Te Uru Rākau | New Zealand Forest Service

Advanced Woody Biomass Harvesting Systems

Literature Review

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Executive Summary

Woody biomass provides an exciting opportunity as a renewable energy source. In New Zealand, energy is already being produced from woody biomass residues. That is, the NZ plantation industry has prioritised growing trees for industrial use (i.e. logs, pulpwood), and the residue material used for energy is secondary. While the recovery of residues from current forestry practices presents a low-cost opportunity, the scope and scale of producing renewable energy will remain relatively small compared to plantations established and grown with the priority being the production of woody biomass.

Woody biomass plantations are typically fast growing, short-rotation tree crops. To maximise woody biomass volume, the regimes are characterised by higher stockings that produce a larger number of smaller trees in short time. As such woody biomass plantations present an economic and logistical problem at time of harvest as the well-developed existing systems for plantation harvests are optimised for larger trees. To encourage the further development of woody biomass, investors will require confidence that such crops can be successfully harvested, not only safely and with low environmental impact, but also economically.

New Zealand has a well-developed forest industry that includes professional harvesting of mature plantations at scale. However, experience with harvesting short rotation plantation woody biomass is limited. In contrast, both South America and Europe have experience with such cropping and harvesting regimes. North America has extensive experience with the recovery of woody biomass as their primary output associated with their commercial thinning regimes in their plantations. As such, this report provides a comprehensive literature review that relates harvesting equipment to the needs of biomass harvesting. It not only provides detail on the international state-of-the-art purpose built and designed systems, but it also places into perspective current New Zealand machines and systems with recommendations to consider for specific plantation and agroforestry scenarios.

1 Report Overview

This report provides a comprehensive review of literature to support our knowledge of advanced woody biomass harvesting systems. As some biomass harvesting practices are not yet fully developed in New Zealand, the literature focusses on our current harvesting system capability and how that may be best adapted to the harvest of woody biomass specific crops. It also provides a comprehensive overview of international practices.

Chapter 3 reviews our current harvesting practise in New Zealand and provides an overview of tree crop management and the role of harvesting systems in achieving the goals of the forest owner. An assessment of Māori forest harvesting intentions outlines multiple forestry pathways which will lead to a number of harvesting methods being employed. The reader is then also given an overview of producing a marketable biomass product.

As many other countries have already experimented with or fully adopted woody biomass forestry regimes, and associated harvesting systems, Chapter 4 draws on the authors' experience and knowledge, with a particular focus on the harvest of 'short rotation forestry' as well as 'short rotation coppice' regimes. An international author with substantial New Zealand experience has summarised the lessons that New Zealand operations can learn from these international developments.

To the layperson, 'harvesting' is often synonymous with just tree felling, but the subsequent extraction and processing components are just as critical, enabling the wood fibre to be delivered to transport infrastructure in a saleable form. Chapter 5 steps through the individual elements that make up a harvesting system, as each element needs to be carefully chosen and optimised to a 'biomass specific' system that meets the goals of safety and economic efficiency. Chapter 5 shows how the harvesting systems may be aligned with forest management goals. It recognises that some major changes have occurred in forest harvesting over the last two decades, primarily associated with mechanisation and more recently, various levels of automation.

Chapters 6 and 7 finally pull the information together to step through the drivers for selecting elements of a harvest system using woody biomass-specific harvesting scenarios, then some recommended systems for broad terrain and product categories. In addition to short rotation forestry and short rotation coppice, it also integrates options for agroforestry as well as current plantations. These latter two are seen as significant for the New Zealand biomass market. New biomass plantings can occur on non-forested land where farming is no longer the preferred option. It can also be an opportunity for current plantation owners, understanding that woody biomass is one more regime option to consider amongst an existing market for timber, carbon and also non-timber values (e.g. slope stabilisation on steep pastures).

2 Methods

A classic review of scientific papers, textbooks and technical reports is combined with that of ‘grey-literature’ in the domain of forest harvesting for this report. After reading readily available texts and preliminary discussions with connected experts, a comprehensive search of online repositories was completed. ‘Grey-literature’ refers to published material such as company reports, websites, marketing material, specification documents, video presentations, and/or opinion pieces. Such material can vary from uninformed opinion to robustly peer-reviewed so grey-literature should be interpreted with some caution.

Multiple databases and search engines were used to compile literature, including:

- Scopus
- Ebsco
- Google Scholar
- Forest Growers Research NZ
- ResearchGate
- ScienceDirect
- SpringerLink
- Publications Office of the European Union
- IEA Bioenergy
- Google (incl. Google reverse image search)
- DuckDuckGo

Key search terms used include a combination of, but not limited to: forest, forestry, plantation, woody biomass, slash, chip, hog fuel, short rotation, coppice, harvesting systems, productivity, terrain slope limits, native, selective, multi age-class, Māori, land expectation value, mechanised felling, yarder, feller-buncher, hot saw, emissions, fuel use, steep slope harvesting, shovelling, harwarder, and so on.

The authors also drew on several decades of local and international research experience in forest harvesting. Dr Raffaele Spinelli (co-author) used his extensive experience to summarise major findings from both central Europe as well as South America.

3 Background

3.1 ALIGNING HARVESTING WITH FOREST MANAGEMENT GOALS

The goals of forest management have a dramatic impact on the technical and economic feasibility of biomass harvesting *for a given price offered for the biomass product*. The overarching purpose of managing any one forest in New Zealand may yield responses as diverse as the forest types in Aotearoa's landscape. In recent decades the management decisions for commercial plantations have typically been compared on the Land Expectation Value (LEV) measure, with higher LEV indicating more profitable decisions (Manley, 2023). Figure 1 below from New Zealand Forest Owners Association (NZFOA) modelling shows that currently, actively managed plantation forestry (in general) provides the highest monetary impact on value chains when compared to pastoral farming and carbon forestry and may also be profitably integrated into farms.

