (Fig. 12).

Fig. 12 Track-based (*top*) and a wheel-based feller buncher (*bottom*). Source: Gustavo Castro

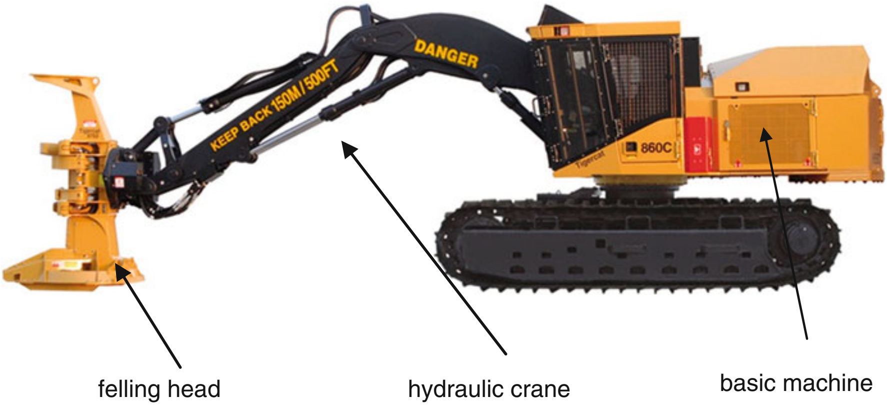


Fig. 13 Basic machine with tracks and a feller buncher head. Source: Tigercat

A feller buncher is a self-propelled machine with a cutting head that is capable of holding more than one tree at a time. The cutting head is used strictly for cutting, holding, and placing the stems on the ground, but does not have processing capabilities.

The existing mechanical configurations are either wheel- or track-propelled feller bunchers. Tracked machines are slower than wheeled machines, but often have the advantage of being more stable on steep slopes. Tracked feller bunchers are also capable of operating on wet and loose soils where rubber-tired machines would be prevented from operating. The basic machines may have self-leveling cabs that extend the slope on which they can operate.

The feller buncher moves toward the tree to be felled, grabs it, cuts it, and holds it in the head while moving to the next tree. Thus, it can cut as many trees as the head and the basic machine can hold in a safe way. Afterward, the bundle of felled trees is positioned in a way that the skidder can easily take it up (Figs. 13 and 14).

The productivity of a feller buncher depends on several factors like terrain, spacing between the trees, size of the individual trees, species, and basic machine. A good average value found in practice is about 300 trees per day.

Stroke Delimber

A stroke delimber is a machine used for removing branches from the stem of felled trees by using a system of knives. Since the system lifts the whole tree during the process, the basic machine has to be heavy to guarantee stability while delimbing the stem. In general track-based machines are used to carry the telescopic tunnel where the knives are fixed. To forward the stem through the delimbing unit, two systems exist: in the first, two iron wheels move the tree; in the second, the knives themselves do this work. At the end of the telescopic system, a saw is installed for a transversal cut of the top of the trees (Fig. 15).

In general the basic machine for carrying the telescope is a medium- to big-sized excavator reaching total weights of more than 26 t. The machine is used for

Fig. 14 A feller buncher grabbing a tree (*top*) and felling and bundling it (*bottom*). Source: Gustavo Castro

Fig. 15 A stroke delimber for cutting off branches in a planted forest. Source: Gustavo Castro

Fig. 16 A processor head processing (debarking, delimbing, and bucking) trees at the road side. Source: Gustavo Castro

medium- to big-sized trees, but it is more and more replaced by the more flexible and economic harvester heads.

Processor and Harvester Head

The subsequent processing steps following tree felling were already described in the manual and motor-manual systems. The trend toward mechanization of forest work led to the development of several machine-assisted solutions for these forest operations. Most of the solutions are combined ones, processing the wood in several steps in one operation.

One of the combined solutions already mentioned is the harvester or processor head. Delimbing, debarking, and bucking can be combined in technical operations in an efficient and economical way by such solutions.

To combine this operation in the stand with a **harvester head** offers the big advantage that the residual biomass keeps well distributed over the harvested area for nutrient cycling from organic matter. The same biomass can be used as a "compacting buffer" to the soil for the machines moving over it. The debarking and delimbing process occurs while the stem is moved by rolls or wheels through the processing head, where knives cut off the branches and the bark. Bucking is done by the felling unit, which might be saws, disks, or felling knives. In such cut-to-length systems, the assortments are provided in a homogeneous and high quality to be forwarded and transported to the wood industry (Fig. 16).

A **processor head** in general is applied in full-tree logging systems. The trees with crowns are skidded to the forest road or a landing place where the assortments are processed at central places. That system is of high productivity because of the work division of highly specialized units. The whole trees are pre-concentrated beside the forest roads in long piles. The processor head, in general mounted on a mobile basic machine, produces the assortments and leaves it classified and piled beside the forest road. This method also allows utilization of the crown slash as biomass. In a highly pre-concentrated form, it can easily be processed by a chipper.

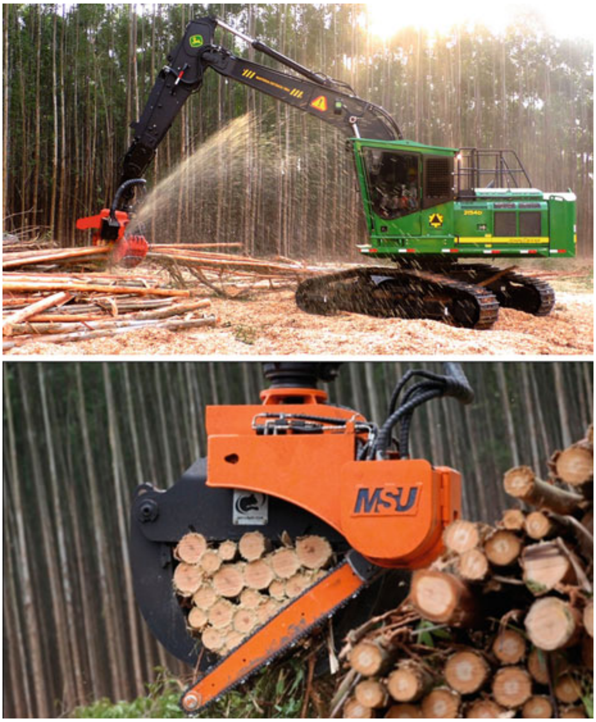


Fig. 17 A grapple saw mounted on a track-based machine. Source: Gustavo Castro

The system is highly productive in forest plantations where the full tree is intended to be utilized. The problem is the intense driving of heavy machines all over the area, the extreme extraction of biomass, and the soil exposed to rain and wind after the harvesting operation.

