Harvesting Systems

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Abstract

Forest harvesting refers to cutting and delivering trees in a productive, save, economic, and ecological process. It includes the conversion of trees into merchantable raw material according to specific industrial or individual requirements and needs. The combination of different technologies, machines, and labor force of the single processing steps of a harvesting operation to a harmonic

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and efficient production chain is the big challenge of a productive harvesting system. Wood harvesting has become an important science and operational factor all over the world in the last decades. In the framework of sustainable forest management, it is one of the key issues where the human impact on using natural resources like forest ecosystems can be reduced. Specifically in tropical countries, the forest ecosystems are very sensitive to any kind of human intervention. In native tropical forest as well as in tropical and subtropical forest plantations, the principles of reduced impact logging (RIL) are regarded as the most critical factor for economic, ecologic, and social sustainability (FAO 2004). Most of the negative image of tropical forest management comes from inappropriate harvesting methods with catastrophic environmental impact. Conventional logging systems (CL) did not take into consideration any sustainability matter, since the objective was always to make fast money and move on to the next exploitation site. In a long-term careful planning, harvesting operations can reduce costs, avoid environmental degradation, improve the utilization of the natural resources, and prevent the injury to personnel. Selecting the most appropriated harvesting system for a given silvicultural management system, terrain and climate condition, available infrastructure and transport system, technological and social restrictions, and finally available financial resources is a key decision in every wood-producing forest enterprise. The harvesting system contributes in a high proportion to the profitability of the wood production and therefore the costs of the raw material provided to the wood industry. For selecting the most adequate harvesting system, not only the investment costs for machines, training of personnel or staff, as well as maintenance costs should be considered. The important question for harvesting is how much does the cubic meter of wood loaded on the truck in the forest cost. In a broader sense, the total costs of the raw material put in the log yard of the respective wood industry crucial to take the decision of the best harvesting and transport system. The performance and productivity of the system as well as long-term factors like environmental degradation of forest production sites determine if the harvesting operations are conducted with an appropriate system or not. The number of wood-harvesting machines and technologies available at a global level is extremely high, multiplying by the options of putting the single processing steps lead to numberless combinations. The article pretends to classify harvesting systems from different points of view and to present some of the most frequently applied harvesting systems in the tropics on a global level. Since the innovation in harvesting technologies and equipment is very high, new systems and combination of single processing steps are found in harvesting practice every year.

Keywords

Harvesting Systems • Logging • Full-tree • Cut-to-length • Tree-length • Chipping • Wood Harvesting

Introduction

Forests occupy huge areas on our planet, where the most sensitive forest ecosystems are located in the tropical and subtropical regions. The global trend toward using more natural resources produced in a sustainable way leads to a higher demand for renewable raw material such as wood. High volumes are harvested day by day and the challenge is to provide the assortments for different utilizations in an economic feasible, social just, and environmental sound way. The variety of characteristics found especially in tropical forest ecosystems, no matter if they are planted, native, or already exploited, requires also a set of different strategies of how to get the wood from the forest to the wood industry and the end consumers.

Wood harvesting therefore has become an essential part of the forest-wood chain, also because of the environmental, social, and economic impact of these activities on forest utilization in general. No matter if the harvesting is done manually, semi-, or fully mechanized, it always consists of a combination of operational steps in the framework of forest management, with the aim of processing the wood of trees and hauling it to landing zones, where it can be piled for future loading and transport to wood industry (Greudlich 1996).

Harvesting operations consist of a variety of activities, such as felling, delimbing, debarking, sectioning, hauling or skidding, piling, and loading. In some cases the wood is already chipped or grinded in the forest, a process where also an adapted harvesting system has to be applied. For each activity are existing innumerous technologies and solutions, from purely manual activities up to fully mechanized options. To find the best combination of the existing solutions or technologies for each single step in the harvesting chain, in other words, to find the best harvesting system, is the big challenge of harvesting planning.

In the past decades, forest harvesting has undergone huge changes, specifically in the tropical regions of the world. Pure economically driven systems have been replaced by ones that also give attention to environmental and social sustainability. The increased awareness of environmental problems induced by this type of land use, movements toward nature preservation, and protection lead to the establishment of reduced impact logging (RIL) principles, aiming to avoid permanent environmental damage induced by harvesting operations (Hawthorne et al. 2011). On the other hand, also changes in the “human factor” of harvesting activities are worth to be noted. Being forest work in general, a labor intensive form of land use, nearly all working activities have to be linked with outermost hard physical stress and extremely dangerous work. The problems are even worse under tropical climate, where high temperature and air humidity can aggravate the working conditions for humans. Nutrition and health status, health care, and existing infrastructure also play an important role in performing socially acceptable and humane working conditions. Another aspect commonly noted is the overall lack of qualified labor in the remote areas where forest management is practiced. These facts lead to a trend toward mechanization of harvesting systems, as well in native as also in planted tropical forests. The planted forests, or forest plantations, have become more important in tropical countries in the recent years. The low productivity in commercial timber, the high ecological sensitivity, legal restrictions, and social problems found frequently in tropical native forest management lead to a trend of establishing intensively managed planted forests to meet the increasing global wood demand, while reducing activities in native forests. In Brazil, for instance, a tropical country with an important forest and wood industry, close to 70 % of all wood consumed is produced in only 1.7 % of the total forest area, being these intensively managed plantations. Of course this trend shows also an impact on harvesting operations standards and the importance of systems used to bring the wood from the forest to the industry.

In this regard, harvesting operations have undergone changes in productivity, quality of assortments, humanization of forest work, and environmental impact and costs. Since the financial contribution of harvesting at the overall forest operation costs is relatively high, the planning and selection of an adequate harvesting system is one of the most important decisions that have to be taken when managing forests. The innumerous options and technical solutions available today make decision taking to a difficult task for highly qualified personnel (Machado and Lopes 2008). Even so, in the last decades some standard harvesting systems have been developed that fit best with the idea of sustainability and also offer an acceptable cost-benefit solution for forest managers. Individual adoptions of the basic systems considering technical, local, legal, social, and environmental restrictions of some regions in the world are performed frequently.

Selection Criteria for the Harvesting System

A harvesting system consists of an interaction of several elements and activities starting from the felling up to providing the assortment for loading at the forest road. The system itself is integrated in the forest-wood chain of the forest industry and determined by the needs of the specific processing or converting industrial unit.

A harvesting system is defined by integrated activities, which allow a continuous flow of wood from the standing tree to a landing zone where processed wood is piled, leading to an optimized use of the techniques, technologies, and equipment applied.

The main activities found in harvesting systems are as follows:

- Felling (cutting of the tree)
- Processing (debarking, delimbing, sectioning, or chipping)
- Wood extraction (skidding, forwarding, cable systems)
- Loading

The activities may present variation in their sequence according to the harvesting system chosen. There has to be a considered degree of mechanization, availability, and qualification of labor and the equipment used. The only exception is the felling process, which always is on first place. These factors may have influence and may be considered when planning a harvesting operation and take the decision about what harvesting system to use.

Considerations for Planning and Selecting Harvesting Systems

Decisions concerning the system to be used for harvesting operations have to be based on careful planning and cost calculation, including operational costs, productivity, utilization of the wood and, other factors of influence or restrictions (FAO 2007). Possible factors of influence are presented and discussed in the following subchapters.

Environmental Considerations

The environmental factors are a combination of several issues to consider before selecting an appropriated harvesting system. They may lead to high additional costs and have to be seen from a long-term point of view. Areas, relief, topography, soil type, special habitats, waterbodies, and climate may be important elements when choosing a harvesting system.

Harvesting operations in general show not only a "visual" impact on the environment but also may lead to severe damages of the ecosystem. The operations affect water, fauna, flora, soils, and other resources according to the utilization standards defined in the forest management plans. Mainly the felling and transport of wood in the stands (off-road) as on the forest and public roads are of direct impact on environment and have to be carefully planned.

The principles of reduced impact logging (RIL) were developed exactly for this purpose and adapted for tropical conditions (Lagan et al. 2007). In most countries, these principles today can be found in local legislation and also implemented in modern certification processes. The operational restrictions linked to the RIL make harvesting expensive and have to be considered carefully in the planning process to meet with the economic sustainability of the forest management activities. Soil erosion, soil compaction, sedimentation in rivers and lakes, water temperature, and chemical pollution are only part of the manifold negative impacts that may be linked to harvest operations and which can be avoided by careful harvesting planning.

Soil Erosion

Before and during harvesting operations, the soil of the area is partially exposed by road construction, landing zones, skidding trails, and the removal of trees. The impact of tropical rainfall and wind on exposed soil can lead to severe erosion problems, where part of the soil is displaced according to the external forces and gravity acting on the particles. The negative impact can be reduced by careful planning of the harvesting operations and technologies used. A crucial point is construction of access roads and landing zones. Location, size, surface sealing, inclination, and water draining may be considered to reduce erosion. The selection of harvesting systems, wheel-or track-based machines, location of the skidding trails, and skidding performance of operations have to be checked for reducing negative impact.

Depending on the climate, considering the season may also be an important restriction, as it is already stated in forest legislation and certification rules of many tropical countries. At least also the post-harvest activities have to be planned. Replanting of sensitive zones and closing of roads with water bars are only a few options that are available to reduce erosion.

Protection of Waterbodies

Closely linked to the erosion problems of harvesting operations are the negative environmental impacts of forest management on waterbodies. Streams, rivers, and lakes are often a source of drinking water, are used for transport or irrigation, and may serve as a source for industrial cooling processes. Beside this, they are essential for nature conservation, especially to wildlife. One of the main concerns of harvesting planning therefore should be waterbody protection to avoid negative impact on environment and high costs for erosion recovery. In local and regional legislation and many certification rules, the issue is taken into account with rigorous restriction for forest management nearby rivers, lakes, and water reservoirs.