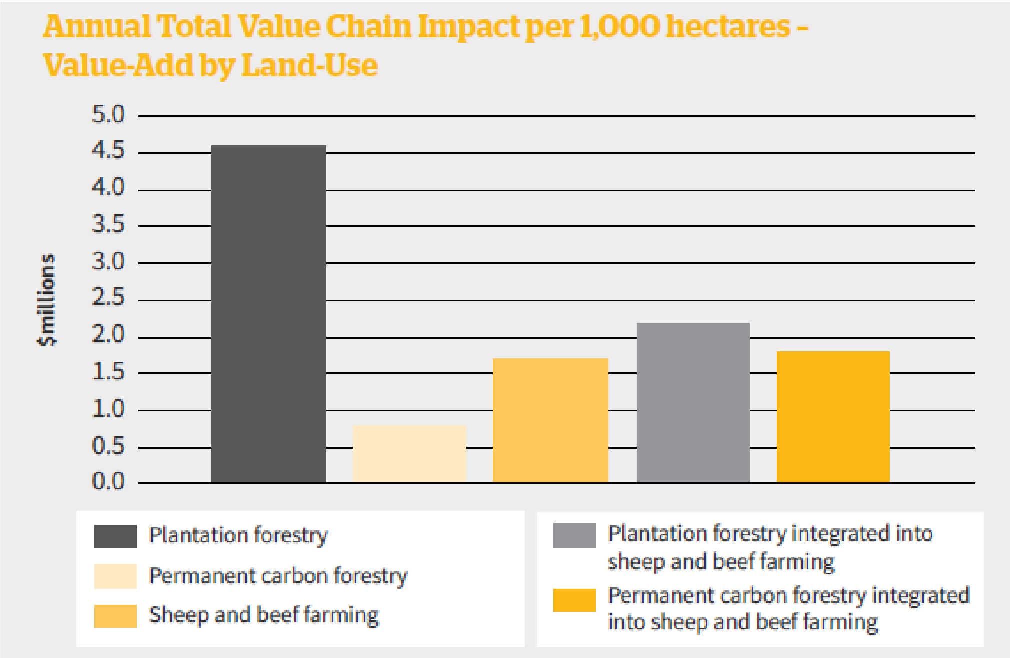

Figure 1: Current land-use 'total value chain impact' divided up into plantation and carbon forestry, with woody biomass not featured, as presented by the NZ Forest Owners Association (NZFOA, 2023).

A commercially-minded landowner is likely to seek an acceptable rate of return on the investment in land and crop, while reasonably mitigating risks (Zinkhan & Cubbage, 2003). Where land use change is possible, this instigates competition with land uses that may yield higher rates of return, particularly for urban-, industrial-, arable- and dairy-capable land. For example, the introduction of carbon markets has profoundly changed many post-1989 forest investments, with returns now being made during the growth of the forest, well before harvesting (Manley et al., 2022) and improving the value of new forest investments. The silviculture and rotation age of timber crops may now be reviewed by the forest owner to reflect this 'new optimum' LEV. At a broad forest management level, the set of options for extracting more from the forest or satisfying 'new' customer demands depends on terrain, log markets, risks to the crop, alignment with carbon goals, timeliness of infrastructure investment and fundamentally, whether it improves the overall return on investment.

Current common silvicultural regimes in New Zealand, 'structural' and 'direct sawlog' (a.k.a. clearwood) focus on creating high value sawlogs and pruned logs, therefore producing only about 0.2m^3 of 'waste' (/residue) per tree (Figure 2) which is the material currently of most relevance to a biomass customer. Notably, the residue is published by the NZFOA as having no value.

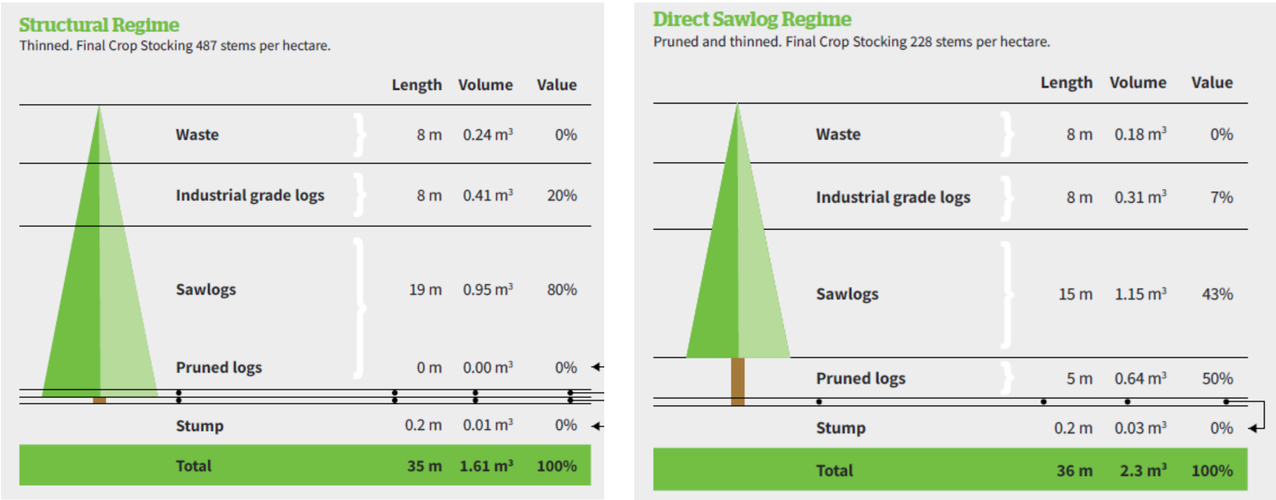

Figure 2: The two most common current forestry regimes, being direct sawlog and structural regimes, show little volume and hence value given to 'waste' (/residues) (NZFOA, 2021).