Grapple Saw

Mechanized bucking today is mainly done in plantation forests with the help of harvester or processor heads in combined processes in forest harvesting operations. One option frequently found in planted forests is cranes for loading and unloading combined with a cutting unit, in most of the cases a hydraulic chainsaw. The felled trees are let in longer units, facilitating the forwarding or skidding process. The assortments brought to the landing zones or forest roads are piled by a grabber mounted on a mobile or fix basic machine, cutting the longer stems to smaller assortments during the piling process. This is a cheap and efficient way for preparing assortments for transport or assortments where short length is wanted (Fig. 17).

In native tropical forests, no mechanized bucking options are applied. The big trees in general are sectioned with the help of a chainsaw in the forest and transported this way to the wood industry.

Wood Extraction

After felling of the trees and further processing in the wanted assortments, the wood has to be extracted from the forest stands to the forest roads for further transport (Cermak and Lloyd 1962). There are many possibilities to do so. Equipment and machines used, depending on the resources available, may also vary from very simple manual operations up to sophisticated and expensive machines of high productivity (Seixas 2008).

Manual Extraction

Skidding, forwarding, or cable yarding is the next step after felling. After a period of wood drying on site for reducing water content, the way of how to get the wood to the next transport means has to be decided. Depending on the further direction of transport, the felling may already occur in the direction of the extraction. Manual extraction of wood in tropical forests is still frequently applied, but only for assortments of smaller dimensions coming from thin trees, like fuelwood or, in exceptional cases, also for pulpwood. In smaller properties, in steep terrain or where mechanization is not possible, it is a still applied activity. In a larger scale, manual harvesting operation is a not viable option, since the physical workload is extremely high and the weight of the wood exceeds the load recommendable for permanent human labor (Fig. 18).

Manual hauling in harvesting operations is reduced to a minimum today. Because of the extremely high physical stress, that process even in poor countries is done with the help of animals. In tropical countries, the workload is even higher because of the hot and humid climate, leading to physical exhaustion of the people working in the forest, especially under bad nutrition conditions (Fig. 19).

Even so, in Africa, Asia, or Latin America, the transport of firewood or for simple construction purposes (fences, shelters, houses) is done by carrying the wood on the shoulders or on the head, often over astonishing large distances.

For operation in small forest plantations, also small sulkies or wheelbarrows are used. But according to modern labor safety regulations and healthcare rules, such operations in the future will be more and more restricted to private use of wood in smaller amounts.

Wood Extraction by Gravity: Roundwood Chutes and Rolling

Stems of harvested wood can be transported downhill by using gravity force and simple hand tools. For this purpose the inclination of the terrain has to be at least 40 %, which can be classified as steep slopes. In a few cases, the stems or even full trees simply slide downhill, but in general, a controlled sliding is preferred. For that purpose, special U-shaped chutes made out of metal or plastic are used (Fig. 20).

Fig. 18 Manual log extraction and piling on short distances in tropical forest plantations (eucalypt plantation (*top*) and teak plantation (*bottom*)). Soure: Leif Nutto

Fig. 19 Ethiopian woman carrying crown slash to local markets over distances of more than 10 km. Source: Jorge Malinovski

Fig. 20 Wood extraction with chutes. Short log extraction in a pine plantation (*left*) and schematic drawing (*right*). Source: Jorge Malinovski

In former times the chutes were built of wood itself, a very time-consuming and therefore expensive activity. The length of a single chute is about 3 m if made of metal and about 5 m if lighter plastic is used. The single chutes are mounted together to a total length of up to 200 m, where the logs are pulled to the transport mean from 12 to 14 m distance at each side. To reduce friction, sometimes, the chutes are treated with oil; in tropical countries, also used machine oils were applied, having an extremely bad impact on the environment and health of workers. The operational productivity of a team of three forest workers is between 25 and 40 stacked cubic meters per day, depending on assortments and terrain conditions. The problem of using chutes is the installation and dismounting of the system, as well as the transport of the material, where about 10–20 % of the whole working hours are spent. Wood extraction by chutes has been one of the most applied systems in several countries over decades, especially in mountainous regions where road construction was too expensive, while labor costs were high and people worked with short log length.

The even more simple system is the use of gravity only by giving the wood an initial impact. The system is often applied in forest plantations where short logs of 2.20 m length and diameters between 5 and 20 cm are thrown downhill at slopes of more than 40 %, while the wood is collected and piled at the forest road. The maximum skidding distance is between 50 and 70 m reaching a productivity of 10 to 12 stacked cubic meters per worker and day (Seixas 1987). The very simple system in general is a cheap method, but ergonomy and working conditions for the forest workers often exceed acceptable limits, especially in tropical countries with high temperatures. Therefore the systems are more and more replaced by mechanization (Fig. 21).