The most important issues for defining the restrictions are as follows:

- Soil type and slope of the terrain (erosion risk)
- Local communities living at and from the waterbodies
- Climate, specifically intensity and yearly distribution of rainfall
- Specific use of the waterbody, like function as water reservoir, fluvial transport, or irrigation in agriculture

These factors decide the protection intensity and size of the buffer zones around waterbodies that have to be respected as well as if they are excluded from any kind of forest management or road construction. Bridges, landing zones, haven, or access roads to rivers need special permissions and have to be built according to rules of lowest impact after newest technical rules.

Keeping a minimum distance from the waterbodies in general already solve a lot of the problems related to erosion and sedimentation. Additional measures that may be taken are careful selection of road location, no skidding trails close to rivers, as well as uphill felling and skidding. Again the season of the year where harvesting operations take place have to be carefully planned, avoiding months of high precipitation. Respecting the buffer zones also solve the risk of water pollution by chemicals like machine and hydraulic oils, cooling liquid, or fuel.

Soil Compaction

Depending on the felling and skidding operations planned for a specific harvesting project, soil compaction may occur in a more or less intensive way. Wheel- and track-based machines may cause compaction of the soil structure, leading to less porosity and reducing water and gas exchange of the soil with the environment. Higher water runoff, reduced tree growth because of disturbed root development, and difficulties in natural regeneration may be a consequence.

The negative impact may be reduced if the harvesting system is planned according to the climatic and edaphic conditions. Track crawlers show less compaction than wheel-based machines, dry soils compact less than humid ones, and also there is the option use cable winches to push the logs or trees out of the stand. Also the layout of skidding trails considering sensitive zones already in the operational planning may reduce negative impact of harvesting operations.

Wood Utilization

The waste of natural resources is commonly agreed as not acceptable in any kind of production process. Harvesting residues have to be regarded as very critical in relation to this aspect, because from the total harvested volume a high proportion of biomass remains in the forest. In tropical forests the volume of a single felled tree in general is very high. Crown slash, high stumps, forgotten logs, and unwanted felling increase the volume of not used biomass, showing a very low recovery between felled biomass and commercial volume. Harvesting planning can reduce the volume of wasted wood and increase the economic return in a significant way.

In conventional logging systems, staff responsible for felling operation are not trained to reduce negative environmental impact or wood waste. High stumps, damages, and losses during felling by poor felling techniques are prevalent. Lianas linking tree crowns and leading to unwanted by-fellings today are cut during the preharvest inventory and do reduce unwanted by-felling substantially. The felled trees often are not found or forgotten due to poor coordination between the felling and skidding teams. Many hollow trees, already rotten inside, are equally felled, without any merchantable wood, but having high ecologic value. New inventory methods and modern equipment like GPS and Geographical Information Systems allow a much more efficient planning of all processes linked with harvesting, which allow to improve the utilization of the wood harvested (Hawthorne et al. 2011).

Legal and Administrative Aspects

Legislation of a country, region, or even municipality may have direct influence on the selection of the harvesting system. The labor legislation of a country can determine the use of certain protection equipment, training standards of forest workers or machine operators, and even the use of technologies in the forest. In Brazil, for instance, the trend is going more and more in direction of fully mechanized systems because of concerns about health, safety, and ergonomic aspects of the labor union representing the forest workers (Gerasimov and Sokolov 2014). The powerful institutions in close link with the government are drivers toward a change in the labor conditions for forest workers, resulting in a higher degree of mechanization. The increasing labor costs, specifically in tropical countries, are also drivers toward mechanization of forest operations. Anyhow, investment costs for machines are high and have to be planned at least for the life cycle of the machines to be used in harvesting operations.

Environmental laws restricting the utilization of native and planted tropical forests are also quite common nowadays in many tropical countries. To protect the environment and meet with the demand of society to the forest, the legal restrictions increase the costs too, also because of increasing fees and taxes on the production of wood in all type of forests. Administrative aspects are also important to be considered in the selection of adequate harvesting systems. Wood harvesting requires short- and middle-term planning on an operational level, with planning, execution, and supervising staff. The personnel have to be trained and instructed to cope with their tasks and duties in an efficient and productive way. The planning of labor force is a middle-term commitment, specifically for machine operators that reach their full capacity only after 3–6 months of training and operating practice, which should be considered when purchasing additional machines for harvesting operations.

Economic Aspects

For the selection of the harvesting system, the investment costs and the related productivity are determining the economic success of the harvesting operations (Seixas and Camilo 2008). Staff necessary and productivity of processing steps have to be oriented on the wood demand of the wood industry. The volume to be delivered on a daily basis has to be calculated, harvested, and transported in a continuous way, and the system has to be designed for that purpose, including the operational efficiency of the different processing steps. The investment costs, depreciation, fuel consumption, operators, and maintenance costs have to be included in the overall calculations and put versus the productivity of the system, getting this way the cost per unit of wood produced (Junior and Seixas 2006).

Operational Aspects

The operational aspects are based on the single processing steps that have to be performed to deliver a given assortment for further processing in the wood industry. Costs for fuel, training level of staff, operational efficiency, and others are short-term factors influencing the decision. Of more medium-term influence for decision taking is the float of machines, logistics, forest road system, wood utilization, and assortments.

In addition, the forest type to be harvested is also playing an important role in decision taking. Tree species, heterogeneity of structure, quality of the trees, individual tree volume, potential assortments, and other factors are making part of the selection process of the best harvesting system (FAO 2001a).

For the single processing steps, the following parameters have to be taken into account:

Felling:

- Topography
- Speed and direction of the wind
- Sequence of the areas selected for felling

- Felling direction
- Wood volume of the individual trees as well as for total harvesting
- Pre-concentration of the wood in the stand (piles, single stems, bundles)
- Soil capacity against compaction or deformation
- Security distance to machines and persons
- Optimized pre-concentration of felled trees or processed wood for further transport

Wood extraction:

- Direction of extraction
- Capacity of machines or systems for skidding, forwarding, or hauling
- Topography
- Availability of volumes per harvesting unit/area
- Soil bearing load capacity
- Distance of hauling

Processing:

- Topography
- Pre-concentration of trees or wood in the stand or at forest road and/or landing zones
- Availability and concentration of crown slash
- Soil bearing load capacity
- Characteristics of the location selected for processing; pre-concentration, available space, distance to loading place
- Distance to other machines or persons working in the system

Impact of Silvicultural Management on Harvesting Systems

Forest management implies an active intervention in a forest, to conduct wood production in a direction where qualitative or quantitative objectives differ from the natural development of the trees. It might be of interest to modify species composition, wood quality, diameter and number of the trees, or rotation cycles, among others. The definition of the management activities have direct impact on the intermediate and final harvesting operations conducted to reach the production goals (FAO 2001b). Each system has some advantages and disadvantages; others are even forbidden or restricted by law. This is the case for the management of forests in many tropical countries. Especially, the native forests underlie severe restriction concerning the management and harvesting operations applied. Some of them are restricted by local legislation, others by voluntary participation in certification processes.

The decision, which components to use in a harvesting system, depends on many factors. One possibility to classify the systems is after the silvicultural management is applied that also determines the intermediate and final harvesting method (Bantel 2010). The most practiced examples are:

- Clear-cut
  - Leaving crown slash and other residues on the site
  - With utilization of residues
- Selective logging
- Thinning
  - Systematic
  - Selective
- Patch and strip harvesting
- Seed tree and shelterwood systems

While in plantations the clear-cut systems are predominant, in planted forests managed for sawlogs also intermediate harvestings by thinnings, the reduced impact logging systems in native forests are based on selective logging (Hartsough 1997). The main objective in such systems is to maintain a permanent forest cover, reducing negative environmental impact. Shelterwood systems and patch and strip management are found in tropical forests enriched by humans, which are more intensively managed than the systems merely based upon exploitation of primary forests.

Clear-Cut Systems

Clear-cutting, as the name already indicates, removes all standing trees in a given area. In some forest ecosystems, forest managers claim to “simulate” the natural regeneration process of such forests, much like a wildfire, hurricanes, or other natural disturbance would do. This is rarely the case in native tropical forests, specifically in the humid tropics. Therefore the application of clear-cut in tropical regions should be limited to intensively managed planted forests or where a change in land use is pretended. The species used in forest plantations managed in clear-cut systems should support full sunlight to grow, like it is the character of many pioneer species like pines, poplars, or even eucalypts. Clear-cuts are an efficient way to convert unproductive stands to productive forests because they allow forest managers to control the tree species that grow on the site through natural or artificial regeneration.

Clear-cutting removes all canopy cover and may cause environmental problems for a given period of time. Directly after harvesting, the soil is unprotected and exposed to wind and water erosion. The changes in habitat for wildlife and other organisms are extreme; in some cases it may lead to extinction of species. On the other hand, combined with corridors of native forests, plantations managed in clear-cut regime may offer an edge effect of both habitats, where generally the number and frequency of insects and bird species are much higher than in pure native forest habitats. In mechanized systems, very common in forest plantations, also heavy machines operate all over the area and may cause soil compaction. The high extraction of biomass makes it necessary to replace nutrients by artificial fertilizers and to prepare the soils for the next rotations with planted trees with ripping and plowing.

Fig. 1 Clear-cut harvesting system in a planted pine forest (*left*) and eucalypt plantation (*right*) (Source: Gustavo Castro and Leif Nutto)

Clear-cuts in forest plantations from a harvesting point of view allow a high degree of mechanization and extremely high productive operations, able to deliver high volumes of homogeneous assortments (Fig. 1).

Thinning Operations

Thinnings are intermediate interventions during a rotation cycle in planted or permanent forests, to influence tree growth and quality by regulation of inner-tree competition. Thinning means a partial harvesting operation with the objective to promote growth of the remaining trees. That makes harvesting complicated, because the objective is not to damage the remaining stands by felling, processing, or wood extracting operations.

