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Recovering Energy Biomass in Conventional Forest Operations: a Review of Integrated Harvesting Systems

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Abstract

Purpose of Review Integrated harvesting (i.e., the combined harvesting of roundwood and residues) has a large potential for replication, since all operations produce residues, which could be turned into a collateral product. For this reason, much work has been produced over the years about the subject, and the current bibliography is abundant, fragmented, and occasionally contradictory. The goal of this paper was to analyze both recent and older fundamental studies about integrated harvesting and extract the essential concepts, which may inform managers as they plan for harvesting roundwood and forest residues together.

Recent Findings The analysis showed that integrated harvesting would generate additional revenue with a little extra effort, provided it is rationally implemented. In particular, residue recovery must be planned in advance to avoid residue dispersal and contamination. Roundwood is generally the main product, and therefore, the characteristics of the main harvesting systems and the value of the additional harvest limit the options for energy wood recovery. The system adopted for collecting forest residues must not incur a higher cost than the value of the energy product and must be compatible with the conditions imposed by the roundwood harvesting operation.

Summary Successful implementation of the integrated harvesting concept requires skillful management of machine interaction, landing space requirement, and residue handling, to minimize cost and avoid product contamination. Residue processing is a crucial step of energy wood harvesting and can be performed with chippers, grinders, or balers, depending on site and market conditions.

Keywords Logging · Residues · Chips · Operations · Efficiency · Productivity

Introduction

The growing bio-economy has created new markets for low-quality wood. This presents new opportunities to further utilize the forest resource and offers additional revenue opportunities to the forest industry and to forest owners. Integrated harvesting of roundwood and residues has represented the most common strategy to match the new market demand as integrated production systems combine production of highly diverse products in the same area [1••]. In forestry, integrated harvesting denotes the coupling of the main harvesting operation aimed at supplying the conventional forest industry with the procurement of additional biomass obtained from forest residues. Thus, integrated harvesting is defined as the harvesting to obtain two families of products, namely: (1) conventional log assortments for structural and industrial use and (2) new biomass products for energy use or biorefining obtained from residues (Fig. 1). This differs from earlier practices that were primarily focussed on

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Fig. 1 Integrated harvesting in a yarder operation: after whole-tree extraction, trees are processed into roundwood (left) and energy wood (tops and branches, to the right)

recovering residues post-harvest, without due consideration for the subsequent product during roundwood harvesting.

Integrated harvesting operations may be single pass or double pass, depending on the system adopted for harvesting conventional assortments [2•]. Single-pass operations are associated with whole-tree harvesting, where the separation of conventional and biomass products takes place at the forest landing, or where whole trees (or tree sections) are loaded onto secondary transport vehicles for subsequent moving to a central processing yard. In this case, conventional assortments and biomass products are moved together to the landing site before trees are delimbed and bucked. Conversely, double-pass operations are defined by the separate extraction of conventional assortments and biomass products, after the trees have been delimbed and bucked [3]. Double-pass operations are generally associated with cut-to-length harvesting, which is defined by tree processing at the stump [4].

A further distinction is described based on the timing of biomass processing and recovery and whether this is concurrent with the harvesting of the conventional product mix, or postponed after the main harvest has been completed and the conventional operation relocated. Each option has its own advantages and disadvantages, especially for what concerns synergy, interference, and landing space requirements [5].

Integrated harvesting can also be defined based on the prevalent product type and whether that is the biomass product or the conventional assortment [6]. With one case, integration will consist in modifying a classic whole-tree chipping operation in order to recover a small harvest of higher value conventional assortments. With the other case, a conventional operation is adapted so that logging residues can be turned into biomass products [7].

In any case, different levels of integration can be identified, with varying degrees of complexity and interdependence. In principle, the higher the integration level, the higher the potential (and the need) for technical and economical optimization, which may possibly lead to increased profit: on the other hand, a high integration level also requires a stronger commitment and a higher risk [8]. With integrated harvesting systems becoming commonplace in many parts of the world [9], and with many studies on integrated harvesting systems completed, the goal of this paper was to analyze both recent and older fundamental studies about integrated harvesting and extract the essential concepts, which may inform managers as they plan for integrated harvesting (Fig. 2).

Residues vs. Residuals

With integrated harvesting, biomass products are obtained from lower value or non-merchantable stand components. Technically speaking, a distinction can be made between residues and residuals: the former represent non-merchantable components of otherwise valuable trees (tops, branches, offcuts etc.), while the latter consist of non-merchantable trees normally cut to waste during conventional harvesting operations [2•].