Fig. 21 Manual wood extraction on steep slopes by using gravity in a eucalypt plantation in Brazil in the year 1975. Source: Fernando Seixas

Manual Wood Extraction with Bogies, Trolleys, or Sulkies

To reduce the friction between the soil and the logs during skidding, wheel-assisted tools have been used for many decades. First constructions with wooden or iron wheels were used to pull logs or wood outside the stands. No matter if pulled by hand, animals, or tractors, the productivity increased with the use of pneumatic wheels, specifically for logs of bigger dimensions. In some countries such systems were even used until the late 1980s. Today the main application of such transport systems is in smaller-scale forestry in the tropics, mainly in animal-assisted systems. In the 1980s, a bogie was developed in Finland which was improved in several ways. The bogie was equipped with four wheels which improved the handling with uneven terrain and obstacles, by keeping the system more equilibrated than the two-wheel constructions. The pulling force to apply reduced even the vehicle being heavier than a simple bogie, while it still was possible to turn the vehicle around its own axis. The weight of these wheel-based vehicles varies between 15 and 50 kg, where the loading capacity ranges from 125 kg for a manual two-wheel sulky up to 250 kg for a bogie with four wheels. Logs with a length of 7 m and a volume of 0.4 m^3 can be skidded with such systems. For bigger logs, other wheel-based constructions are available, but they have to be pulled by several men, animals, or machines (Fig. 22).

The weight of the equipment influences significantly the productivity. Ole-Meiludie and Omnes (1979) found the productivity between a 25 kg sulky and a 50 kg one resulted in a single man system in a loss of 30 % for skidding logs between 3 and 5.7 m length in slightly undulated terrain.

For applying such manual systems, the correct working technique is important for saving energy. The contact points where the chains or ropes are fixed on the log have to be selected carefully according to the terrain. In plain terrain, the log has to be fixed at the center of gravity. In slightly undulated terrain with inclinations up to 30 %, the log has to be put on the point of support corresponding to one third of its length. In steep slopes with 50 or more percent of inclination, the weight of the log

Fig. 22 Four-wheeler in Finland. Source: Jorge Malinovski

has to be used for breaking the system for downhill transport. For heavy logs it might be recommendable to use two vehicles to transport the log without direct soil contact.

The planning of skidding by bogies or sulkies is very important. A team of at least four, better six, men should handle the bogies, sulkies, or trolleys because of the high workload. The felling of the trees should be conducted already in skidding direction, where the skidding trails have to be prepared in a way suitable for using the wheel-based systems and be kept clean of crown slash and other residues of the harvesting operations.

Animal-Assisted Extraction

Where available, animals are used for off-road, track, or road transport to avoid pure manual operations. In many tropical countries, animal skidding continues to be an attractive economical choice; even so, the common trend is to replace the animals by machines with higher productivity and less restrictions concerning weather conditions and terrain. Another advantage of animals is the possibility to restrict skidding to narrow skidding paths and to reduce soil damages.

Depending on the continent or country, a variety of animals showed up to be useful for skidding and wood transport in harvesting operations. Skidding with animals in general is limited to smaller logs of native forests or material coming from forest plantations. Careful planning of the harvesting operation considering the animal capacity and the maintenance is necessary, if this way of skidding is intended to be applied. In tropical countries a couple of additional considerations have to be taken into account to avoid any discomfort or health implication to the animal. The hot and humid weather conditions restrict the use of animals in skidding operations to a few species used as domestic animals in the tropics. The animal should be strong, tolerant to the climate, and suitable for the work, and correct nutrition should be possible. Most of the horse races are not suitable for skidding under tropical conditions, resting mules, donkeys, oxen, some buffalo

Fig. 23 Wood extraction with mules in a tropical forest plantation. Source: Jorge Malinovski

races, or Indian elephants as draft animals. Animals have to be fed at least three times at an 8 h working day; due to heavy duty, they need additional concentrated feeding stuff. They also need frequent veterinary attention. For harvesting, planning an additional reserve of 20 % has to be held for replacing exhausted or sick animals.

Wood Extraction with Mules or Horses

Horses have been used as draft animal over centuries in temperate zones all over the world. Due to fast mechanization in industrialized and also developing countries, they lost in significance since the 1940s. The weight of a horse is between 400 and 700 kg, depending on the race. The drag force reaches between 0.6 and 0.9 kN which is equivalent to 15 % of its weight, while, for instance, oxen only reach 10 %. For a short period, a horse can even exceed the abovementioned drag force (Fig. 23).

Horses are intelligent, sweet tempered, and easy to be trimmed. They work faster than many other animals and reach a daily working level of up to 7 h. As already mentioned, the use of horses for skidding operations in the tropics is not very common, since these animals show low tolerance to disease under tropical climate. In steep terrain they easily get nervous and out of kilter as compared to mules or oxen. Therefore the preference in tropical countries is given to the much more rugged mules. The mules have higher needs regarding food and caretaking in tropical regions. At the same time, the productivity is rather low compared to oxen. While a mule in general works alone, oxen can be used in pairs, increasing productivity per trip and also the weight that can be skidded.

Wood Extraction with Oxen

In Asian countries, oxen are the most common draft animals used. They have a gentle character, can be fed with grass of lower quality, and are able to work over longer periods, even in a rather slow mode. They have to be trimmed for skidding operations when they reach an age of 2 or 3 years. Experiences from Costa Rica show that it takes 12–14 months to trim oxen for skidding when the animal is 2 years old. In Malawi the animals can be used for skidding operations until they reach an age of 8 years. While a cow reaches a drag force of 0.5–0.6 kN, an ox can