With little volume available through 'waste' cuts from the stem, low value 'industrial grade' logs (see Figure 2) are the next most promising source of biomass from the existing regimes, with good volumes at next-lowest cost.

A forest owner that is solely a supplier of wood products is in a different position to one that also owns the downstream processes using wood fibre. Structural and direct sawlog regimes, coupled with a competitive domestic and export market for the various log products made from the tree offer the independent forest owner some ability to survey the market before harvest and direct their supply to the highest bidder, at the expense of silviculture costs and harvesting efficiency. An integrated grower *and* user of wood fibre, without an open market view (for the wood fibre) can highly optimise the growth and harvest of the trees for their own needs, without concern for 'hedging' (compromising) or remaining open to the sale of alternative products. The market positions of each of these types of forest owner are quite different, and therefore their respective views of market risk will be different, and therefore the tree crop and harvesting decisions will also differ. This point will be reflected on throughout this report.

Different plantation forestry options (species & regime) that do not fit the 'traditional' timber production goals that New Zealand commercial forest owners and managers are familiar with have been extensively reviewed in New Zealand. Short rotation forestry, trees – typically *pinus spp.* & *eucalyptus spp.* – planted at high stockings and harvested at young(er) ages can satisfy a biomass market opportunity (Jones et al., 2022) that retains an ability to hedge; adjusting silviculture practise and ultimately diverting products to other markets if the biomass/bioenergy demand fails to deliver confidence in returns.

Short rotation coppice, where rootstock is replaced only every few rotations (Dimitriou & Rutz, 2015; Sims et al., 2001) has been investigated locally, however typically uses species with little value beyond markets for comminuted or energy wood material. Intensive management of indigenous species and continuous cover regimes for both exotic and indigenous species have also been well explored from technical and economic standpoints (Bown & Watt, 2024; Pizzirani et al., 2019; Salekin et al., 2024; Watt & Kimberley, 2023). Agroforestry, widely spaced or strategically placed trees over pastures, has seen significant research investment, and also uptake by the pastoral farming sector (Mackay-Smith et al., 2021).

New Zealand’s current harvesting systems in aligning with the goals of plantation forest owners share many similarities with systems operating in the Pacific Northwest of North America. This is likely the result of similar terrains, tree dimensions and a cross-pollination of harvesting knowledge between the regions. A strong focus on efficient timber production has been maintained since the era of privatisation in New Zealand. In recent years, efficient production and worker safety goals have coalesced, with fully mechanised harvesting operations now ‘the New Zealand standard’. New Zealand has extensively adopted mechanisation for ground-based operations, and for steep slope operations is internationally recognised as being a leader in the development of high production, fully mechanised cable logging systems (Harrill et al., 2019).

3.2 MAKING BETTER USE OF HARVEST RESIDUES

New Zealand clearfell harvesting systems are well optimised to handle trees in whole- or log-form, and are relatively inefficient by comparison at handling the smaller by-products (Visser, Spinelli, et al., 2010). Regardless of productivity losses, where there is agreed reward for the handling of the material, as allowed by a local market for the product(s), loggers can segregate the more desirable large woody biomass from the branches and slovens at the landing. There are examples of low-value material segregation for biomass or bioenergy in most regions of New Zealand, from small scale firewood collection for home heating to large scale supply to energy intensive factories. Where no markets exist, the piles of waste biomass from log processing are accumulated and allowed to decompose.

Targeted extraction of woody residues from the cutover for sale as a biomass product is rarely undertaken. The conditions for a successful (profitable) operation preclude most New Zealand forests from this. There are however some local specialists in the work. For success, there should be a combination of:

1. Minimal topographical challenges,
2. Quality roading infrastructure,
3. Short distance to customer,
4. Acceptable market demand/price offered,
5. Sufficient volumes of large woody biomass on the cutover, near to the roading infrastructure,
6. Efficient machine operators; and,
7. Low costs of owning and operating the machinery.

Post-harvest cutover residue extraction is rarely profitable as it is uncommon to be able to satisfy enough of these constraints. There are however regulatory drivers for retrieving woody debris >2 m long and >10 cm in diameter at the large end from erosion-prone cutovers. This is best achieved currently during the clearfell harvest, and not as a separate and dedicated operation. With the legislative change only relatively recent, it is not yet clear whether a substantial market has or is developing to make use of the newly accumulated material.

3.3 MĀORI AND FOREST HARVESTING INTENTIONS

Māori forest management intentions are diverse, reflecting the various forest types, terrains, economic drivers of tangata whenua, and also relationships with the whenua across Aotearoa. *Nga Pou a Tane | the National Māori Forestry Association* put forth a collective vision of significantly developing Māori forestry and forest value chain business interests through to 2040, while also giving space and capability to nurture te reo and tikanga through iwi-led kaitiakitanga (Ngā Pou a Tāne, 2024). Miller et al. (2005) provide an overview of the changing nature of Māori-owned forest lands, and the strengthening position of Māori ownership in production forestry. They however note that, compared to indigenous forests, the exotic forests are the *"adopted son" who provides protection of remaining lands, employment and economic benefits*. Dewes (2022) spoke of an intent by Māori (not all Māori) to use exotics as a vehicle for financing a transition to native forestry, due to several ownership structure, economic and land-class headwinds for Māori forestry enterprise. Successful forestry outcomes for Nga Pou a Tane are holistic, including establishing mana motuhake (independence), improving the health and mauri of awa and whenua, along with generating fiscal returns. Harvest of forest resources remains part of the relationship between tangata whenua and Tāne's forest, and the nature of harvest will continue to take many forms.