According to the production goal, two types of thinning, selective and systematic, are applied. Systematic thinning is used in very homogeneous forest just to reduce competition by eliminating a given number of trees. It is possible to cut complete lines of trees or a fixed number of trees in a line. Systematic thinning is easier to plan and execute. Operators of chainsaws or machines do not have to be trained in case of cutting complete tree lines, and the operation can easily be mechanized. The productivity in felling and processing operations is not as high as in clear-cut system, because the quality of the remaining trees requires careful working. Directional felling is important for not to damage tree crowns of future crop trees, and the processing should also be performed without damaging the bark or root collars of the remaining stand (Schardt et al. 2007). Wood extraction operations also should be executed with care to avoid damages and value reduction of the remaining trees.

The operations are even more difficult in selective thinning. In this case, trees of outstanding growth and quality are marked to be future crop trees, and direct competitors are removed. The irregular distribution of the future crop trees reduces the speed of the felling and processing. Also the pre-concentration of the felled and processed wood in general is lower and more distributed in the stand, reducing productivity of the wood extraction. Machine operators and forest workers have to be trained carefully for such operations (Fig. 2).

Fig. 2 Systematic thinning in a pine plantation taking of complete lines of trees (*left*, Gustavo Castro) and a mechanized selective thinning in a eucalypt plantation (*right*, Leif Nutto)

The operation of intermediate harvesting systems is more complex and requires detailed planning of all operational steps. Mechanization has to be evaluated carefully because the gain in productivity as compared to manual and motor-manual operations is not as high as in clear-cut systems (Salmeron 1980). Using machines, the risk of causing damages on the remaining stand is higher, also considering soil compaction and root contusion. The length of the produced assortments is influencing on productivity of the wood extraction system to be used and also on the potential of damages during the manipulation and loading process. The longer the assortments produced, the higher the risk of damages. Extraction of full trees is rather difficult and rarely applied in such systems.

A general trend in forest plantations is toward mechanization, because of high risk of accidents and concerns about ergonomic aspects against manual and motor-manual forest work. For mechanization, spacing and alignment of the planted trees is of decisive importance if a new system can be applied or not. In native tropical forests, thinning operations are rarely performed, and if it is the case, mainly motor-manual systems are applied.

Single-Tree Selection

Single tree selection or target diameter harvesting is one of the most applied silvicultural systems in sustainably managed native tropical forests. The idea is to use the commercial volume of wood that grows in periods of 20–30 years. Since this volume in general is rather low with a value between 1 and 2 m^3/ha/year, the volumes harvested vary between 25 and 40 m^3/ha in one rotation cycle. This volume is concentrated in a few trees of big dimension and of good quality. Usually trees of predefined species that reach a given target diameter are felled. The trees are selected and marked in preharvest inventories, in general with diameters above 60 or 70 cm. In many cases, even bigger diameters of more than 1 m are harvested. The options that can be used for the felling process therefore are very limited, being there no other possibility than the use of chainsaws. Machines that would be able to handle the felling of trees with such diameters are rare and would be very heavy, causing damages on the sensitive soils of tropical forests and the remaining stand.

Since in single-tree selection systems, it is pretended to use natural regeneration; such damages would put in risk the production goals.

The productivity in chainsaw felling in tropical forests is difficult to estimate. Usually, the large volume of the individual trees increases productivity of the felling operations; on the other hand, the necessity of directional felling and the cutting of buttress is very time-consuming. The other processing steps are also performed by the chainsaw operator. For wood extraction, heavy machines have to be used, because of the high weight of the big dimensioned tropical trees (Seixas 2008).

In native tropical forests utilized by communities, the target diameter of the trees to be felled in general is adapted to the technologies available to the people. If chainsaws are used, the felled trees are often cut to lumber with the saws, but the productivity and recovery rate are extremely low.

Shelterwood, Seed Trees, Group Selection, and Other Systems

There exist a variety of other silvicultural management systems in tropical countries, which influence directly on the harvesting systems that might be applied. In *shelterwood* systems, some bigger trees are left distributed all over the area to "protect" the natural regeneration or even the enrichment plantings under the canopy of older trees. The trees are removed when the regeneration has been successfully established. The first harvesting operation is the felling of most of the dominant trees to promote regeneration. In a second step, the shelter trees are removed after a certain period. Both operations are highly delicate because soil disturbance and damages on regeneration should be avoided. The felling, processing, and skidding of the shelter trees are even more complicated to keep the regeneration intact. The forest workers have to be highly experienced and well trained for getting the system working. The *seed tree* system is comparable to the shelterwood, only showing a variation on the number of mature trees left on the area in order to provide seeds for establishment of the regeneration. In this system the function of the remaining trees is different, and in general it work with less trees in the dominant layer. The problems concerning harvesting operations are more or less the same. In the *group selection* system, a number of neighbor trees are selected for felling, creating with this way gaps of different sizes. Depending on the number of trees felled per group, the gaps perform isolated spots without trees in an intact forest, where regeneration can be established. Harvesting operations are easier to plan and conduct under such conditions, but productivity is low while costs for access and transport in general are very high. *Enrichment plantings* can be done as widespread planting of single trees or in stripes or corridors in the native forests. The latter offer more options to plan the harvesting system because also mechanized options are available.

In general, the planning of harvesting, technological options, and the respective productivities and costs are highly influenced by the silvicultural management system applied, which generates a series of limiting factors for the harvesting operation, the productivity that can be reached in the single operational steps and the related costs for a cubic meter of wood delivered in the wood industry.

Harvesting Systems

The restrictions and other factors that may be considered when planning a harvesting operation and the system to use are very complex, as well as the technologies and resources available. Therefore it is often difficult to decide which system fits best under given circumstances. In the following, some often used combinations are presented. The examples are focused on schemes of forest plantation harvesting, but may equally be applied in the respective native forests.

Options of Combination in Harvesting Processes to a Harvesting System

As already mentioned, the main objective of selecting a harvesting system is to find an acceptable balance between environmental, economic, and technical issues.

The environmental concerns mainly are focused on soil degradation like compaction, impacts on water quality, disturbance, or rutting. Also the soil nutrient source is an important matter. In ecosystems depending on organic material, the tree limbs, foliage, and crown slash are crucial. The long-term site productivity has priority, to meet the environmental as well as the economic targets of the wood production. The organic matter left behind after a harvesting operation under some climate conditions may cause a high fire risk, so that it is recommendable to reduce amount of biomass left behind.

Technical restrictions are given by the economic targets of the wood production. Damage to residual trees in thinning and partial cut may put in risk the value of the future crop trees depending on the silvicultural strategy. Stand characteristics and terrain conditions cause restrictions to the technologies that may or may not be used. Skidding distances, landing size and spacing, road systems, and transport means are also factors that have to be considered. At least the equipment availability, logging expertise, and technological assistance in the region where the harvesting operation takes place are of importance. Considering all restrictions, the selection of the most productive and long-term sustainable system has to be performed to meet the economic objectives of the forest management and wood production.

A more or less international classification system established in recent years is based on the length of the wood harvested and processed in the forest. The form of the wood or the length used for wood extraction to the landing zones as well as degree of mechanization in the used system has become part of this classification. The existing systems today can all more or less be integrated in one of the following systems:

- Cut-to-length
- Tree-length
- Full-tree;
- Whole-tree
- Chipping

Some enterprises base their classification system upon technical criteria, but the most used systems on a global level are the full-tree or cut-to-length, no matter if the harvesting takes place in planted or native forests.

With the diverse technical options, human resources, and machines available, the combination of these factors allow a variety of possible harvesting systems. The most common systems applied in native and planted forests today are:

- Chainsaw + skidder + loader
- Chainsaw + mini-skidder + loader
- Chainsaw + winch (skidder) + loader
- Chainsaw + self-loader
- Chainsaw + cable system + processor + loader
- Harvester + forwarder
- Harvester + skidder + slasher or processor head
- Slingshot + forwarder
- Feller buncher + harvester + forwarder
- Feller buncher + slingshot + forwarder
- Feller buncher + skidder + processor + loader
- Feller buncher + skidder + stroke delimber + slasher
- Feller buncher + shovel logger + skidder + processor head + loader
- Feller buncher + skidder + knuckleboom loader
- Feller buncher + skidder + chipper
- Feller buncher + clambunk + processor head or slasher
- Feller buncher + skidder + flail delimber + chipper
- Feller buncher + skidder + flail delimber + slasher
- Feller buncher + skidder + slasher or processor head
- Combo machines (harvester and forwarder in one machine)

As it can be seen from the list above, pure manual or animal-assisted operation has become rare. Also the use of agricultural machines for forest harvesting operations has been reduced in the last decades. These practices are mainly performed by small landowners or communities that produce wood for their own needs. If the destiny of the wood or its products is outside the country, laws or market exigencies do not longer support such systems that rarely can be classified as low-impact logging or sustainable in terms of international standards.

According to Seixas and Camilo (2008), two main aspects have to be considered when selecting the most appropriate harvesting system:

(a) The individual solution for a processing step in a harvesting operation is not always the best option for the overall harvesting system.
    Due to the existing interaction between the single processes in a harvesting system, the gain in productivity of one process step may cause problems in the subsequent one, leading to a disturbance or even an overall fail of the whole production chain. The applied techniques, machines, or human resources in a system have to harmonize with each other to be efficient.

(b) The system has to be evaluated after its total costs.
Not the costs of a single process step of a harvesting system crucial, but the costs of the wood provided loaded on the transport mean. A higher investment in a machine might be justified by the reduced total costs per cubic meter of produced wood.

The trends today in the tropics are clearly toward wood production in planted forests, since the productivity and sustainability in native tropical forests have to be considered as problematic and expensive. Native forests do not offer the quantity and quality of wood that is necessary for the wood industry to make long-term planning and investments in production. Brazil may serve as an example, where more than 70 % of the wood consumed by the industry is produced in planted forests, participating with less than 2 % to the total forest area of the country. This shows the importance of tropical forest plantations at a worldwide level, while sustainable native forest management is losing in importance.