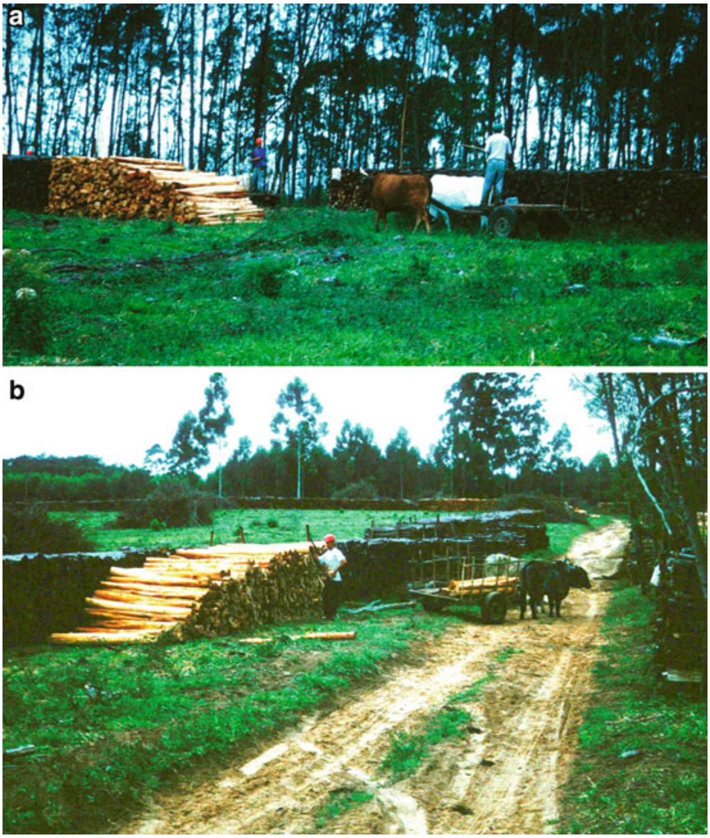


Fig. 24 Wood extraction with oxen in a degraded secondary tropical forest. Source: Leif Nutto

get to a value of 0.6–0.8, corresponding to 10 % of his body weight. The daily working period may not exceed 5–6 h. In the tropics, the oxen in general are smaller than in temperate climate zones and can skid less weight. The average productivity of a pair of oxen reaches 2–2.5 m^3 a day, skidding at the maximum a stem of 0.6 m^3 over a distance of 400 m (Fig. 24).

Wood Extraction with Elephants

The elephants, or better the Indian elephants, are used as draft animal in some countries of Southeast Asia, like India, Burma, Sri Lanka, Thailand, or Laos. The weight of an adult Asian elephant is of 3–4 t. The animals in general are fed with grass, leaves, bamboo, wild banana, or young twigs of trees. They need about 250 l of water and 250 kg of food per day. Due to this fact, elephants can only be used in regions with humid climate, where enough water and food are available. Starting from age 3, elephants are started to be trimmed, which in average takes 5 years. Only then he can be used for light work at the beginning until with advanced age, size, and abilities, he can be used for skidding operations. The animal reaches

Fig. 25 Wood extraction with elephants in planted forests in India. Source: Dennis Dykstra

maximum work productivity at the age of 30–50 and should retire at the age of 60. The working speed of an elephant is about 4 km/h; if the animal should work at different places, transport by truck is recommended. For skidding operation, an animal should have a rest every 500 m. For average skidding distances of 1,000 m, an elephant may reach a productivity of 450–600 m^3 per year in flat terrain (Fig. 25).

Motor-Manual Extraction

The off-road transport of the wood can be classified after the way how the material is transported. In a **skidding** operation, the wood is draft by a machine or an animal. The wood can be fixed by a cable, by a chain, or with a grabber. The use of a winch also makes part of the skidding process. **Forwarding** is a process where the wood is carried with the help of a supporter, trailer, or a machine without touching the ground. A third possibility is the use of a **cable** or **skyline** system. In a skyline system, the wood is transported fully suspended, while in a cable system, the wood partially touches the ground.

Which system to use depends widely on the resources available by the forest owner or forest manager. Smallholders, farmers, or communities might have no financial resources or technical know-how available to work with a high level of mechanization, where logging companies operating on large scale have a high degree on mechanization.

Fig. 26 Self-loading trailer with tractor in a forest plantation. Source: Gustavo Castro

Tractors with Self-Loading Trailer

Tractors with self-loading trailers came from adaption of agricultural equipment to forestry needs. In smaller-scale forest management, the acquisition of expensive forest equipment is not always a viable option. The adaption of machines produced in large scale and therefore cheaper offers a compromise between costs and benefits. Tractors with self-loading trailers offer an economic solution in smaller, mainly man-made forests. It may be operated in planted forests or in forwarding smaller-dimensioned wood in terrain with a slope up to 10 % (Fig. 26).

The minimum power to operate the system is a tractor with at least 80 HP. The bigger models are able to forward logs of smaller diameter between 1.0 and 7.0 m and load up to 15 t. The crane is mounted on the trailer or on the tractor. An average load volume is about 13.5 stacked m^3 per trip with maximum forwarding distances of 300 m. Under good conditions, the productivity may reach 20 stacked m^3/h.

Mini-Skidder

Mini-skidders are agricultural tractors adapted to work in forests. In general only the bigger back wheels are with traction, and a hydraulic grapple is mounted for skidding the logs or trees. This type of tractor in general is multifunctional and can be adapted for several works in agriculture, cattle breeding, and forestry. The forest work is restricted to smaller-sized trees, reduced harvesting volume, and not too steep terrain. Soil compaction is higher because the machine is not adapted to reduce negative impact of driving in forest stands. Under favorable conditions, these machines are three times more productive than tractors equipped with a winch (Machado 1984) (Fig. 27).

Winch Systems

Winches are used when wood has to be extracted and the soils are too sensitive to drive over or when the machines have no access to the stands because of slope or

Fig. 27 Mini-Skidder, an adapted agricultural tractor in a forest plantation. Source: Gustavo Castro

Fig. 28 Skidding with tractor-based winch. Source: TMO

dense vegetation that cannot be removed. The winch can be mounted on several types of basic machines, from agricultural tractors up to specific machines designed for forest work. For the skidding operation, the tractor is positioned with the rear part in the direction of the logs to haul, and the cable of the winch is pulled to the felled tree or the log and engaged in it. In plantations smaller machines can be used, but for big-sized logs of tropical native forests, heavy machines are necessary. In general also a rear shield is necessary that can support the machine to stand still while the heavy weight is winched to the tractor (Fig. 28).