Current forestry practices leave a *"lingering dissatisfaction"* among some (Hēnare, 2014), stemming from several reasons, but including the economic reliance on one tree species and also the lack of kinship with monocultural production forests. Another view is that there is an intent to diversify the forestry models on Māori land during the transition, but there are other drivers including fostering reciprocity with Tāne's forests, re-establishing Mana, and providing economic and environmental resilience for connected communities.

Literature on specific harvesting methods associated with and unique to Māori-owned forests is scarce. Similar constraints apply, insofar that harvesting must balance economic, environmental and social needs, but aligned with the Māori worldview. It is likely that today's conventional logging systems and expertise will continue to be used for the immediate future. Current/recent harvests of trees from Māori-owned forest lands such as that of the *Lake Taupō Forest Trust* (Hammond & McKinlay, 2005) and *Ngāi Tahu* in Te Waipounamu reflect that. For harvesting indigenous trees on Māori-owned land (where conducted), Hammond (2001) speculates the use of manual methods, with skilled bushmen in combination with heavy-lift helicopters. This has been ongoing at a low level across New Zealand since the 2001 article. If Hammond's prediction occurs at scale, the current logging workforce (or new entrants) may need to adapt to a new (uncommon in the current climate), yet historical method of logging for these selective harvests. Māori have a substantial stake in forestry (NZFOA, 2021) and so have a wealth of skill and experience with today's harvest systems, though through interpretation of the comments of Dewes (2022) and Hēnare (2014), may ultimately be aiming for unique approach to extracting resources from Tāne's forests.

The authors recognise that mātauranga Māori belongs to Māori. Gaining knowledge specific to harvesting would be best done through ongoing engagement and dialogue with Māori forestry entities.

3.4 'PREMATURE' HARVEST FOR BIOMASS

Only a relative description can be given for 'short rotation'. A 25-year rotation is the standard for NZ-grown radiata pine, which would be considered very short for pine plantations in Europe where a conventional rotation is never shorter than 60 years. Similarly, 14 years is a very short rotation for mountain spruce, but 14 years has been the standard rotation length for poplar plantations for more than 100 years. The concept underlying "short rotation" would be better termed as "planned premature harvest". A short-rotation plantation is one that is harvested earlier than its traditional homologues.

Two questions arise from this:

1. What defines premature?
2. Why harvest prematurely?

Premature simply means "before maturity": before the trees have developed all their growth potential and are smaller than they would be if the harvest was conducted at the time when it is normally conducted. Traditionally, trees are harvested when their size is large enough for them to produce an optimum mix of valuable log sorts – generally sawlogs and/or structural timber, within the context of the markets and distribution networks available in the vicinity. Short rotation forestry, to the contrary, with smaller tree sizes typically yields a mixture of low value, non-structural industrial log sorts: pulp, energy wood or chip wood, but produces higher volumes of wood fibre from the land.

Southland Plantation Forest Company of New Zealand Limited (SPFC) is a unique example in the New Zealand forestry landscape of a large, integrated joint venture, producing predominantly *Eucalyptus nitens* hardwood chips under a short rotation forestry model for supply to the shareholder's pulp and paper mills in Japan (Southwood Export Ltd., 2023). The crop is harvested at an average age of 20 years across SPFC's 10,000+ ha Southland estate using fully mechanised Cut-To-Length (CTL) harvesting systems (paired harvesters and forwarders), before sending the logs by truck to a dedicated chipping plant near South Port, Bluff. The authors are not aware of any other forest owners in New Zealand growing and supplying solely wood chip at a similar scale.

Premature harvest is generally for faster returns (minimising capital immobilisation), to take an opportunity presented by high prices offered in the market, or for maximising volume growth on a site. These options reflect the intentions of different types of forest owner, and SPFC as an integrated company growing/sourcing their own feedstock likely falls into the latter category. The main issue with premature harvest for an independent forest owner supplying a wider market is product quality, especially when that is defined by tree size. Stocking may be increased to grow the same volume per hectare within a shorter timeframe, but that will negatively impact individual tree size. Assuming constant prices and stocking, if product quality (and therefore value or returns) depends on tree size, then an opportunity cost may reasonably be incurred by early harvest.

Small tree size not only causes product value losses, but it also impacts harvesting productivity, where applying the same harvesting system. Piece size is a main driver of harvesting productivity, which has been demonstrated (and quantified) by countless studies. The "piece-size effect" is valid for all work techniques and machine types and describes the inverse relationship between piece size and work productivity. The smaller the work object, the lower the work productivity, because work time does not decrease as fast as object size. Therefore, from the viewpoint of harvesting, short-rotation forestry must be regarded as a special case of small-tree harvesting and efficiencies can be gained by no longer treating the tree (or product) with the same individual attention that is afforded to trees yielding valuable structural or clearwood log sorts.

Research and experience indicate two main ways to offset the small-tree handicap: continuous harvesting and mass-handling. Both aim to overcome the limitations of the piece-size effect by avoiding the processing of each piece individually.