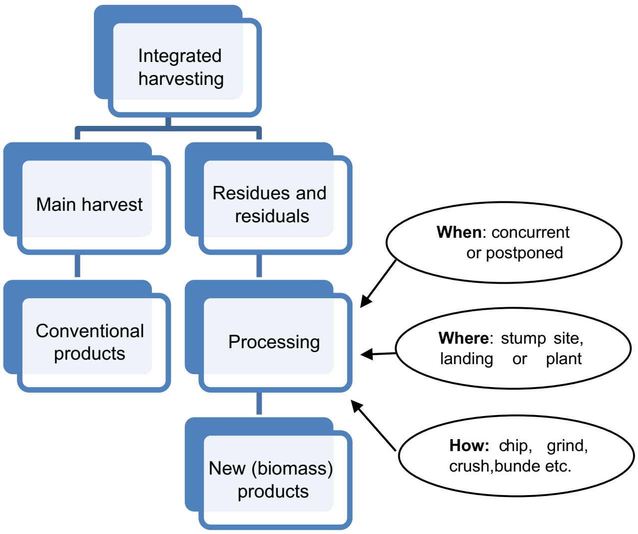

Fig. 2 A conceptual scheme of integrated harvesting

The amount of residues and residuals available after conventional harvesting varies with stand type, silvicultural prescription, local market demands, and harvesting method, among others. Residue loads normally range from 30 to over 200 green tons ha^{-1}, with the lowest figures recorded in low-yielding Mediterranean and boreal forests [10, 11]. Conversely, the highest figures come from high-yielding poplar and pine plantations [12, 13].

The most easily procured fractions of logging residues are stem wood and larger branches, which represent the largest fraction by volume and may account for 30–40% of the residue left on site, regardless of the stand type [13–16]. This is the most attractive fraction of the overall residue resource, because of its better fuel and storing qualities, compared with smaller branches, bark, leaves, and cones [17, 18]. Furthermore, leaves and bark contain the highest concentration of nutrients, and their removal may detract from soil fertility and biodiversity [19]. Complete removal of all residues is technically difficult and financially counterproductive. Skillful operators only collect quality residues within easy reach, because profits are generally too small to justify any further effort to collect small branches and scattered residues [9]. As a result, residue recovery rates are moderate, ranging from 40 to 70% [20, 21, 22••]. For practitioners, a good rule of thumb is that the implementation of integrated harvesting will yield 1 ton of residue stem wood for every 10 tons of conventional assortments, although this ratio is highly variable and may not accurately reflect specific conditions [23].

In fact, stumps also qualify as forest residues and they are recovered in some instances. However, stump recovery has been excluded from this review because it requires very specific technology, it is a relatively localized practice, and it is the object of such a lively controversy that it may deserve a separate paper [1••, 2•].

Reasons for Recovery

In addition to increasing the flow of market products from logging activities, there are two further reasons for recovering residues from conventional harvests: (1) an increased revenue stream for the forest owner or industry and (2) the disposal of logging waste that may hinder subsequent management activities and/or increase the risk for insect or fire outbreaks.

The additional products obtained through integrated harvesting may increase operation profitability, especially when the new harvesting method simplifies tree handling and increases utilization of the equipment on site [24, 25]. Ultimately, integrated harvesting increases value recovery by turning residue into a merchantable product or by upgrading some of the biomass material to high-value conventional assortments [26]. A number of studies indicate that where the price of whole-tree chips is relatively low, it is preferable to try and turn some of the harvests into logs, even when they are eventually used for energy, as load densities during transport would be improved [27–30]. This is true as long as integration does not result in an overly complicated operation, in which case, whole-tree chipping may become a better option [31, 32]. As a result, a detailed analysis about the procurement method to be employed should always be carried out in the planning phase of the operation [25, 33].