Harvesting systems can consist of several combinations of the different processes shown in the former chapters. Manual, motor-manual, and mechanized working steps may be joined together to perform a productive and economic solution for the given restrictions in the target area (Simões 2008). In planted forests, the trend is toward fully mechanized solutions. This is not only because of the productivity of mechanized systems, but also because of stricter working law and working safety. Manual and motor-manual work in forests is extremely hard, often leading to physical exhaustion, increasing the probability of accidents during work. Under tropical conditions, the problem becomes even worse, since the heat and air humidity cause additional physical stress. The restriction coming from the human labor force, increasing wages worldwide, and the low productivity lead to a shift toward full mechanization of all working processes. A few, highly trained, and skilled operators produce in a safe way with high productivity the raw material needed for wood industry. The example shown in the next chapter is therefore based on mechanized harvesting processes. That does not mean that under other circumstances, like farm forestry or for small communities, the combination of motor-manual options with animal skidding is not the most economic or only viable solution.

Classification of the Harvesting System After the Time of Wood Extraction

The time the wood is remaining in the forest after felling and in some cases also processing, in some cases is used to classify the harvesting system. There might be several reasons to leave the felled trees or the processed wood for some period in the forest before processing or hauling. One of the most important arguments for waiting some time before skidding, forwarding, or hauling the wood is the water content of the felled trees, resulting in additional weight in the off-road and road transport. A “green” tree often contains a high water content of 100 % of the dry weight, losing a high percentage of this water in the first few days. The tree crowns of felled trees also continue with evapotranspiration, sinking this way the water content of the wood. In other cases, it is simply favorable to separate the felling and processing of the trees from the wood extraction process. This may have safety, operational, or organizational reasons and has to be considered in the harvesting planning.

Hot System

The term “hot system” is well known from industrial or logistic processes. All partial activities in the harvesting operation are realized in a short period of time with only small delay between the different process steps, keeping the moisture content of the wood. For some industrial processes, this may be important. For production of thermomechanical pulp, for instance, the higher the water content of the wood, the better works the industrial processing of the wood and the higher is the TMP quality and recovery rate. Other important argument is the fast attack of fungi of some tree species, which influence negatively wood utilization, requiring the use of a hot system to reduce losses in quality.

For a hot system working smoothly, some measures have to be taken:

- Careful planning of the harvesting activities, including maintenance and other periods, machines are out of order.
- Flexible contracts with third parties, if involved.
- Work the maximum as possible with own labor.
- Requires a high degree of mechanization.
- Excellent road system with permanent utilization (even in rainy season).

Cool System

A cool system separates the different process steps of a harvesting operation in time-independent activities. There is no sequence of one or more processes, i.e., there is a time gap between the single working steps of processing and extracting the wood. The difference to the hot system can be seen in the wood piles, felled single trees, or tree bundles in the forest stand. The system is mainly defined by the utilization of the wood, where a reduced moisture content is not influencing negatively in the further processing of the wood. This is the case for chemical pulp, charcoal, reconstituted wood, chemical pulp, or wood for energy. The great advantage of the reduced weight of the dry wood is to increase productivity in hauling and transport operations.

The Main Mechanized Wood Harvesting Systems

Since mechanization is getting more and more important, a schematic presentation of the most commonly used systems may be useful for orientation and decision taking. There are also presented machines frequently used for the different process

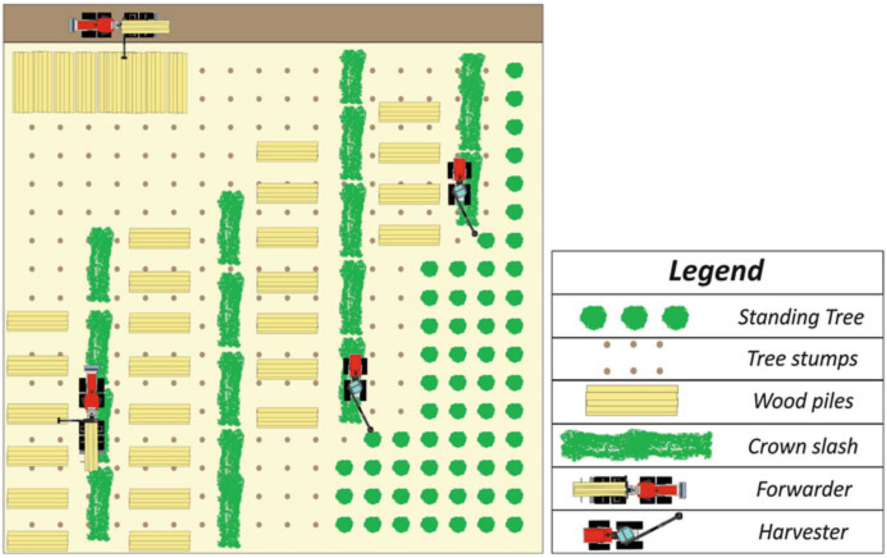

Fig. 3 Scheme of a fully mechanized cut-to-length system in a forest plantation (Source: Gustavo Castro)

steps of the different harvesting operations. Technological innovation is high in the sector, and permanent development and improvement may occur, leading to changes in systems and/or combinations of manual, motor-manual, and mechanized harvesting operations (Nordfjell et al. 2010).

Cut-To-Length

The cut-to length system is characterized by processing the felled tree at the spot where it was growing: felling, delimbing, debarking (where necessary), and sectioning into predetermined length (Bertin 2010). All the activities are performed in the stand. The stems cut the trees' stems in sections of 1–7 m. The final length of the sections depends on the industrial utilization of the wood, the capacity of the applied technologies or machines, and the dimension of the wood extraction system. Manual, animal-assisted, or mechanized systems are able to forward, skid, or haul predefined weights or volumes. Finally the capacity of the transport means, especially length and size of trucks, trains, boats, ships, or if applied size and type of rafts, may perform a limiting factor. A schematic presentation of the system is shown in Fig. 3.

According to Malinovski and Malinovski (1998), the system based on short logs is widely applied because it allows a lower degree of mechanization and more manual, motor-manual, or animal-assisted operation steps. In thinning or selective logging systems, damages on the remaining forest may be lower if the wood to be extracted is shorter. Also the environmental impact may be reduced, especially regarding soil compaction (Malinovski and Malinovski 1998).

Fig. 4 Harvester and forwarder as the main machines used in the cut-to-length system (Source: Gustavo Castro)

For Nurminen et al. (2006), the *cut-to-length* system is environmentally correct, flexible, and safe and allows a uniform high-quality product compared to other systems. After Blinn et al. (2000, apud Leinonen, 2004), the advantages are:

- Adequate for natural regeneration systems.
- Can be used in an efficient way in small forests because the whole system works based on simple working steps that either can be manual, motor-manual, semi-, or fully mechanized.
- Requires less piling space on forest roadside.
- Can be used with several silvicultural systems, also in permanent forests, because trees and stems are processed in the forest, reducing this way damages on the remaining stand.
- Crown slash and residual biomass remains well distributed in the forests. This is positive for nutrient cycling and reduces soil compactions if machines are used.
- No systematic access (skidding trails) have to be created because the corridors for wood extraction can be kept small and narrow.
- If a mechanized system is used, the machines move on a carpet of crown slash produced by the processing unit and reduce soil compaction. This makes the system available for use on sensitive soils (Fig. 4).

The mostly used machines in this system are *harvester*, *forwarder, self-loading tractors,* and *skidders* equipped with *winches* (*piggyback*). It is the most common harvesting system in Scandinavian countries, in any kind of forest plantations, and the main system on a global level. The system is also called s*hort-wood* or *log-length*, but the main term used at an international level is *cut-to-length*.

Full-Tree

This system is based on the harvesting of the full tree, consisting of stem and crown, but without the roots and a tree stump that are left behind in the stand. Further processing in this system is done at the forest roads, intermediate log yards, or landing zones. The first step of the harvesting operation is cutting the tree and felling it. The tree as felled is taken with the crown for further processing to a predefined zone. As a full green tree in general is heavy, at least the skidding operation is mainly based on machines and only rarely be applied in animal-assisted systems. As compared to a cut-to-length system, the processing (delimbing, debarking, and sectioning) is separated from the felling process. In a mechanized system, it requires an additional machine, making planning and harvesting organization more complex, besides requiring a higher initial investment. The system is often applied with bigger-sized trees, requiring specifically designed heavy machinery to perform the harvesting operation (Salmeron 1980; Sessions and Havill 2007; Thees et al. 2011; Wehner 2001). It may be applied in flat as well as steep terrain. After Penna (2009), the system has also been applied successfully in harvesting systems in forest plantations (Fig. 5).

If it is intended to use the biomass of the full tree, including branches and crown parts for bioenergy, the system is highly productive since bark, leaves, branches, and finer parts are available and pre-concentrated just beside the forest road or

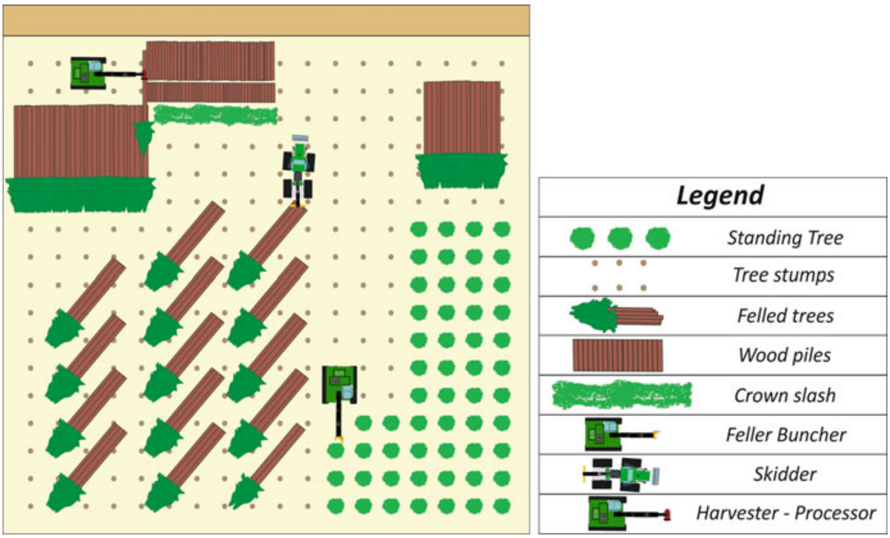

Fig. 5 Scheme of a full-tree harvesting system in a forest plantation (Source: Gustavo Castro)

Fig. 6 Feller buncher (*up, left*), skidder (*up, right*), processor (*down, left*), and log loader (*down, right*) are the main machines used in full-tree systems (Source: Gustavo Castro)

intermediate log yards. On the other hand, the assortments produced from stem wood are also available and nicely separated for loading and transport at the forest road.