Agricultural tractors should at least have 100 hp to cope with the duty of skidding the trees with the help of a winch. The drum with the cable can be designed for different duties. In plantation cable length can reach 200 m, but the diameter of the same is only 1.2 cm. In native forests the cable has to have at least 1.8 cm of diameter to guarantee secure skidding of big logs. Such cables are very heavy and difficult to pull out, especially in flat terrain where the advantage of gravity cannot be used for pulling out. Some tractors can move the drum or have a hydraulic aid to pull out the cable and reduce in this way the physical workload of the forest workers. In this case, skidding distances are limited to 50 m because of the high weight of the cable. The forest road should at least have a width of 4 m for efficient work with the winch-equipped skidder.

In forest plantations where the assortment consists of short stems of 2.2 m of small diameter, a team consists of one machine operator and four helpers. In general a winch system is only applied in very steep terrain with over 60 % of slope.

Specific Forest Machinery and Equipment for Wood Extraction

Fully mechanized forest harvesting operations are becoming more and more interesting in tropical forests. The machines used for wood extraction today are specially developed for this purpose, meeting the ergonomic, safety, and environmental requirements of sustainable forest management. Tropical forest plantations often are very homogeneous and managed in clear-cut systems, where fully mechanized systems are highly competitive (Forest and Rangelands 2011d). Here a variety of machines with specific design for forest operations have been developed in the last decades. It has to be mentioned that these machines often were developed in Europe or North America, where working conditions are different. Machines used in tropical regions have to be "tropicalized" with adapted refrigeration systems, larger air filters, and air condition for the operator cabin.

Skidder

A skidder is a special designed forest tractor for the draft of wood partially touching the ground. There exist several models starting with 4×4, 6×6, and 8×8. Skidders were developed in the late 1960s as a strong and agile machine able to operate with low costs. The rugged machine with simple maintenance is able to handle nearly all sizes of trees or stems, even very strong ones, making it the most preferred option in tropical forests.

Skidders exist as several models, wheel or track based. The decision on which model to choose depends on the skidding conditions found in the target area. Track-based machines have the big advantage of causing less soil damages, but at the same time, they are very slow. The maximum skidding speed is between 3 and 5 km/h, which result in low productivity if skidding distances are long. Wheel-based machines on the other hand are much faster and show higher productivity rates, but often cannot be used for skidding operations during rainy season or on sensitive soils.

The skidder has a grabber mounted at the back part of the machine. This grabber is able to take up a single stem or a bundle of stems or full trees and skids them to the forest road or landing zone. Some models are equipped with a clam bunk, enabling the operator to collect several stems or bundles in one trip. Most of the skidders are also equipped with a front shield to open skidding trails and to pile logs at landing zones. Skidders equipped with a winch are able to pull stems over distances of 50–60 m, reducing the impact on the forest soils by concentrating skidding activities to a specifically designed net of skidding tracks. Such skidders beside the winch have a back shield which is fixing the machine during the pulling process with the winch. In many cases they have no grabber, because the stems are fixed with and skidded with the cable of the winch. At the market, skidders from

Fig. 29 Grapple skidder with four wheels (4 × 4, *top*) and six wheels (6 × 6 *bottom*). Source: Gustavo Castro

10 to 38 t are available, equipped with engines of 96–300 kW. The productivity of the machine depends mainly on the skidding distance and the performance of the operator, besides the factors already mentioned in the introduction of this chapter (Figs. 29, 30, and 31).

Wheel-based skidders may operate in terrains of 30–40 % of slope, the latter only true for 6 × 6 or 8 × 8 machines. Skidding distances of up to 400 m are viable. The track-based machines may operate at slopes up to 50 %, with maximum skidding distances between 120 and 180 m. Skidders were developed for long log or full-tree harvesting systems, being not competitive in short log systems. As already mentioned, skidding whole trees on sandy soils in a clear-cut system leaves the soil completely uncovered with all protective organic material removed. In times of heavy rainfalls, the risk of erosion is not acceptable from an environmental point of view.

Clambunk Skidder

A clambunk skidder is a machine that is able to skid bundles of stems or whole trees from the place of felling to the forest road or a central processing zone. The loading is done with a grapple mounted at the skidder. The trees or stems are put in a bank which can be closed with a claw. Depending on the size of the machine, volumes between 2 and 3.5 m^3 can be skidded at once. Like the normal grapple or winch skidders, part of the wood is also dragged on the ground (Fig. 32).

Some of the clambunk skidders have the same basic machine as a forwarder and can be converted to it; others are specifically designed for this purpose. The machines have an excellent handling and can be used also in steep terrain of up to 25°.

Fig. 30 Eight-wheel skidder with assisting tracks (*top*) and a track skidder (*bottom*). Source: Tanguay / Caterpillar

Forwarder

Forwarder are self-loading forest tractors, generally designed for transport of short logs in forests. The loading weights vary between 5 and 22 t and the power of the engine from 95 to 205 kW, depending on the model. The productivity largely depends on the pre-concentration of the wood and the hauling distance (Malinovski 2007). The machine is highly flexible to cope with difficult terrain found in off-road transport. Depending on soil type and humidity, wheel-based machines are able to handle slopes up to 30 %. In more sensitive soils and steep slopes, the use of flexible tracks put over the wheels is useful. Forwarders today are also used with assisting winches anchored on the uphill side, allowing to work in terrain up to 80 % (Fig. 33).

A forwarder consists of a load carrier in the back, a crane, and a basic machine. The crane sometimes is equipped with a telescopic arm, increasing the activity radius when the machine is loading. The maximum lift may reach 1.8 t, depending on the model of the overall configuration of the system. After filling the load carrier, the forwarder moves to the forest road or a landing place, where the wood is piled for road transport. In hot systems the forwarder may unload directly upon a truck. Many studies about the risk of soil compaction have been conducted in the past (Schardt et al. 2007; Seixas et al. 2003).