Mass-handling involves processing more pieces within the same cycle. In conventional forest harvesting, one example is the use of feller-*bunchers* (a term often used incorrectly in New Zealand). An accumulating felling head cuts and holds multiple trees within the same cycle, and the bunch that it assembles is treated as a single work object. Mass handling principles are carried forward through the extraction and processing elements of the harvest system also.

Continuous harvesting removes the cycle from the relationship, entirely. With continuous harvesting there is no longer a cycle, or the better: the cycle is no longer the cutting of a single tree. Trees are cut and processed whole, one to the next, without pause.

Both strategies have been applied to short-rotation plantations, in a variety of different technology solutions. The case studies reported here show a sample of those solutions and exemplify the results.

3.5 PRODUCING A MARKETABLE BIOMASS PRODUCT

Unlike typical roundwood products (logs) that are broadly classified by diameter, length and quality measures, but are all produced by one machine (the mechanised log processor), comminuted biomass products are divided broadly into two options (chips and hog-fuel) and the production of either requires specialist machinery. A chipping machine (chipper) can only produce chips, and a grinder can only produce hogged material. ISO standard classes (ISO, 2021) exist for subdividing each of the chip and hog-fuel product classes into tighter specifications, however a biomass product produced by mobile plant often requires screening to satisfy specific market demands (e.g. maximum fines content), or increase the value of the product (Nati et al., 2015).

ISO 17225-9 specifications include ranges of acceptable:

- Particle size,
- Moisture content, and
- Ash content.

Moisture has limited opportunity to escape piles or stores of comminuted material, or can even increase if exposed to the elements (Hall, 2000). As a result, the moisture content is considered ‘locked in’ at the time of processing unless managed carefully or fed into a further process for drying. With low moisture content being desirable for many end users, forest owners in New Zealand are now making use of unused landings for drying stacks of log offcuts from conventional harvesting (Johnston, 2023). After several weeks or months (depending on season) the stacks are ready to comminute, offering a higher energy product for customers (Visser et al., 2014). Other forest owners promote the collection of woody residues from accessible cutovers, post-harvest, for similar reasons.

Fresh timber that is fed into comminution processes creates a high moisture-content biomass product, but with low fines content (Visser, Hall, et al., 2010). Under the right circumstances (terrain / stand / machinery configuration / infrastructure / delivery distance) this may offer a low delivered-cost product due to the comparatively lower expenditure on handling, but this comes at a cost on quality (heat output). Where stored for significant lengths of time the wet material decays through microbial activity (composting) losing dry-matter, and therefore also energy content (Barontini et al., 2014). This additionally can generate human health risks for dealing with the material, via the release (and possible inhalation) of fungal spores. Barontini et al. (2014) showed that poplar chip piles with more comminuted leaf material from the tree tops heated quickly to temperatures approaching 70°C due to the moisture and nutrient availability, compared to piles of comminuted stemwood which warmed, but not to the same degree. SCION is currently conducting similar work on harvest residue pile heating in New Zealand and making core temperature observations up to 90°C (Parker et al., 2024). The key is to recognise that the chipped or hogged material is perishable, and when incorrectly managed can lead to quality losses or significant risks, such as self-combustion.

4 International Experience

The following narrative has been organised according to what has been identified as the two main types of short rotation plantations, namely: Short Rotation Coppice (SRC) and Short Rotation Forestry (SRF). The former is a tree crop that is established at the densest spacing and harvested at the shortest rotations, and therefore is regenerated by coppicing to offset a very high establishment cost. The latter is a conventional tree crop, which is established at higher stocking and harvested on shorter rotations than a common forest plantation. SRF can also be regenerated through coppicing, but that is not generalised since financial performance is not as affected by establishment cost as for short-rotation coppice.

In character and appearance at harvest, SRC appears as a dense thicket of woody shoots, while SRF offers closely planted, small trees.

4.1 SHORT ROTATION FORESTRY (SRF)

A short rotation forest is a dedicated wood crop designed for forest land. Cuttings (or seedlings) are planted in single rows, with a spacing of approximately 3 m between the rows and 2 – 2.5 m along the rows (1,300-1,700 trees ha^{-1}). Stem size at harvest can reach 15 cm Diameter at Breast Height (DBH). Rotations typically vary from 5 to 8 years. The current trend is towards longer rotations, which may offer reduced management cost and a wider product mix. The limit for such development is the traditional poplar plantation, harvested at 10-15 year intervals for timber and biomass. Regeneration can be obtained through either coppice or replanting, depending on the species and management intent. Coppicing allows the spreading of establishment costs over multiple harvests, but it is only viable with species that resprout vigorously from cut stumps. Coppice management generally also requires singling (removing excess sprouts), to grow good quality stems. Replanting offers the benefit of using the newest genetics every time the plantation is re-established, which may be justified if the rotation is long enough and genetic selection keeps making fast, significant progress (Whittock et al., 2004).

4.1.1 SRF in the USA

Between the late 1990s and the early 2000s, several fully integrated US companies established short-rotation hardwood plantations on ex-pastureland to build a secure supply of fibre for their paper mills. Initiatives developed especially on the Western Board, where supply heavily depended on the accessibility to Federal land, which was expected to reduce due to a shift to conservationist policy by the United States Forest Service (USFS) and the Federal Government. Poplars were widely used for rapid growth rates and they could be selected, hybridised and cloned with ease. Poplar wood also has a high cellulose-to-lignin ratio, and recent advances in pulping technology are helping to increase both the pulp yield and the strength properties of the paper obtained from poplar fibre. The largest of these plantations were established along the Columbia River in Northeastern Oregon and Southern Washington by *Boise Paper Solutions* and *Potlatch* (Stanton et al. 2002, Stanton et al. 2020). These were unique examples of intensively managed crops, grown on an irrigated desert landscape. Poplar hybrids were planted at a spacing of about 1666 stems ha^{-1} and harvested after 6-8 years. After harvesting, stumps were suppressed (localised agrichemical application) and new trees replanted (as genetic selection was progressing fast). The relatively low value of the product and the need to compete on a global market required the highest operational efficiency, therefore harvesting was highly mechanised. The crop was easy to harvest, as the plantations offered flat terrain, even stand structure and clearcut harvests, which opened a whole range of mechanisation options. Optimisation and experimentation were conducted for many years. The homogeneous stand structure offered an ideal setting for comparative studies and made modelling easier than under the more variable site conditions of traditional forests.