The negative aspects of this system are the extreme nutrient extraction, driving with heavy machines all over the area, and the unprotected soil exposed to wind and rainfall. If the biomass is not used for energy generation, it has to be transported back to the stand and be distributed. Extracted nutrients have to be replaced by expensive fertilization. Some of the advantages of the system according to Blinn et al. (2000, apud Leinonen, 2004) are:

- The system can be applied with natural regeneration.
- Efficient use and assortment production of heterogeneous tree species and diameters.
- Can be used in steep terrain.
- Facilitates future planting operations since there is a “clean” area available (Fig. 6).

The machines commonly used in a full-tree harvesting system are:

- *Feller bunchers (for felling)*
- *Skidders*, *clambunk skidders (for skidding)*
- *Stroke delimber*, *knuckleboom loader*, *processor*, *slashers*, *grapple saw*, *and log loaders* (for processing and loading)

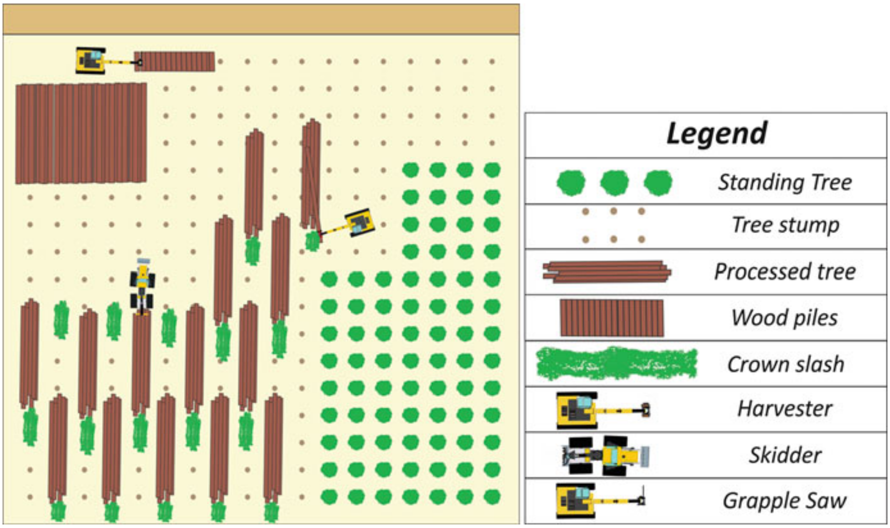

Fig. 7 Scheme of the tree-length harvesting system (Source: Gustavo Castro)

Tree-Length

In this system, the tree is semi-processed (delimbing, topping) at the place where it is felled and taken to the forest road or landing zone in length of over 7 m The sectioning is done in a separate processing step beside forest road or in an intermediate log yard. The system is independent of the relief of the terrain and shows a high flexibility. The origin is located in North America, where about 90 % of all the harvesting operations were performed this way (Machado and Lopes 2008) (Fig. 7).

The scheme in Fig. 5 shows a fully mechanized tree-length system in a forest plantation. The main justification for this harvesting system is the even lower costs per cubic meter of produced wood put in the log yard as compared to the cut-to-length system. The advantages of the system are practically the same as described in the full-tree system, but Blinn et al. (2000, apud Leinonen, 2004) cite some more:

- The crown slash, even being pre-concentrated, remains in the stand near the spots of felling, reducing nutrient extraction and exposing the soil.
- It is highly productive in clear-cut systems.
- It may also be applied in partial cut systems or thinnings, if skidding trails are wide enough.

A disadvantage on the other hand can be seen in the crown slash left on the area which is complicating planting and other silvicultural operations like soil preparation (Fig. 8).

Machines frequently used in such systems are feller buncher, track- and wheel-based harvester, skidders, clambunk skidder, slashers, and grapple saw. Like in the

Fig. 8 Machines used in the tree-length system: feller buncher (**a**), grapple skidder (**b**), and grapple saw (**c**) (Source: Gustavo Castro)

full-tree system, the long assortments produced in the stand are heavy and difficult to manipulate in manual operations or in animal-assisted skidding. In tropical plantation where thin trees are harvested, motor-manual felling and skidding by horses were performed in former times, but today such systems are replaced by machines because of ergonomic and productivity aspects.

Infield Wood Chipping

After Marques (2010), the production of wood chips infield is an alternative for biomass and pulp and band paper industry, regarding best recovery of biomass available per tree. Compared to the traditional systems, the chipping offers some considerable advantages. If harvesting forests with low volume of the individual tree, the system turns out to be more productive. The quality of the chips produced may be

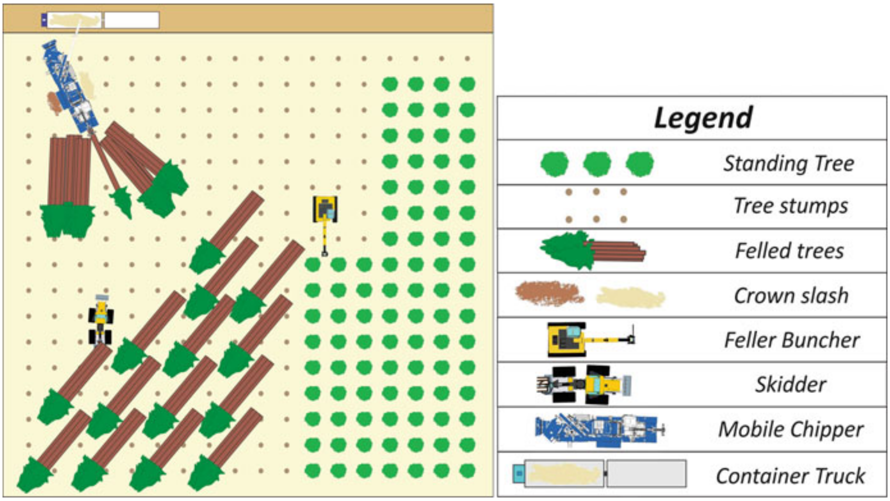

Fig. 9 Scheme of an infield chipping system (Source: Gustavo Castro)

as high as in fix chippers in mill yards, but the mobile chippers offer more flexible strategies concerning the strategic and operational planning of the mill supply.

In this system the trees are felled and extracted to the forest road for further processing. Mobile chipper units are able to delimb, debark, and chip the wood in one operation. For the system working well, the most crucial point is to feed the mobile chippers in a continuous flow, to guarantee the optimal machine efficiency, high productivity, and acceptable costs. Any problem in felling or skidding operation breaks the supply chain and increases costs, specifically of the chipping unit, significantly (Fig. 9).

The investment necessary to mount an infield chipping system is one of the most limiting factors. The chipping process itself can be performed in three different ways:

- **Green chipping:** chipping the full tree including wood, bark, branches, twigs, and litter, recommendable for companies that focus on bioenergy production.
- **Brown chipping:** wood without bark and litter for producing more homogeneous chips for sensitive combustion units for energy production.
- **White chipping:** only stemwood is used for producing chips of high quality, allowing only a very low percentage of bark, branches, and other fine material. The system is mainly used by pulp and paper industry in industrial plantations (Fig. 10).

The machines used in such systems are Feller Buncher (wheel or track based), Skidder, Clambunk Skidder and the Mobile Chipper system according to the chip type intended to be produced.

Fig. 10 Machines frequently used in infield chipping system (white chipping): wheel-based feller buncher (**a**), grapple skidder (**b**), and mobile chipper with delimbing and debarking unit (**c**) (Source: Gustavo Castro)

Whole-Tree

According to Machado (2002), Malinovski and Malinovski (1998), and Pulkki (2006), the system is based on the removal of the whole tree, including the root system. The harvesting system is only recommendable if the roots represent an additional value, covering at least the costs of the removal of the same. This may be the case if the roots contain a high content of valuable extractives or if there is a use as biomass or bioenergy.

The adoption of the system requires favorable topographic, edaphic, and climatic conditions (Machado 1989, after Penna 2009). Up to date, only a few machines adapted to this operation are available at the market. The removal of the tree with the root system requires heavy and powerful machines, being a complicated and difficult operation to coordinate. After Penna (2009), the skidding of whole trees also causes severe damage on the vegetation, natural regeneration, fauna and important soil organisms (Fig. 11).