Fig. 31 Skidders equipped with a winch in forest plantation (*top*) and in a native forest (*bottom*). Source: Tigercat / Leif Nutto

Fig. 32 A clambunk skidder in a forest plantation. Source: Gustavo Castro

Harwarder

In harvesting operations, the activity of loading and unloading takes 50–75 % of time consumption. To reduce this time, integrated systems were developed in the last years. A *harwarder* is a combination of harvester and forwarder and able to cut,

Fig. 33 Forwarder of different sizes with six wheels (*top*) and eight wheels (*bottom*). Source: Gustavo Castro

delimb, debark, and section the trees before loading and forwarding it. This way, all the process steps of a harvesting operation are done by only one machine (Fig. 34).

The main advantage of the system is that the processed wood is directly "stored" in the load carrier, avoiding a separate working step with another machine. On the other hand, the compromise between a pure felling and processing machine and forwarder reduces the productivity a little bit. In clear-cut systems in tropical forest plantations, combined machines showed to be less productive. When used in thinning or selective logging systems, in many cases, they have advantages in flexibility and productivity of the operations. Realizing all processing steps with only one machine can also reduce soil compaction by less frequent driving in the stand.

Shovel Logger

A shovel logger consists of a basic machine that can be specifically developed for forest operation or a simple excavator with an adaption to move wood (Fisher 1999). They are powerful machines that can lift or drag high weights with a grapple mounted at a crane. The equipment is used for full-tree or whole-tree harvesting

Fig. 34 Wheel-based forest tractor equipped with a crane for felling, delimbing, bucking, and loading as well as with a load carrier for off-road transport (combination of harvester and forwarder, harwarder). Source: Komatsu Forest

Fig. 35 A shovel logger working in a conifer planted forest. Source: Gustavo Castro

operations. Its function in a harvesting system is to skid, pre-concentrate, or lift trees for any kind of further transport, skidding, or forwarding operation. It can be considered to be a multifunctional machine that also is able to open skid trails after clear-cut and thinning operations or for simple constructions in swampy terrain. In some cases, they are also used for loading trucks (Fig. 35).

Some shovel loggers are designed for operating in steep terrain and are able to level the operator cabin according to the relief of the harvesting area. In sensitive or swampy soils, it is recommendable to use a basic machine with enlarged tracks to improve the distribution of the load on the soil.

Helicopter Logging

Helicopters rarely are used for logging operations in the tropics. In tropical forest plantations, ground-based systems are much more competitive, and in native tropical forests, the access through the canopy in selective logging systems is seldom given. Besides, the logs of native trees are big sized and heavy and would need large helicopters to lift them (Akay and Acar 2008). The overall system is extremely expensive, often exceeding by far the value of the wood. On the other hand, the system can be used at any slope (0–100 %) or terrain conditions, including sensitive soils, reducing in this way environmental impact (Castro 2011b).

The harvesting with helicopter assistance can be conducted in several ways:

(a) *Standing stem harvesting:* This process consists in a selective logging system where species, diameter, height, volume, and weight are known and the trees are felled, lifted by the helicopter, and transported to a landing zone. The system is of very low impact because felling in general is done motor-manually and no ground-based machinery is used.
(b) *Buncher harvesting:* This process is pre-concentrating the wood before transporting it with the helicopter. The trees are felled, processed, and concentrated to bundles or small piles. This can happen motor-manually or, if the terrain allows it, also by machines. The helicopter lifts and transports the wood to a landing zone (Fig. 36).

Fig. 36 Logging operations assisted by helicopters. Source: Erickson Air Crane

The main characteristics of helicopter logging are the vertical transport of the wood, fast cycles, low environmental impact, and to be able to fly with wind up to 90 km/h. The disadvantages are the high fuel consumption of the helicopter, the operator and machine costs per working hour, the limitation in weight of the trees or stems that can be transported, the need of highly trained and specialized personnel, and the dependency on only one machine (helicopter). In some cases the stems have to be cut in shorter length so that the helicopter can lift them, reducing in this way the value of the stem.

Cable Yarder

Cable yarding or skyline systems are applied when the terrain is too steep for wheel- or track-based machines in skidding or forwarding operations or where the soil is of low carrying capacity (Forest and Rangelands 2011a). While cable logging works with ground pulling or high lead, skyline systems allow a fully suspended wood transport. There are innumerous ways to classify skyline systems. Only to mention some of them, they may be distinguished after:

- Mobility – stationary, semi-stationary, or mobile
- Anchoring – fixed or possible lowering
- Number of ropes (cables) – one-, two-, or three-rope cable ways
- Yarding distance – short (>300 m), middle (300–800 m), or long (800–1,600 m) (Figs. 37 and 38)

Cable yarding systems in general are more expensive, are of lower productivity, and require highly trained operation teams. In tropical regions they are mainly used in forest plantations in very steep terrain (slope > 30 %). Since they also need access roads to work properly, besides the economic viability, there are mainly environmental restrictions to consider in the decision. Plantations are often managed in clear-cut systems leaving the soil exposed after harvesting operations. In steep terrain there is a high risk of erosion and loss of soil fertility, those losing the claim of sustainability in the forest management (Thees et al. 2011).

In forest plantations the conditions found for economic cable logging systems are promising:

- High wood volume to haul because of clear-cut systems
- Homogeneous forests with smaller log diameters
- Good infrastructure (forest road system)

The average productivity of a short distance system is about 4 m^3/h, 8 m^3/h of a medium distance system and 12 m^3/h in systems with more than 800 m of hauling distance. In clear-cuts of tropical plantation, the productivity might reach up to 20 m^3/h.

Fig. 37 Mobile cable yarders with different technical specifications. Source: Jorge Malinovski

In native forest such systems are very limited by missing infrastructure, low harvesting volume per hectare, and the weight of the logs of big dimension. A kind of skyline system is balloon logging, where the anchor points to lift up the cables is done by a balloon, carrying the weight of the ropes and the hauled trees. The system was tried to be applied in tropical rainforests, but there were many limiting factors. The forests in general are managed as permanent forests with target diameter harvesting systems. The structure of the forest after harvesting is still very dense, impeding the transport of the suspended logs of large dimension. High costs and low productivity paired with the need of highly skilled operating teams make the cable yarding system a rarely chosen option in native tropical forests.