The overall benefit of recovering residues is often associated with the avoided cost of logging residue management and the higher utilization of base machines [34]. In many cases, this is a stronger driver than the additional revenue accrued through recovery [35]. Residue recovery is also becoming increasingly important in the light of wildfire management, particularly in Southern Europe and Western North America. It has been estimated that between 2 and 11% of the productive forest land can be lost under residue piles, thick enough to impede effective replanting operations [36, 37]. Furthermore, the implementation of whole-tree harvesting results in the accumulation of residues at the landing site that is problematic in terms of fire, pest, and hydro-geological hazards [38, 39]. Intense rainfall events, likely to increase in frequency due to the effect of climate change, increase the risk for debris flow, which becomes especially damaging to downstream land and infrastructure in the presence of heavy residue loads [40]. Therefore, large residue accumulations may need to be dismantled, at a significant cost for the owners [23]. In the past, the most effective solution was controlled burning, but this practice is being challenged due to air quality concerns [33, 41]. Emission loads in terms of particulate matter can be reduced by combusting the residues within structures such as biomass power plants and mobile air curtain burners, but the use of the latter dedicated equipment has increased burning cost above 10 US dollars t^{-1} [42]. Thus, the biomass market might offer a preferable solution, even under circumstances when residue recovery barely breaks even.

Residue Processing

The recovery of forest biomass generally requires some form of processing aimed at increasing the density and the homogeneity of the feedstock. This is normally obtained through comminution or compaction and unitizing [43].

Comminution is performed by two main types of machines—chippers and grinders. Chippers use sharp tools (knives) to cut or slice the wood, while grinders use blunt tools (hammers) to smash or crush the wood [44]. Based on specific tool characteristics and on the rotational speed of the working mechanisms, grinders can be divided between grinders proper, shredders, and crushers. Chippers and grinders are generally used to process different materials: in particular, grinders are used when dealing with contaminated wood, as their blunt tools are less sensitive to the wearing effect of contaminants [45•]. Grinders are mostly used in large-scale residue recovery operations and they offer a rather coarse product, unsuitable for use in some plants, especially smaller plants or ones with delicate infeed systems [46]. In addition, grinders are often used in combination with an extra loader, which increases the overall costs and adds complexity to the design of the procurement system [33]. In contrast, chippers are more often applied to clean wood and offer a finer and better product [47].

Compaction of raw forests residues into dense units of uniform size and weight is obtained with balers and bundlers. In particular, bundlers produce compacted residue logs (CRLs), with a shape and size resembling conventional wood logs [48]. This allows the complete integration of the supply chains of timber and forest fuels, with significant savings in overhead and fleet management costs [49]. Moreover, compacted residue stores much better than both chips and loose slash, because the solid outer surface of CRLs greatly limits rewetting during storage, especially in case of snowfall [50]. Finally, the possibility of transporting CRLs on the same vehicles used for logs is both convenient and cost-effective. If the bio-energy plants are located along main traffic routes, using general purpose transportation vehicles for biomass delivery favors backhauling, which will significantly reduce transportation cost, especially in the case of long-distance deliveries.

Depending on the system, experts advise that it may be best to process residues as early as possible to accrue the high-density benefit all along the supply chain [51]. Where access conditions are ideal, the biomass can be processed in the stand, in order to increase the efficiency of extraction [52, 53]. For example, direct delivery of pre-processed residue loads to the roadside reduces landing space requirements and facilitates operation in those situations where the forest infrastructure is poor or fragmented [54]. On the other hand, roadside processing generally allows the use of larger and more powerful machines with potentially better performance [55]. The position of the biomass processing stage within the work chain influences the efficiency of the supply system, defines different working methods, and determines the type of biomass that will be transported to the end user [34, 56]. Eventually, operations managers need to balance the advantages and disadvantages of processing the residue at different stages along the supply chain [57]—a complex problem that has often been tackled through modeling, simulation, and logistics planning [58, 59].

In fact, difficult terrain conditions may prevent processing in the stand, and the residue must first be extracted to the roadside and then processed [60]. That is also the case with whole-tree harvesting, which implies moving all residue to the roadside landing. In such instances, one may still need to decide whether to process the residue at the first point of accumulation by the roadside, or move it to a secondary landing that may offer better access conditions to industrial processing equipment and large transportation vehicles [61].

Cost and Revenues

There are different ways of costing the biomass component of an integrated harvesting system [62, 63]. In particular, the marginal cost approach will charge to the biomass component only the specific additional cost of separate handling, whereas all cost incurred when handling it together with the conventional log component is charged to the latter. With this approach, the cost of felling, extraction, and delimbing-bucking in whole-tree harvesting is entirely borne by the conventional assortment, and the cost of biomass production will only include piling, loading, and carting the biomass to the user (or piling, chipping, and carting, if the biomass is chipped at the landing). Conversely, the joint-cost approach is based on distributing all harvesting cost between the two main components, based on their relative proportions of volume or value. Of course, that applies only to those tasks where the two components (i.e., roundwood and biomass) are jointly handled.