The machines used in such harvesting systems are mainly track-based hydraulic excavators and tractors with special equipment, wheel-based skidders, shovel logger, processors, and log loaders. The transport of the cutoff root system is not recommendable, since the awkwardly shaped roots require voluminous

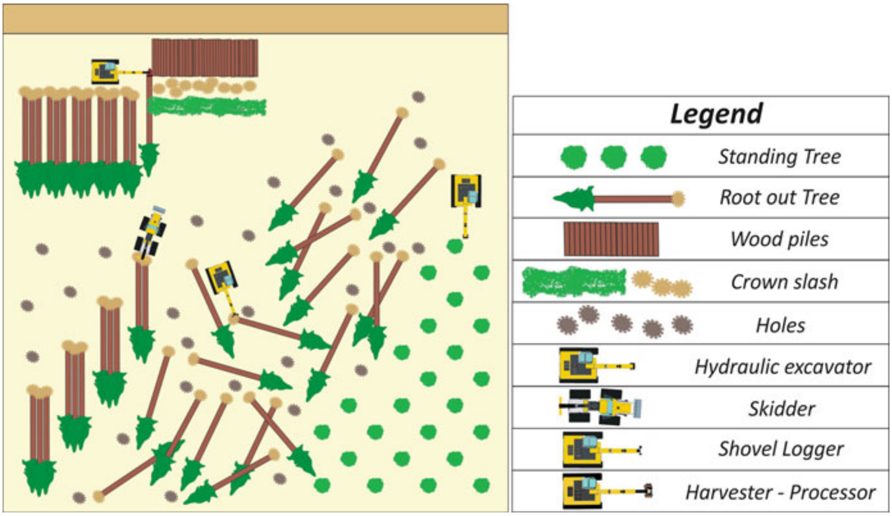

Fig. 11 Scheme of a whole-tree harvesting system (Source: Gustavo Castro)

transport means. To avoid this problem, the system often is completed by a chipper or grinder producing chips for container transport.

Case Studies of Common Harvesting Systems in the Tropics

To show different harvesting systems frequently applied in tropical forests, two case studies about harvesting systems, machine combination, and their productivities and costs are presented for a native forest management and a eucalypt forest plantation.

Case Study 1: Harvesting System in a Native Forest

Today a clear trend to mechanized harvesting operations can be observed. Even so, in native forests, the felling of trees is dominated by motor-manual operations. Powerful chainsaws are used to cut the trees of big dimensions with in general hard tropical wood of elevated density. For extensively managed native forests, trees of big dimension are the most valuable ones. Its utilization is limited to motor saw felling, since the machines that would be able to handle the size and weight of the trees for mechanized felling would be too heavy for low-impact harvesting. Even companies with high investment potential have no other option to the use of chainsaws for felling.

The harvesting system to be presented in case study one is based on a semi-mechanized system in a primary tropical rainforest of the Amazon region.

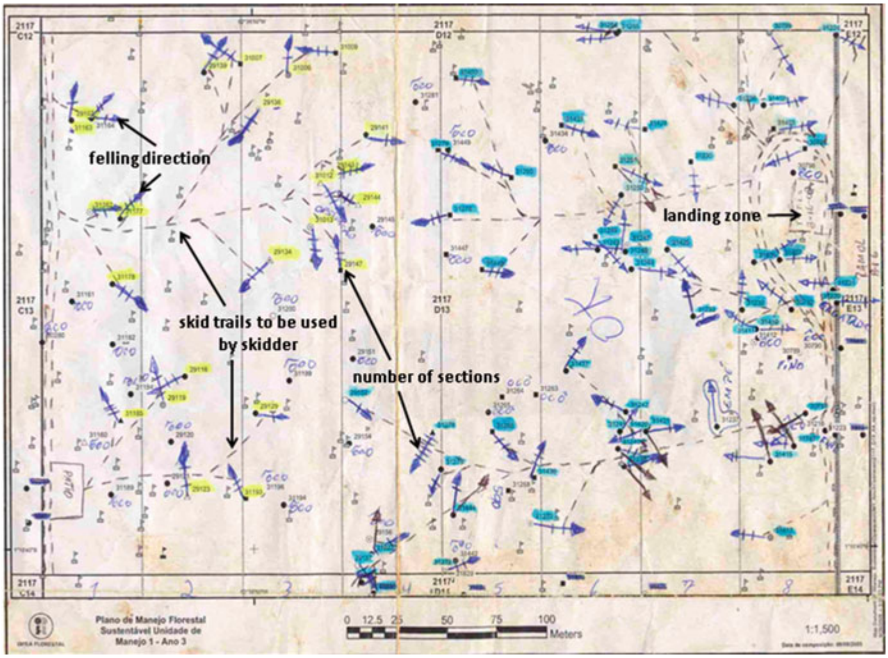

Fig. 12 Detailed operational planning of the harvesting operation (micro-planning) at a detailed level of 10 ha units (Source: the authors)

The overall forest management system practiced by the company is classified as sustainable after the principles of reduced impact logging (RIL) (Putz et al. 2008). The company is certified by the Forest Stewardship Council (FSC).

The harvesting system, based on a single tree selection model, consists of the following operational steps (predefined activities shown in Fig. 12, micro-planning of harvesting):

- Felling: by chainsaw, directed felling in predefined direction.
- Delimbing: by chainsaw, in general the crown is cut off by after reaching the predefined "commercial height" of the stem.
- Sectioning: the log length is predefined after the requirements made by the sawmill and the restriction given by the transportation system. The chainsaw operator is doing the bucking.
- Wood extraction: by four-wheel skidder; in the case study are presented and compared.
  - A system based on a grapple skidder driving on roughly planned skid trails to the trees to avoid unnecessary movements on the productive forest area.
  - A system based on a skidder equipped with a winch, moving on a systematically designed skid-trail system.
- Intermediate log yard manipulation and loading: wheeled front-end log loader.

Fig. 13 Felling of large trees in Brazilian Amazon (Source: Grammel 1995)

In the chapter "Harvesting Planning," the steps for planning a harvest operation in the framework of sustainable forest management are presented. In the following are presented two examples, differing in the skidding process and the productivity between both.

The inventory data and the operational planning allow the harvesting team to operate with high precision in a unit of 10 ha size (400 × 250 m). The terrain is plain to slightly undulated; from a primary road, secondary roads go to the right and the left every 250 m in a systematic way (Fig. 12).

The micro-planning of the 10 ha unit contains detailed information for the felling, skidding, and landing zone staff:

- Species, identification number, and coordinates of the tree
- Diameter of the tree and length of the commercial stem
- Direction of felling
- Number of logs to be crosscut from the stem
- Coordinates of the felled trees, number of logs to skid per tree, skidding trails, and direction to be used
- Location of the landing zone

Based on this information, the trees can be felled causing the lowest damage possible (felling direction), and the assortments are provided in the best way for skidding operations. Before felling, the chainsaw operator checks if the tree is hollow by making a heart cut. A chainsaw operator in the average has a productivity of 4 m^3 per hour in felling and bucking. This value is possible with the high volume of the big-sized trees to be harvested. On the other hand, the productivity in felling is influenced by the problems of directional felling, where in some cases a hydraulic jack has to be applied. The cut-to-length process is easy since the logs remain at least in length of 5 m (Fig. 13).

When the chainsaw operators finished their work (felling, bucking), the maps are passed to the skidding team. The operator of the skidder knows exactly how to get to the felled trees with lowest environmental impact possible (Fig. 14).

Fig. 14 Skidding operation in native forests with help of a grapple skidder (Source Leif Nutto)

The skidding trails to be used by the machine are defined by the engineering crew before the operation starts. The number of stems in the operational map shows the operator how many stems are to skid from a felled tree. The whole skidding operation is planned in a way that reduces the area driven over to a minimum (Seixas et al. 2003). The grapple skidder drives to each felled tree and takes as many logs as possible according to the machine specification. The average skidding distance in the case study is 150 m. The average productivity under these conditions was 29 m^3/h. The operational efficiency of the skidder was 72 %, reaching a final productivity of 20.9 m^3/h, corrected by unproductive times like maintenance, refueling the machine, operator necessities, or defects (Lopes 2007).

A second possibility, with less environmental impact considering soil disturbance and damage to remaining trees, is the use of a winch. A skidder equipped with a winch needs less driving upon the area by designing a specific net of skidding trails, according to the range covered by the cable of the winch. The planning of the winching requires a careful planning of the skidding trails. The distance between the systematic skidding trails have to be designed according to the cable length and the maximum winching distance (Fig. 15).

The winch of a skidder in a tropical native forest has to be equipped with a cable of 18–20 mm to be able to support the heavy loads during the pulling process. The major problem of cables with such diameters is the heavy weight, being the pulling of the rope through the understory of a tropical rainforest a heavy duty. The maximum length for the winch cable therefore has to be set to 50 m. Considering that the trees might be felled in direction of the skidding trails, a maximum distance between to trails of 120 m (2×60 m) seems to be plausible (Fig. 16). To reduce the workload of the winch operators, the spool-out process of the rope can be assisted by a hydraulic tool, making the operator only carry the weight of the cable while and not to pull it out actively. The trees must be felled in the same direction to the skidding trails in a fishbone pattern to reduce the length of skidding distance and damages on the remaining stands. This improves

Fig. 15 Skidder with winch (*left*) and winching process (*right*) (Source: Grammel 1995)

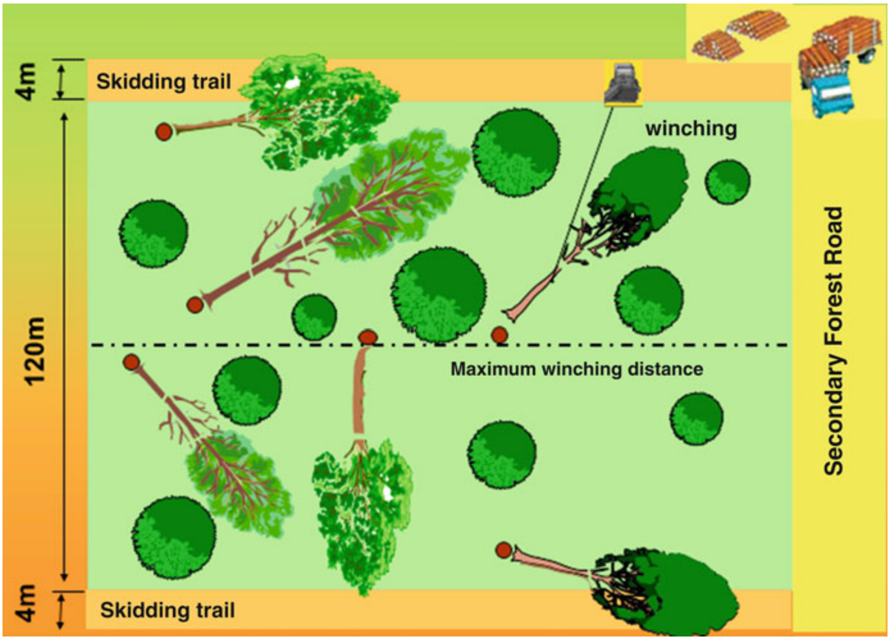

Fig. 16 Scheme of a skidding system using a skidder with winch (Source Leif Nutto)

Fig. 17 Piling of logs at a landing zone beside a secondary road using a wheeled front-end loader (Source: Leif Nutto)

productivity significantly. Crown parts have to be cut and reduced in size in a way to allow skidding through it.