Machinery for Chipping, Grinding, and Bundling

Chipper

A chipper is designed to cut the wood or a whole tree or a stem in small chips (Forest and Rangelands 2011b). They are not exclusively for chipping wood, but also other materials of similar consistency. Since the production of biomass for energetic purpose became more interesting, chippers are also used to process crown slash, bark, and other plant materials. The more dirt is attached to the biomass, the more difficult is the use of a chipper because of defects or high maintenance costs.

Fig. 38 Cable yarders in steep terrain of tropical pine plantations. Source: Leif Nutto

The size of the chips depends on the configuration of the chipper and the material (Cremer 2008). Since the 1980s, chippers have been integrated in harvesting systems. With the right system, high-quality chips can already be produced on the forest side. Some chipping modules are already able to delimb, debark, and chip the wood in one machine.

Chippers used in forestry systems in general are mobile modules, with powerful engines of 240–900 kW and a weight between 2.4 and 55 t.

The chipper can be mounted on the chassis of a trailer, a self-driving track-based system, a truck, or any other kind of mobile unit, depending on the size and weight of the machine. It may be combined with a grapple and a crane as a self-feeding machine or be used with an external loading system (Fig. 39).

The chips are directly ejected in a container or truck for further transport. The configuration of the system determines the quality of the chips, from “dirty” chips for rug energy generation up to clean and high-quality chips for pulp production (Fig. 40).

Fig. 39 A combined machine for feeding, delimbing, debarking, and chipping. Source: Gustavo Castro

Fig. 40 Mobile drum chipper in a forest plantation. Source: Gustavo Castro

Grinder

Grinders are more robust machines able to process material that would damage the knives of the chippers. A grinder is fragmenting the material by rugged tools; in the case of wood, it is generally used to clean forest areas for cultivating the land, to reduce the size of wooden residuals after forest operations, or to produce combustion material. They may reach a weight of 50 t and can be mounted as a mobile unit like chippers. The engines have a power of up to 1,200 hp (Fig. 41).

Slash Bundler

In the 1990s, machines have been developed to bundle crown slash and other harvesting residues for further transport and utilization, specifically for energy

Fig. 41 Self-driving grinder (remote control) for stumpage removing in forest plantations. Source: Gustavo Castro

production (Leinonen 2004). The bundling unit in general is mounted on the basic machine of a forwarder, collecting the harvesting residues and compacting them to bundles driving through the stands where the harvesting operation has taken place. If the crown slash is pre-concentrated at the forest road (full-tree harvesting and processor head at forest road), the bundler can also be mounted on a truck.

The bundles in general have a length of 3 m and a diameter adapted to the operational necessities, reaching up to 80 cm. A slash bundler may produce up to 20 bundles per hour (Leinonen 2004). If produced in the forest site, the bundles are collected in a further process by a forwarder (Machado 2008) (Fig. 42).

Loading Equipment and Machinery

After the hauling process, the wood in general is pre-concentrated at the forest road or at specific landing zones for loading and transportation to the end consumer (Seixas and Camilo 2008). There are many ways to load the wood for further transport, depending on the size of the logs and the assortments and the technical options available. In many tropical countries, labor force is still cheap and unskilled workers are available. Work safety and health protection in many cases are still regulated in an insufficient way, allowing and considering legal aspects and outermost hard work under dangerous conditions, which is already forbidden in other parts of the world. Today it should be a voluntary commitment of forest managers, forest owners, and companies to put health and safety of the workers in the first place. Outermost hard work or putting the life and health of a person in risk today is not acceptable (Silva et al. 2008).

Fig. 42 Slash bundler for compacting crown slash for transport. Source: John Deere Forestry

Loading today in general is done in a mechanized way. If wood volumes are small or specific loading machines are not available at all, a variety of options exist where the wood can be placed on transport means in a safe way. Loading can be done as:

- Manual or animal-assisted loading, with or without ramps
- Semi-mechanized loading
- Machine loading
  - Mobile machines (wheels, tracks)
  - Fixed machines

Manual and Semi-Mechanized Loading

Manual loading operation should only be planned if the assortments produced during the harvesting operations are short and of small diameter. In many pulpwood or fuelwood plantations, the logs are between 10 and 20 with a length of 1 or 2 m, allowing a manual loading of trucks and trailers. Even so, such operations are of very low productivity, requiring low wages to be competitive with mechanized loading systems. Loading of bigger logs should be planned with the help of machines or, if not available, at least using animals or gravity systems. Manual

Fig. 43 Extremely dangerous manual loading of eucalypt logs under wet and slippery conditions in Ethiopia. Source: Leif Nutto

loading like it is shown in Fig. 43 is extremely dangerous and should not be planned or conducted under any circumstances. Even so, it still is practiced in a large number of countries, specifically in the tropics. It puts the health and life of the forest workers in risk.

Manual or animal-assisted loading of bigger logs should always be done from the opposite side of the truck pulling the logs with ropes. Under no circumstances any person should be on a lower position than the log to be loaded.

If there is no possibility to lift the wood with the help of a machine, a ramp has to be built to load the logs. In general two or three smaller trees are felled and positioned at the truck to be loaded that they form a ramp (Fig. 44). A rope or cable should be fixed at least at two points of the log, and the load has to be pulled from the opposite side of the truck. The pulling can be done manually or by animals, a winch, or a tractor. No person should stay in the danger zone during this process.