4.1.2 SRF in Europe

Short rotation poplars have also attracted the interest of European wood industries which are leading the resurgence of Short Rotation Forestry on ex-arable land. Interest is justified by the capacity of these plantations to match the strategic needs of Europe's modern wood industries, rather than the plantations' ability to produce wood at a lower cost than could be obtained from conventional forests. Large wood fibre users have a strategic need to guarantee a steady fibre supply. This comes at a time when wood markets in Europe are undergoing significant structural changes, driven in-part by recurring diplomatic tensions which periodically block wood imports from Russia and surrounding countries. In Europe, most new planting is occurring in the East, in countries such as Hungary, Poland, Romania or Slovakia, which offer an ideal combination of good soil conditions, moderate land price and rapidly developing economies. International wood industries such as *Egger*, *Ikea* and *International Paper* are the leaders of this new effort (IPP 2020, Werner et al. 2012). These companies all aim to produce a mix of logs and biomass chips, obtained from poplar trees grown at the typical stocking of 1666 stems ha^{-1} and harvested within 5-8 years, where trees obtain a mean DBH of 14-15 cm. This size additionally offers at least one 4 m log with a 7 cm Small-End Diameter (SED) over bark. Only a small proportion of trees (ca. 20%) offer a second 4 m log that meets the same SED specifications. A strong interest towards similar new plantations is also developing in the Baltic and Nordic countries, but has not yet developed into any active large-scale projects.

4.1.2.1 European Union Subsidies to SRF and SRC – a brief history

The European Union (EU) has joined in creating a Common Agricultural Policy (CAP), aimed at harmonising agriculture in the EU, promoting efficiency, filling gaps and supporting those sectors and countries that suffer from structural handicaps. EU Directives on the subject represent a framework within which individual member states develop their own dedicated regulations. This explains a large variability in how CAP is implemented in the different member states. In 1988 the concept of "structural funds" was introduced, which aimed to support regions of Europe and sectors of the EU economy that lagged behind. That was the first time support was targeted at forestry activities, which were typically conducted in less developed areas. Stronger and more focused regulations followed, which specifically targeted afforestation, such as Reg. 1609/1989 and 2328/1991. However, the strongest support to SRF and SRC was given by Reg. 2080/1992 (Forestry measures on farms) and 2878/1992, which sanctioned 5-7 year programmes and extended into the early 2000s. Those two regulations were binding to member States, although much flexibility was left to implementation. Therefore, they had different impacts on different States, depending on the intensity of the local measures. Regulation 2080/1992 in particular had the stated goals of "reducing agricultural surplus", "enhance forest resources", "provide greater ecological balance in countryside management" and "combat the greenhouse effect". The EU budget for the first 5-year programme was equivalent to NZ$34 million (2024 value), which had to be matched by member States: therefore, the EU funding would represent between 75% and 50% of the actual total subsidy received by the farmers, the rest being drawn from the State's own budget. Funds were made available in the following five ways: i) aid for afforestation, ii) aid for investment in infrastructure (typically roads), iii) annual subsidy for plantation maintenance in the first five years, iv) compensatory payment for a farmer's loss of income, v) aid for the improvement of existing forest and woodland (typically precommercial thinning). Between 1994 and 1999 over 1 million hectares were reforested in Europe, owing to Reg. 2080/1992. Italy and Spain set and attained the most ambitious targets for afforestation: respectively 230,000 ha and 300,000 ha. In contrast, countries with a strong forestry economy such as Austria, Germany or Sweden, focused on investments in infrastructure (forest roads) and improvements of existing forests (pre-commercial thinning).

Concerning afforestation, the specific level of support changed with the State and within the State with the Region, where regional devolution had been applied. Using the Piemonte Region in Italy as an example, support for SRF development was as follows: i) up to 5000 €/ha for supporting establishment cost, ii) up to 600 €/ha year for post-establishment tending, for the first 5 years after establishment and iii) 725 €/ha year (farmers with at least 25% of their revenues derived from their farms) or 185 €/ha year (other subjects) as compensation for loss of income for the first 20 years, only for long-term afforestation – not SRF or SRC.

In 1999, the EU passed act 1257/1999 "The Rural Development Regulation" aimed at providing a single legal instrument to harmonise the rural development policy with the market and price policy, which are the two main components of CAP. That new instrument also addresses afforestation of farmland and includes subsidies to cover establishment cost (e.g. 1000 to 1600 GBP/ha in pre-Brexit Britain), as well as to compensate for the loss of income, the latter in the measure of 725 €/ha year.

Today, short rotation plantations ("short rotation coppice") are classified as "permanent crops" and are funded within the Basic Payment Scheme under the CAP Guidelines 2014-2020 established by Regulation 1120/2009. In most member states short rotation plantations are also qualifying as Ecological Focus Area (EFS) to fulfil 'Greening' requirements. This might include further cultivation standards (e.g. no mineral fertilizer) which are defined at the national level.