The logs are hauled to the predefined landing zones where they are piled by a wheeled front-end loader for further transport by trucks. This machine shows enough flexibility and speed to work on several landing zones or intermediate log yards, piling the skidded stemwood and loading the trucks (Fig. 17).

The skidding operations in tropical native forests are always a compromise between productivity, i.e., costs and the impact on the sensitive forest ecosystem. To know which system to choose, the advantages and disadvantages of both options have to be carefully evaluated. In Fig. 18 are shown the inventory data and the planned skidding tracks for both systems. At the left is presented a secondary road system (red lines) completed by a systematic skidding trail net (green lines) where the winch-equipped skidder moves during skidding and winching operations. The area is crossed by a primary forest road (gray line) where the logs are being transported to a sawmill. The black dots represent the location of the trees defined by the coordinates measured in the preharvest inventory. At the right side the same area is shown in with a skid trail net for a grapple skidder that has to drive to each felled tree to skid the stems to the landing zone.

A winch-equipped skidder with a systematic skid trail system with distance of 120 m between the lines reaches a productivity of 14 m^3/h. The operational efficiency of the winch skidder is lower with 70 %, because the cable winch requires more maintenance than the grapple of the other skidding system. The operational efficiency therefore is only 9.1 m^3/h, which might be considered as low for a mechanized wood extraction system (Schroeder 2006).

Both systems are valid options, considered as RIL systems and accepted by the FSC (Forest Stewardship Council 2009). But there are significant differences in productivity and environmental impact. In a closer look, a comparison between the area driven over by the skidders, the systematic skidding trails with a distance of 120 between the lines reach about 3.5 % of the total harvested area (Fig. 19). The value increases with reduction of the distance between the lines, reaching 7 % for a

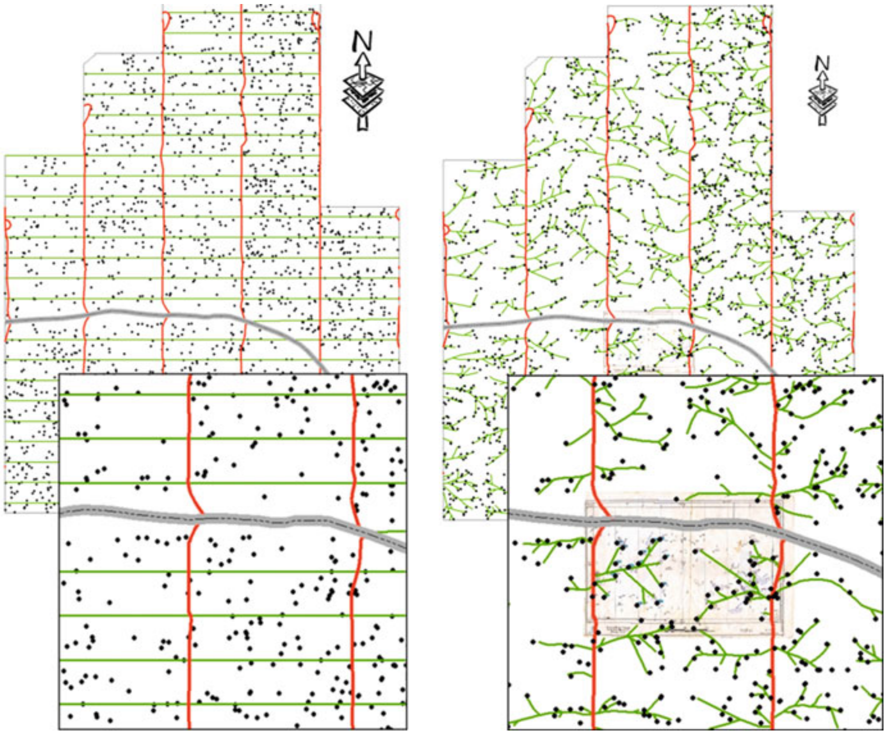

Fig. 18 Design of a systematic skid trail net for a skidder with winch (*left*) and a skidding all over the area with a grapple skidder (*right*). (*gray line* = primary road, *red line* = secondary road, *green lines* = skidding trails) (Source: Schroeder et al. 2007)

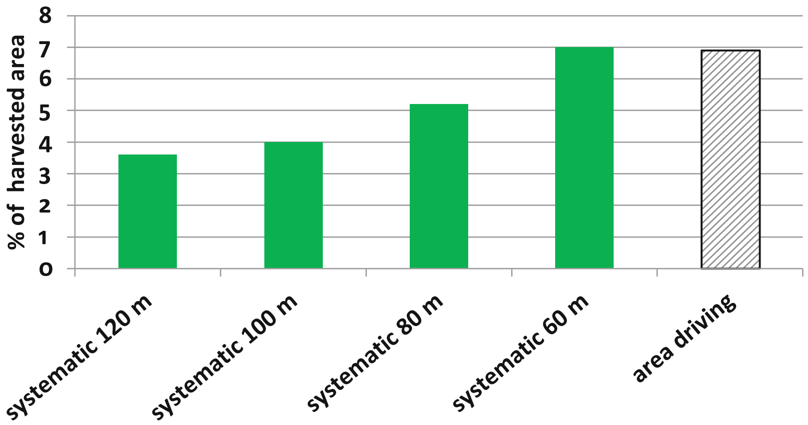

Fig. 19 Percentage of the total area used for skidding in different systems. Average distances from 60 to 120 m between the skidding lines of a winch-equipped skidder compared to area use of the use of a grapple skidder (Source: Schroeder et al. 2007)

Table 1 Comparison of productivity and costs of both systems presented in case study 1

	System 1, grapple skidder		System 2, winch skidder	
	Productivity (m^3/h)	*Costs[a] (US $/$m^3$)*	*Productivity (m^3/h)*	*Costs[a] (US $/$m^3$)*
Felling and bucking (chainsaw)	3	7.41	3	7.41
Skidding	20.9	4.55	9.1	10.45
Loading, piling, and switching between landing zones (mixed calculation)	23	3.49	23	3.49
Cost/m^3 (US$)		**15.45**		**21.35**

[a]Including all costs including maintenance, fuel, depreciation, labor, etc.

distance of 60 m, which corresponds to the average percentage of the grapple skidder system (Schroeder et al. 2007).

In terms of area consumption, a systematic skidding trail system of 100–120 m distance between the lines causes much less soil disturbance than a grapple skidder system, by reducing the unproductive area caused by operational issues by half. Systematic systems have the advantage of concentrating all machine activities to a few and predefined areas. Assuming that an area of 100,000 ha of a native forest is managed, the area affected by the winch skidder system would be 3,500 ha; the grapple skidder reaches close to 7,000 ha, which is a considerable loss of productive area, beside the impact caused by soil compaction.

For decision taking, which harvesting system is the most appropriated one, in general the productivity of the single operational steps and the related costs are crucial for profitability of the harvesting operation (Barreto et al. 1998). In the presented case study, there are no options to the chainsaw felling. For the given natural conditions, the size and weight of the logs and the flexibility needs of the machines, the front-end loader is non-optional too. The only variable option remaining in the harvesting system is the skidding operation, where the comparison of productivity and costs may give additional information to decision taking. The respective values are presented in Table 1, where the skidding system is the driving variable.

For calculating the complete harvesting system, the volume to be harvested has to be defined. Assuming that a sawmill based on tropical hardwoods needs 4,000 m^3 of roundwood a month, the harvesting system has to provide this volume. Working in a one-shift system with 22 working days a month, the system can be mounted based on the productivity data of the single harvesting operations.

A chainsaw operator reaches a productivity of 24 m^3 a day equivalent to 528 m^3/month, about 7.6 or rounded eight persons have to be hired. The front-end loader reaches a monthly productivity of about 4,040 m^3, which is more or less equivalent with the monthly harvesting volume. The difference is found in the skidding options. A grapple skidder reaches a productivity of 3,700 m^3/month, a winch skidder only 1,600 m^3/month.

When using a grapple skidder, the following harvesting system would be recommendable to produce 4,000 m^3/month:

- Eight chainsaw operators
- One grapple skidder, working additional two Saturdays a month to produce 4,000 m^3
- One wheeled front-end loader

Costs per m^3 of loaded wood: 15.45 US$

For the winch skidder with a systematic skidding trail system (distance 120 between lines), the system would be the following:

- Eight chainsaw operators
- 2.5 winch skidders
- One wheeled front-end loader

Costs per m^3 of loaded wood: 21:35 US$

The costs per cubic meter of wood loaded on a truck are 28 % more expensive for the system using a winch-equipped skidder. This is due to the lower productivity of the wood extraction using the winch. The final decision has to be made considering the environmental impact of the system, the sensitivity of the soils, and other possible operational systems (Barros and Uhl 1995).

Case Study 2: Harvesting System in Eucalypt Plantation

Beside the native tropical forests, also the plantations based on mainly exotic species became increasingly important for global wood supply. Due to intensive management, innovation and optimization processes in harvesting systems are more frequent. Compared to the rather extensive management of native tropical forests and the heterogeneous conditions found in such forest ecosystems, the productivity of the applied management and harvesting systems are much higher (Alves and Ferreira 1998).