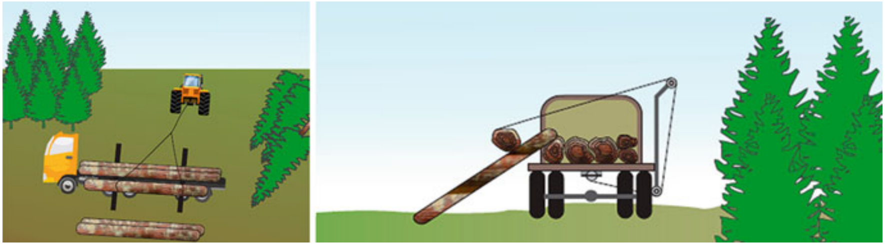


Fig. 44 Loading of a truck pulling the logs over a ramp to the truck (*left*) and using a winch propelled by the own truck (*right*). Source: The authors

Fig. 45 Loading with a ramp and a tractor. Source: The authors

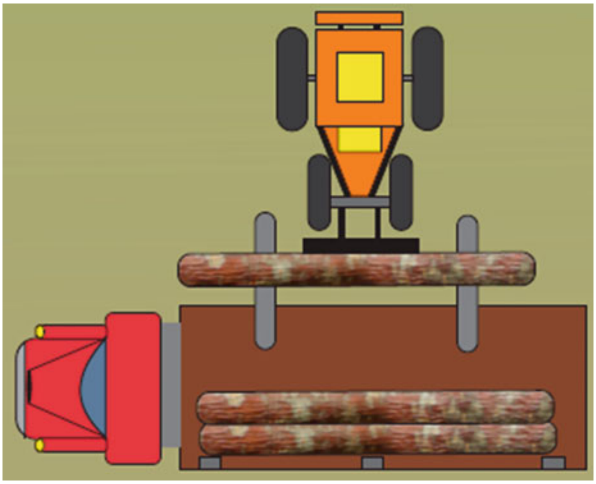
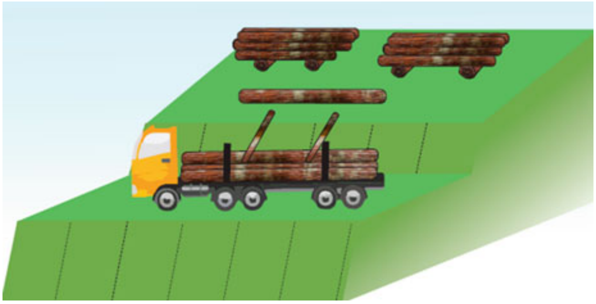


Fig. 46 Ramp on the upper side of a batter that might be constructed in mountainous terrain. Source: The authors



Another option is to use a tractor with a front-end loader pushing the log on the ramp upward (Fig. 45). If there is no machine available to lift the load, this option is of higher productivity than to use cables or ropes.

In mountainous regions, there is always the option to build ramps using gravity. On the uphill side, a ramp is built or the batter of a forest road is used (Fig. 46).

Fig. 47 Multifunctional knuckle boom loader mounted on a trailer. Source: John Deere Forestry

The logs are piled on the upper side and then rolled on the truck. This is a cheap and frequently applied option where no adequate machine for loading is available.

In case of short logs of small diameter as it is a common assortment in tropical forest plantations managed for fuelwood, pulpwood, and particle or fiber board production, manual loading of the logs for transport on trucks or carriages is quite common.

Mechanized Loading

Mechanized loading is the predominant form of wood loading today. The health risk and critical ergonomics of lifting heavy weights over longer periods led to the use of specific machines for wood loading in harvesting operations.

Log loaders are wheel- or track-based machines equipped with cranes and grapple to lift the logs on further transport means. At the beginning, machines from other sectors like construction or logistics were used, but today, more and more specifically designed machines for wood loading and unloading are developed. The cabins of the operators can be lifted to have a better view and to get a better performance and more safety during the loading process. Overload sensors warn the operator if the wood lifted is too heavy and puts in risk the stability of the machine.

There exist a variety of log loader models on the market today. One of them is the knuckle boom loader which is mounted on a truck or trailer chassis. In some cases, they are equipped with a processor head and can do delimbing, debarking, and bucking before loading the logs (Fig. 47).

Track-based machines with long cranes and a grapple are also commonly used for wood loading. The high weight of the basic machine allows a wide range to get the wood and load it on trucks or trains (Fig. 48).

Front wheel loaders are machines used in civil constructions and are adapted to transport and load logs. They are frequently used for loading and unloading heavy logs harvested in native tropical forests. They are often found in log yards to feed sawmills with logs. Since the front loader is fixed, the machine cannot stay on the

Fig. 48 A log loader mounted on a track-based excavator machine. Source: Gustavo Castro

same place while loading. A permanent driving between the piled wood and the truck is necessary, reducing the performance of the machine as compared to the ones with a lever (Fig. 49).

Final Comments

As it could be shown, a nearly infinite number of wood harvesting machinery and equipment exist today. The trend is clearly going toward higher degree of mechanization, because of the high risks in forest work, heavy workload, working safety, and also productivity. This is also true for tropical forests, no matter if planted or native, because of increasing awareness of sustainable and social correct acting in all forest operations, required by the global markets. Even so manual and animal-assisted harvesting operations will still remain an important option for a long time in tropical forest, simply because of missing alternatives from an economic point of view. Especially for communities and small farmers, it is very difficult to make investments in technical equipment and the necessary maintenance for successful operation.

The existing equipment and machinery are constantly improved and adapted for tropical conditions. Especially for machines, the climate conditions like heat and dust may lead to severe damages and adjustments are necessary. When selecting appropriated harvesting equipment, these considerations are important.

Every harvesting equipment or machine has its advantages and disadvantages. For making a decision on which to use, all limiting factors have to be carefully evaluated. The harvesting operation itself consists in a combination of different equipment for felling and processing the wood, off-road transport, and loading. Manual, motor-manual, animal-assisted, and mechanized operations may be mixed individually and adapted to local restrictions to obtain the most efficient and technically viable system.

Fig. 49 Wheel front-end loader in the landing zone of a tropical rainforest (*top*) and at the log yard of a sawmill (*bottom*). Source: Leif Nutto

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