The impact of costing method choice is proportional to the abundance of the biomass component, and therefore, costing method choice is especially important when biomass represents a relatively large proportion of the total harvest [63]. Neither of the two methods is preferable to the other, because the principles underlined by both are equally valid: opting for either method mainly depends on the general strategy of the user and on where they want to shift the cost burden. Neither method creates or removes actual costs, as the total combined cost is always the same for both methods. However, under certain conditions, the integrated operations can also lead to lower overall costs in the supply chain—but that is the result of optimization, not of adopting a specific costing method. [33]

Once a costing method has been chosen, costing the production of the biomass product may be relatively simple. Yet, attributing a value to different products may be more difficult, because the market factors that determine price are often beyond the control of the producer. Much depends on the potential users, their distance from the site, and the specifications various users set on their supplies. This is especially true for regions where biomass utilization is still an emerging industry. In well-developed markets, price is often associated with product quality, and the most stringent quality specifications are only met through the skillful processing of certain residue types. It is very unlikely that processing technique alone can offset the limitations of an inherently poor feedstock type [64].

Harvesting System Configurations

The combination of residue type, processing method, and position of the processing stage along the supply chain describes the harvesting system. The many different types of harvestable residues and the wide variety of main operations in variable forest settings make the number of possible system layouts very large. Pottie and Guimier already defined almost 30 individual systems in their review of harvesting and transport systems for harvesting residues and residuals [2•].

The choice of any given system depends on the specific conditions at hand. Some can justify relatively complex chains in view of increased value recovery and operation economy. However, a simple and straightforward process-oriented solution is often the most economical, because each time the biomass is handled, extra cost is incurred. This simple principle has been demonstrated many times in recurrent studies using simple deterministic models [65, 66], as well as more sophisticated and powerful techniques, such as linear programming, discrete event simulation, and stochastic simulation [67–70].

The easiest and cheapest way, when transportation distances are short, is to transport biomass directly to the end user, where the residue is processed into fuel [71]. Some authors suggest to pack whole trees into bundles and to postpone any further sorting and processing until the biomass is delivered to an end user, or to a central processing yard [72, 73]: the cost of processing is generally lower if the operation is conducted at a central site, due to the possibility of using cheaper power in the form of electricity and to scale economy, which is seldom the case with forest landings. The amount of biomass accumulated on site is generally too small for deploying large, expensive, and highly productive equipment [74]. However, this will only work where the log and biomass product have the same, or at least neighboring, destinations. A logical outcome is that an integrated bio-energy plant at a log processing facility is economically most feasible, also because much of the energy generated can be used directly by the facility.

In general, repeated handling of the residues should be minimized to avoid excessive costs [75]. In fact, additional steps can only be included in the process when their contribution to overall efficiency is higher than their additional cost [33]. That is the case of pre-piling landing residues to increase chipper productivity, which may result in a 30% reduction of overall processing cost [36]. Similarly, fuel-adapted cut-to-length operations may offer a significant improvement in fuel quality and a reduction of biomass production cost [20]. On the other hand, margins are very small and most residue recovery operations operate under a delicate balance, where even smaller adaptations can result in a financial loss, rather than an incremental profit [76].

Ultimately, landing residues are likely to be one of the lowest cost options for recovery of additional woody biomass, and they are available in large enough quantities with reasonable quality [9, 77–79]. In fact, the increasingly large demand for biomass products will require the integration of different sources and supplier types at a landscape level, which may justify concurrent use of alternative methods/chains [80].

Global Overview

It is difficult to draw a worldwide overview of all current integrated harvesting solutions adopted across the world, but one can still sketch a rough general picture of the mainstream commercial systems currently used in Europe and North America, where energy biomass has a large and growing market. As a first step, it may be useful to point out what are the main factors that have determined the choice of these solutions in order to understand the origin of the eventual differences. The choice of a specific biomass recovery system is generally determined by (1) the price and the specifications of the biomass, the two things being generally correlated, and (2) the method adopted for harvesting conventional assortments, which is seldom modified for the sake of biomass production.