4.1.3 SRF in Sub-tropical Countries

Short rotation forestry plays an especially important role in the global supply of industrial fibre, used for manufacturing pulp and paper products. In that regard, the most successful examples come from the Southern Hemisphere, and especially from Australia, South Africa and South America (McEwan et al. 2020).

Plantations in the Southern Hemisphere are generally established with either pine or eucalypt species, the former targeted to the production of sawlogs, the latter to the production of industrial fibre (largely pulp). For the purpose of this report the latter is most relevant, better matching the specifications described earlier because the plantations feature the highest stocking, shortest rotations and the lowest product quality.

In most cases, eucalypt plantations are established at a stocking of 1666 stems ha^{-1}, are managed for pulp production and are harvested on 5-11 year rotations. Those plantations are generally established under favourable soil and climate conditions, often using genetically selected hybrid and clonal propagation material. That results in exceptional growth rates, which can reach 30-40 m^3 of solid wood per hectare per year. The incredible growth rates explain why many forest companies in Europe and North America have transferred their capital towards highly productive land in the Southern Hemisphere.

Brazil represents perhaps the most successful example for the application of this new production model. Brazilian tree farms cover almost 8M hectares and yield over 200M m^3 of round wood per year (IBA 2017). The role of Brazilian SRF plantations in not limited to fibre supply alone: plantation forestry offers a recognised contribution to the economic and social development of the country, while representing one of the most effective measures for offsetting the country's substantial increase in CO_2 emissions (Stape et al. 2010).

Australia and South Africa grow approximately 0.6M ha of fast-growing eucalypt plantations, each. Despite the relatively small area and the lower growth rates when compared with Brazil, those plantations represent a strategic asset for the local wood industries and offer a crucial contribution to rural development.

Compared with the pioneer character of most willow and poplar projects, eucalypt plantations in the Southern Hemisphere represent a successful large-scale endeavour, well-established on the global market and are currently one of the main pillars of the global pulp and paper industry.

4.1.4 Harvesting SRF

Like for conventional forestry, SRF can be harvested according to two main harvesting systems: Cut-To-Length harvesting (CTL) and Whole-Tree Harvesting (WTH). All harvesting systems, regardless of machine combinations, fall into one of these categories. The former involves processing trees into logs where they are felled, then extracting logs to the roadside, while the latter is based on the extraction of whole unprocessed trees to the roadside (or landing), where they are processed into (generally) various products. Both systems have their pros and cons: CTL uses fewer machines, offers task independence (each unit can work on its own, without closely depending on other units upstream or downstream) and requires less landing space (some infrastructure savings), but has limited capacity to handle trees *en masse*; the contrary is true for WTH (Spinelli et al. 2009a).

4.1.4.1 Cut-To-Length (CTL) Harvesting

This harvesting system relies on two machines only: a harvester and a forwarder (or alternatively, the harwarder alone). The harvester fells, delimbs and crosscuts trees into fully specified log sorts, while the forwarder later moves the logs to the roadside. CTL requires the harvester to fell and process one tree at a time. For that reason, CTL tends to incur higher harvesting costs (ca. +20-25%) than a properly planned and managed WTH system, especially if the latter is provided with adequate landing space. However, CTL offers simpler logistics and therefore remains competitive with WTH as long as harvest volumes are not lower than 100-120 m ha^{-1} (ca. 40 dry tonne ha^{-1}) and stem size not below 0.07 m^3 $tree^{-1}$ (DBH ca. 12 cm). CTL also offers work patterns that are generally more sympathetic to the remaining standing trees, when applied to thinning or selective harvest scenarios, when compared to WTH that must fell and navigate full length trees out of the stand without damaging the remaining crop.

Figure 3: SRF CTL harvesting with small machinery and segregation of products at the stump.

Several studies have been conducted for the optimum deployment of CTL harvesting in SRF, leading to the following overall considerations:

- given the small-tree size, lowest costs are obtained with small harvesters (i.e. thinning harvesters, Figure 3). The machines are less productive than full-size harvesters, but they are also much cheaper, and the small tree size does not allow a full-size harvester to reach its full production potential. Therefore, the only reason to use a full-size harvester in SRF is to retain the flexibility to harvest conventional forestry without needing to buy an additional machine;
- a few manufacturers offer multi-tree CTL heads, capable of processing more than one tree within the same cycle (normally 2 trees). Crosscutting accuracy is slightly diminished, but productivity increases by an average of 10% (Magagnotti et al. 2021);
- given that most SRF trees will yield just one 4 m sawlog, but 1 out of 5 trees would produce a second log, the productivity gains by renouncing the search for the second log are (in many log markets) false economy. The sawlog value differential generally justifies the machine time searching for it;
- settling for lower SED specifications (e.g from 8 to 7 cm) does pay. Therefore, SED specifications should be set as low as technically possible for the target log product.

4.1.4.2 Whole Tree Harvesting (WTH)

With WTH, felling, extraction and processing (i.e. delimbing and/or crosscutting into logs) are decoupled and performed by different machines. Then, processing can be conducted at a more comfortable work site, with highly specialised machinery, personnel and product flow for improved speed and value recovery (Spinelli et al. 2009b). Most

New Zealand final harvests operate in this way, however there are opportunities to adapt for greater harvesting efficiency. With respect to SRF harvests, WTH allows maximising the potential benefits of mass-handling. Trees are formed into bunches as they are felled, and then handled as bunches all along the harvesting chain (Spinelli et al. 2002). Depending on the target end-product, bunches can be fed directly to a whole-tree chipper, or alternatively a chain flail (Figure 4) for delimbing first before loading into a slasher saw (Figure 5) for cross-cutting the high value butt logs from the stems, all without needing to break bunches into individual trees (Hartsough et al. 2002).