For case study 2, the harvesting system of a eucalypt plantation managed for pulpwood is presented, including the recent optimization of the operations by changing the combination of the machines (Malinovski et al. 2006). The assortment produced for the pulp mill consists of logs of 6 m length without bark. The wood is only transported between 70 and 100 days after felling, making it possible to work with a “cool system.” The assortment implies the use of a “cut-to-length” system, already presented in the article. A normal cut-to-length system works with a harvester for felling, delimbing, debarking, and sectioning and a forwarder for wood extraction and piling (Thompson 2003). Loading is made with a track-based excavator with a grapple (Oliveira et al. 2009). The productivity of this harvesting system with an average single tree volume of 0.38 m^3 is shown in Table 2.

Table 2 Harvesting system for a cut-to-length assortment of 6 m length without bark

Machine	Productivity (m^3/h)	Operational efficiency (%)	Number of machines (#)	Total productivity (m^3/month)	Machine costs (US$/h)	Costs (US$/$m^3$)
Harvester	27	78	11	100,000	110.33	4.09
Forwarder	43	79	7	100,000	99.82	2.38
Loader	130	82	2	100,000	72.95	0.52
Total			**20**	**100,000**		**6.98**

The harvesting system presented in Table 2 is a module for a monthly production of 100,000 m^3. It works in a three-shift system of 6 h each (18 h a day) at 24 days a month (in average). The machines in the system perform the following working steps:

- Harvester: felling, debarking, delimbing, and cut-to-length
- Forwarder: forwarding and piling at forest roadside
- Loader: loading of trucks

The overall costs of the system are 6.98 US$ per cubic meter of wood loaded for transport on trucks. The productivity of the module is designed to provide 1.2 million m^3 of pulpwood per year.

The company applying the system wanted to verify if there is a possibility to reduce costs and to have some other benefits by changing the harvesting system including a feller buncher for the felling process (Figs. 20 and 21). The new system consists of:

- Feller buncher (felling and bundling felled trees)
- Harvester: delimbing, debarking, and cut-to-length
- Forwarder: forwarding and piling the wood at forest roadside
- Loader: loading trucks

In Table 3 are shown productivity and costs of the modified harvesting system.

The feller buncher shows a high productivity of 140 m^3 per hour in the felling process. The machine is able to bundle between 5 and 8 trees in one process, and this way the felled trees are pre-concentrated for the harvester processing the wood (delimbing, debarking, and cut-to length). Since the trees are pre-concentrated, the productivity of the harvester in this process is higher (Bramucci and Seixas 2002). The same effect can be noted for the forwarder, reducing the driving time in the stand due to higher volume of pre-concentrated wood (Malinovski 2007). The overall costs per cubic meter of wood produced and loaded on a truck are 2.5 % lower in the new system.

As already mentioned, additional gains and benefits were expected from the new system. The feller buncher cut the trees very close to the ground level, leaving stumps of only 5 cm, while harvester heads are more sensitive and cut the trees at a

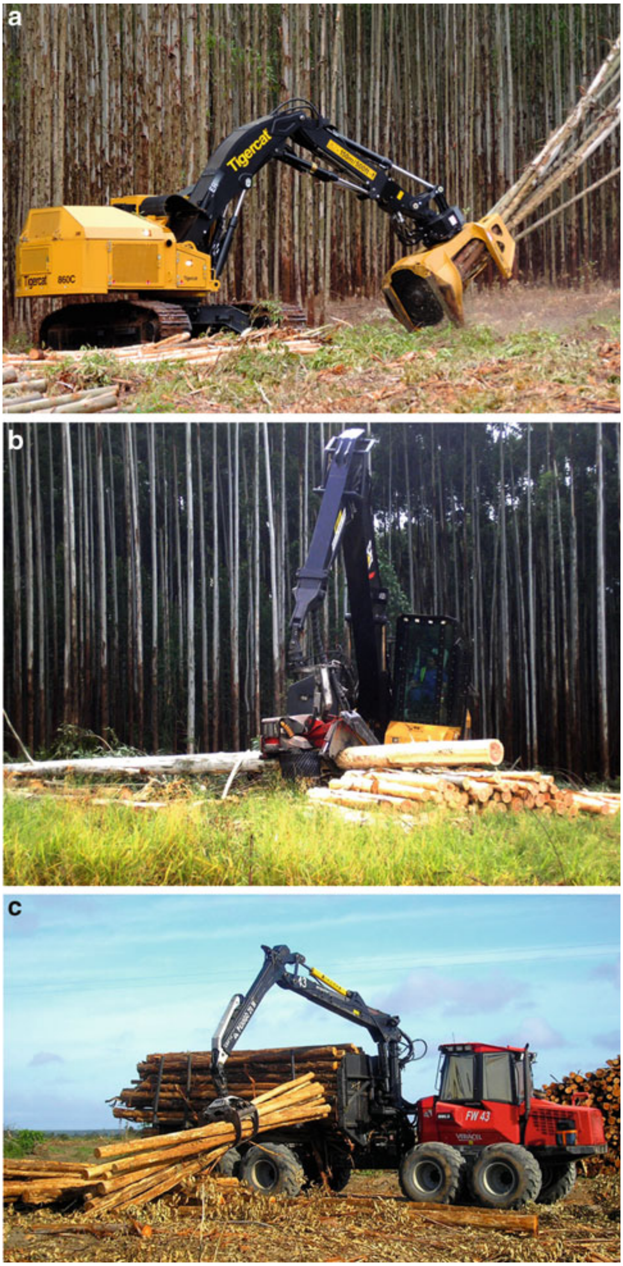

Fig. 20 Cut-to-length system using a feller buncher (**a**), a harvester working as a processor (**b**), and a forwarder for wood extraction (**c**) (Source: Gustavo Castro)

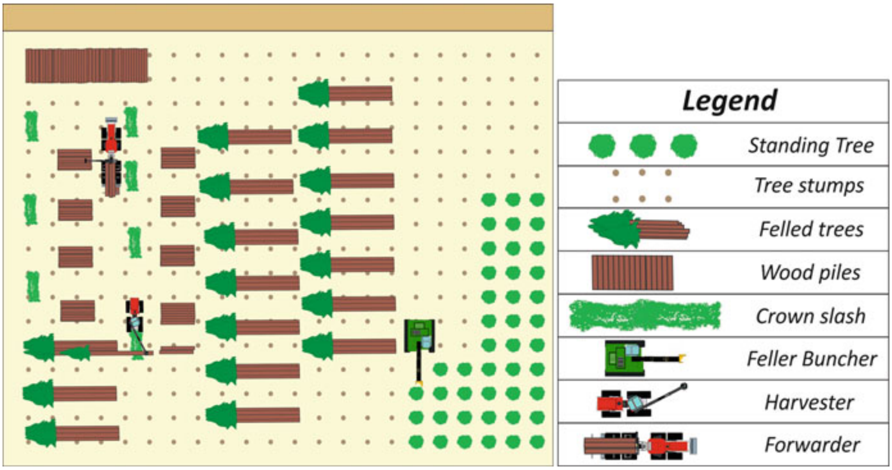

Fig. 21 Scheme of the optimized harvesting system using feller buncher, harvester, and forwarder producing the assortment eucalypt cut-to-length without bark (Source: Gustavo Castro)

Table 3 Harvesting system for a cut-to-length assortment of 6 m length without bark including a feller buncher in the system

Machine	Productivity (m^3/h)	Operational efficiency (%)	Number of machines (#)	Total productivity (m^3/month)	Machine costs (US$/h)	Costs (US$/$m^3$)
Feller	140	83	2	100,000	135.75	0.97
Harvester	35	74	9	100,000	110.33	3.15
Forwarder	46	84	6	100,000	99.82	2.17
Loader	130	82	2	100,000	72.95	0.52
Total			**19**	**100,000**		**6.81**

height between 15 and 20 cm. When replanting the area (not using a coppice system), the tree stumps left behind by the harvester have to be reduced by a milling cutter causing additional costs. The volume harvested by a feller is about 2–3 % higher as compared to a harvester, so an additional gain in wood produced per area unit is obtained.

Another advantage is the use of an automatic spray system for herbicides implemented in the forwarders felling head. If the harvested area is planted with new genetic material, the resprouting of the eucalypt stumps has to be impeded with chemicals. The chain of the hydraulic saw of a harvester head has to be changed every 2 h. If the distribution system of the chemicals is implemented in the head, the operator has to use complete personal protection, including, gloves, overall, and glasses. This is very time-consuming and complicating the change of the chain.

A problem frequently faced with harvesters is the accumulation of biomass and dust at the heads and the machine, causing a high risk of fire when getting in contact with hot machine parts. The head of the feller is protecting the machines much better from slash and litter, and the harvester head used only for processing is accumulating less biomass on machine parts too.

Comparing the two harvesting systems, the merely gain in costs is not so high (Moreira 2004). Assuming a yearly production of 1.2 million cubic meter of pulpwood, the expected benefits of the system including the feller buncher are only about 205,000 US$. For an overall evaluation, also the additional benefits obtained in additional wood volume, less operations necessary in silviculture (stump reduction, application of chemicals), and the improved safety in harvesting operations have to be taken into account. The example presented in case study 2 shows that there are innumerous options of improving already highly productive harvesting systems.

Final Considerations

Harvesting systems are complex and offer innumerous varieties and combination of different options for the different process steps. Because of health and safety reasons, the trend is clearly going toward semi-mechanized and mechanized systems, also in tropical countries (Malinovski 2008). The choice of a harvesting system is depending on the general framework of the forest management, including social, ecological, and economic restrictions which may be of influence for the decision taking. There might be highly developed standards of harvesting systems that are applied nowadays, but this does not mean that there is not always a way to improve the performance of a system or they have non-monetary gains like more safety and less environmental impact. Highly qualified and trained personnel are necessary to keep always the highest level in knowledge about the existing technologies and procedures on the market. Frequent updating and innovative thinking may help to make the best choice in combining a harvesting system that meets all requirements of a modern and highly demanding logging operation (McDonagh 2002).

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