North America

In North America, whole-tree harvesting is the main harvesting method, and the main customer for the biomass component is represented by large power stations that offer low prices but are relatively liberal with fuel quality specifications. Due to a lack of market for products other than sawlogs or pulplogs, residue piles generally consist of a large component of stem wood. Residues are generally concentrated at a landing, where they are piled into large burn piles and can present various degrees of contamination with dirt, derived from skidding the felled trees to the landing for processing and from the low price offered for the biomass, which does not justify much care during handling. This is especially true for postponed biomass harvesting, when the biomass recovery operation reaches the landing after the main operation has been removed. It follows that the biomass operation often must deal with large conglomerated residue piles that have been bladed to the landing sides into burn piles, in order to free space for the incoming loads. For this reason, North American operators tend to favor large and powerful grinders over chippers, due to their better tolerance for contamination [81].

However, due to evolving markets for new products such as pellets, there has been increasing interest in integrated operations, in order to reduce costs and improve the overall quality of the biomass fuel [33]. Chippers are preferred in concurrent biomass recovery, when the operator has better control on residue handling and can reduce contamination [82]. For plantation thinning operations where the biomass makes up a high proportion of the end product volume, chippers are preferable for the comminution of bunched small trees. Furthermore, chippers can be obtained in smaller sizes than grinders, which is a main asset in concurrent operations, where space is at a premium and material flow is too small for matching the capacity of a large industrial grinder [83].

Northern Europe

Deployment conditions change in Northern Europe, reflecting a wide variety of biomass users. In many regions, medium and large size power and district heating stations still represent the main customer, but generally offer moderate prices. Fuel quality specifications vary, but they are generally tighter than in North America. What is most important is that cut-to-length harvesting is dominant in all the Nordic countries and harvest residues such as tops and branches are left on the cutover. Therefore, residues must be moved to a landing before or after comminution [34]. Today and in the largest majority of cases, residues are moved to a landing in loose uncomminuted form using a forwarder with enlarged loading space [84]. Forwarding is simple and cost-effective and minimizes contamination. In turn, minimal contamination favors the use of powerful drum chippers, which are more productive and fuel-efficient compared with grinders [85]. Another good reason for using chippers instead of grinders is the better quality of the chips, which is generally rewarded by a higher price.

Central and Southern Europe

In Central and Southern Europe, the situation is even more diversified, due to the presence of the widest range of user types: from large power stations to small-scale residential users. The use of biomass fuel is especially common in mountain regions where a colder climate results in a larger demand for heat and justifies the additional investment required by a modern biomass plant. If the cold season is long enough, then the savings accrued when using cheaper biomass fuel (compared with gas or oil) easily offset the higher price of a relatively more complex plant, designed to accept solid biomass fuel, instead of easier-to-handle liquid fossil fuel [86].

Of course, relatively small-scale plants set tighter quality specifications on their biomass fuel, but the cost of displaced fossil fuel is so high that biomass is still competitive when sold at a price between 50 and 80 € per green ton. Such prices often justify considerable efforts towards quality improvement, including extended storage, raw material selection, screening, and even active drying [87].

Furthermore, in the mountain regions of Central and Southern Europe, harvesting is often performed through cable yarding, and residues are only recovered if they come to the landing as part of a whole tree. It is never profitable to cable yard logging residue after stump-site processing. Fortunately, the overwhelming success of mechanized processors based at the landing has caused a decisive shift towards whole-tree harvesting and residues do end up at the landing [88]. Residue accumulated at yarder landings induces a disposal problem, because forest owners generally demand their removal due to the potential negative effects on forest health (e.g., insect infestations) and landscape amenity.

As described above, there is often a local or regional market for wood fuel, and the extraction method usually prevents heavy contamination. Residues are generally comminuted using a drum chipper in a postponed operation, given the small size of most landings. The price for high-quality wood fuel is often good enough to justify chipping low-value conventional assortments, such as pulpwood and low-grade sawlogs [28].

Important Factors to Consider

When setting up an integrated harvesting system, success will depend on how well the operation is planned and managed, and a good understanding of these fundamental principles will be critical to designing the most effective system under any given set of circumstances [33, 89].

Impact on Mainstream Operations

More advanced levels of integration may develop once a strong enough demand has been established for the additional biomass. Such integration may require the adaptation of current harvesting routines, and placing additional demands on the equipment normally used for the main operation may lead to production losses. While that is not always the case, recent studies report productivity losses in the roundwood harvesting operation that range from 10 to over 25% [13, 90]. However, increased utilization of the equipment used for mainstream operations might also reduce the overall cost of the operations [34]. Regardless of the potential effects on operation productivity, biomass recovery will need additional space at the landing and that also represents a new cost [91].

Ultimately, adapting a conventional operation to accommodate a collateral product stream may impact the manufacturing of the main product range, which is generally more valuable than the additional biomass recovered. While the impact could be beneficial and result in an overall productivity increase, an important first step is to carry out a detailed holistic planning analysis of the entire operation to determine and monitor what the potential impacts and cost of an altered system are. Estimating production gains or losses is relatively straightforward, as part of the continuing reporting and follow-up by harvesting managers and contractors. Effects on the performance and the profitability of the main operations should be weighed against the revenues accrued from the additional biomass harvest, and if any additional benefit is accrued from avoiding post-harvest residue disposal (e.g., removing fire hazard), this needs to be factored in.

Interaction

Biomass recovery operations are often characterized by a high level of interdependence. A chipper (or grinder) used for direct loading of trucks will be left idle when no trucks are available. Furthermore, if residues are fed to the chipper (or grinder) as the loads arrive to the landing in a concurrent recovery operation, then the chipper may incur additional waiting delays [92].

The result is low chipper (or grinder) utilization which is one of the largest challenges in an integrated operation. When using chippers, this can be addressed with two main planning strategies, namely: (a) accepting the low utilization levels and utilizing a low-cost pre-owned chipper at the landing for intermittent use, and potentially finding other tasks for the operator when the machine is not in use, or (b) trying to minimize interaction by proper planning and creating appropriate buffers upstream and downstream from the chipper.

An upstream buffer is obtained by letting a large enough pile of residues accumulate before moving the chipper in. Downstream buffers can be obtained in several ways and most typically by the following: discharging chips on the ground and accepting some product losses, estimated at 4–5% [93]; parking a sufficient number of roll-on containers on site before starting the operation [56]; using set-out truck trailers and moving them around with machines available on site [94, 95]; installing proper surge bins on site, which is generally feasible on semi-permanent large sites, only [96, 97].

A radical solution for minimizing interaction delays consists of organizing a postponed recovery operation with stand-alone residue processing techniques or technologies, such as bundlers or chipper trucks equipped with their own interchangeable containers [98, 99]. However, the productivity of these technologies is still small compared with their cost, and their use is justified under special conditions only, for instance, when space constraints prevent resorting to a standard chipper and truck operation [100].

Space Requirements

A residue recovery operation has obvious space requirements, which will change with operation type. Less space is necessary for the collection and removal of loose uncomminuted residues than for chipping the residues into trucks, bins, or heaps. Similarly, a postponed biomass recovery operation installed after the main operation has moved out will have more space available, but this option implies that the landing is large enough for accumulating all the residue when the main operation is in progress or that they are moved to a satellite yard in the immediate vicinities [101]. This might also mean that residues are sitting far away from the roadside where they are out of reach of the chipper or grinder: in that case, handling costs on site will increase significantly because one has to move the residues closer to the comminution equipment, or to deploy expensive all-terrain chippers.

The fresh density of loose forest residues is estimated between 70 and 180 kg m^{-3} [36, 102]. If every ton of conventional product is joined to 100 kg of residues, then the volume of residues associated with 1000 t of conventional product harvest will range from 550 to 1400 m^3. [23]. Assuming that a loader can safely pile residues to a maximum height of 4 m, then the additional space required to store the residues obtained from 1000 t of conventional product harvest will vary between 140 and 360 m^2, or between 20 and 50 linear meters for a pile width of 7 m.

An example could be made by applying these estimates to the average New Zealand landing, which covers ca. 4000 m^2 and processes over 6000 t of conventional log products [101]. If all the residues passing through this landing had to be stacked in 4-m tall piles, then one would need to create an additional space estimated between 900 and over 2000 m^2, with an increment of 20 to 50% over the original landing surface. Therefore, it may be preferable to use off-road trucks for moving the residues to a separate site in the immediate vicinity—possibly an older landing—for storage and later processing [78, 103].

Biomass Quality

When product quality is suitably rewarded, integrated harvesting offers great opportunities for biomass quality improvement. This can be obtained in several ways, by addressing moisture content as well as particle-size distribution and ash content. Here, the first fundamental difference is that moisture and ash content are best managed before chipping occurs, while particle-size distribution is mostly managed during or after chipping—even though managing moisture content before chipping may affect particle distribution as well.

Moisture content reduction will raise the value of any fuels by increasing their effective energy density and improving transportation efficiency at the same time [104, 105]. The simplest way to reduce moisture content is to properly store the uncomminuted biomass until it dries to the desired level. That may require extra efforts in the piling or decking and take several months, depending on the target moisture content and the micro-climate at the storage site [106]. Air drying can be especially slow with solid wood elements, such as offcuts and cull logs, which have a relatively small surface to volume ratio. In this case, drying can be sped up by splitting [107]. This operation also offers the advantage of reducing log diameter to the benefit of smoother chipping and lower chipper wear. Another strategy to improve drying is to cover the material during storage, which has shown benefits both in regard to the drying rate and contamination caused by snow and ice [108].

Particle-size distribution is another fundamental quality attribute for industrial chips. In general, particles must be as even as possible and the product must contain minimum amounts of oversize particles and fines [109]. Furthermore, different users have different preferred size specifications [110]. For instance, many gasification plants require 40-mm long chips to support efficient conversion, whereas small-scale residential heating boilers target chips in the 20-mm length range. Generally speaking, the smaller the plant, the smaller the chip it can accept [111].

Particle-size distribution targets are generally obtained by adjusting chipper settings and selecting suitable raw material. Nevertheless, it is almost impossible to produce a load that contains absolutely no fines and no oversize particles [112]. If customer specifications are very tight, screening is the best solution, and it has already been in use at many European sort yards. Screening can be performed with different equipment, each characterized by specific capabilities and cost. Static sieves are the simplest and consist of a frame and a steel net with the appropriate mesh size. This is also the cheapest solution, but not the most common or effective for wood chip applications. Oscillating screens are available in stationary or mobile versions and are commonly used for removing oversize particles from energy chips [113]. Rotary screens are also available in stationary and mobile versions, and they are especially common at composting plants for separating dirt and fine particles from coarse elements [114]. Finally, star screens are generally mobile and they are relatively new, but increasingly common in large wood chip sort yards [86].

All these screening options consist of stand-alone devices, requiring some working space. A more compact solution for screening consists of vacuum airlift segregation and deflection sorting, which work on the different accelerations achieved by particles with different sizes [115, 116]. These systems were tested in the past to produce bark-free pulp chips from whole trees, and they were discarded because fiber losses became unacceptable when trying to reduce bark content below 5% [117]. However, the specifications for biomass chips are not as strict as those for pulp chips, and research on these older methods might be resumed in the light of the new product needs.

Finally, ash content is minimized by avoiding contamination with dirt, before, during, and after processing [118]. Mixing logging residues with dirt negatively impacts both product quality and production efficiency, because (1) it prevents turning the biomass into a quality product and (2) it makes it necessary to use a less efficient grinder, resulting in a higher production cost [119]. Casual handling of the residues is only justified when the market is not going to reward quality anyway, and work pace is so fast that residues must be hastily pushed to the side, lest they interfere with the main process. Otherwise, the rule number one of residue handling is to avoid contamination: mixing wood with dirt denies profitable recovery, beyond any hopes [111]. Ash content is also reduced by removing bark and foliage, the latter generally obtained by letting the residue dry on the cutover before removal.

Conclusions

While many have an intuitive understanding of integrated harvesting, individual perceptions are often incomplete because the term defines a vast family of forest harvesting methods, with many conceptual and technical variations. As a consequence, successfully integrated harvesting requires intensive planning and preparation at all stages of the supply chain design process.

For the same reason, integrated harvesting has been the subject of many studies, and the core literature used for this review is only the subset of a much larger corpus. Nevertheless, this selection spans over 50 years during which integrated harvesting has been researched and offers valuable information for a representative summary of present knowledge.

While more knowledge is always welcome, convenient use requires that the essentials are logically structured and presented as concisely as possible. That was the goal of this review, which covers all main issues and shows the basic trends. Such information is especially important, because logging residue is the main source of low-quality wood, suitable for conversion into biomass products. While most projections agree on the future important role of small trees and dedicated biomass plantations, logging residues from conventional harvesting operations currently represent the bulk of industrial harvesting of additional biomass, and its role is likely to remain important for many years to come.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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Papers of particular interest, published recently, have been highlighted as:
- • Of importance
- •• Of major importance

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