Figure 4: A chain flail delimber-debarker spinning idle.

Figure 5: A worker inspecting the bar saw assembly on a slasher saw log bucking machine.,

There are three main options, depending on the desired end product:

- **Whole-tree chips:** If low-grade chips are the main product target (e.g. for delivering to an energy or particleboard plant), then bunches of whole stems (branches, bark and needles/leaves attached) can be fed to a whole-tree chipper either stationed at the landing or roving through the stand. It has been observed in places like Eastern Canada that harvest small piece sizes on flat terrain, because of the high cost of the chipper (and therefore the need for high utilisation rates) the most productive system that incurs the lowest cost is that combining a feller-buncher, grapple skidder and stationary (landing-based) chipper (Ghaffariyan & Brown, 2015);

- **Pulp chips:** Pulp chips are pure wood fibre, with a minimal bark and contaminants (2% to 5%, depending on specifications). When manufacturing pulp chips from small trees, the fastest, most effective solution is offered by chain-flail delimber-debarker-chippers (CFDDC). These are purpose-built machines, obtained by joining a chain flail (which removes a large proportion of bark, leaves and fine branches) to an industrial chipper. The two separate machines (also available on the market) can be arranged in line to perform the same job, although often not as smoothly. CFDDCs are cumbersome and expensive, but also very productive (Hartsough et al. 2000). Chain flail discharges are generally collected, hogged and sold for low-grade fuel;
- **Logs:** If logs are the target product (e.g. for later processing at a mill), then the most efficient solution is a chain flail coupled with a slasher saw. Bunches are fed through the flail at variable speed, depending on whether one only needs to remove the limbs or also the bark. Once through the flail, the bunch is placed on the slasher saw for crosscutting into logs (Spinelli et al. 2021). Crosscutting several stems concurrently does not offer the same measurement accuracy as obtained when trees are processed individually by a mechanised processor, but it proceeds much faster while also being quite effective if the trees in the bunch are relatively homogenous. Most SRF plantations are grown from clonal stock and therefore tree size variations at harvest are observed to be relatively minor. Furthermore, the feller-buncher can be tasked with drafting large trees from small at the stump, which has small negative impact on feller-buncher productivity but improves the work quality and productivity of the slasher.

Given the relatively small size of SRF trees, extraction can be done with a grapple skidder, a clambunk skidder or a forwarder – the latter offering the benefit of minimising soil contamination of the wood (Spinelli and Hartsough 2006).

4.1.4.3 Continuous Harvesting

SRF trees are small enough that continuous harvesting has also been considered and tested, at different times and in different countries. Continuous harvesting means that trees are not grabbed and handled individually, but continuously collected in a smooth motion, similar to how grain is harvested. None of the design and build projects yielded a piece of equipment that made it to production. Not that all designs or prototypes were poor however. The inability to deliver commercial production of a machine may have actually stemmed from not enough SRF plantations at those specific times to further support commercialisation. It is useful to recall some of the main projects, especially those that yielded a functional prototype. Four notable machines are/were as follows:

- **Hyd-Mech FB7:** That was a continuous feller-buncher developed in the late 1980s in Canada and tested by the US Forest Service (Stokes et al., 1986). The machine was a drive-to-tree feller-buncher, capable of cutting up to 10 trees in one continuous sweep, for an estimated productivity of ca. 1000 trees per productive hour. A larger version was later produced, the FB12, but the project was discontinued.
- **The Missoula Technology and Development Centre (MTDC) Tree Harvester** was a continuous-travel feller-forwarder with a collecting bunk and saw assembly mounted on a *Timberjack 520A* forwarder base. When trees are severed, a rotating "bat" knocks them into the collection bed where they lay

horizontally. Bunches are side-dumped from the bunk. The machine was designed for dense natural stands of small trees but was also tested on hybrid poplar plantations in western Oregon.

- The **Whole Tree Harvester** by Energy Performance Systems Inc., Minnesota was a very large, fast, continuous travel machine designed to sever then transport trees up a conveyor in an upright position before bunching them for discharge to a trailer. The machine was designed for trees from 4” to 30” in diameter and was set on two pairs of rubber tracks and a pair of caster wheels to support the felling unit. This went through a number of design iterations and trials between 2004 and 2013 (Ostlie, 2013).
- The **Bionic Beaver** (see Figure 6) is a purpose-built cut-and-chip harvester designed to perform the same job as the modified agricultural forage harvesters (see next Section) currently used with SRC, this time with larger trees spaced further apart. The machine is built in Australia and has recently been tested in Brazil (Sulman et al., 2023). A hot saw felling head cuts the trees, which are lifted by a chain conveyor and dropped into a horizontally-placed disc chipper – all in one smooth flow. The horizontal position of the chipper is designed to make operation independent of tree height and density, because trees do not need to be laid horizontally for feeding to the chipper as in modified forage harvesters.

Figure 6: Bionic Beaver cut and chip harvester.

4.2 SHORT ROTATION COPPICE (SRC)

This is a dedicated wood crop designed for surplus agricultural land and is managed intensively (El Kasmioui and Ceulemans 2013). Rotation length is kept to a minimum and density to a maximum, to resemble a conventional agricultural crop as much as possible. Intensive management assures the highest surface yield and the shortest waiting time. As opposed to traditional agricultural crops, SRC can provide further benefits such as groundwater protection, ecological planning, phyto-remediation, stormwater or effluent treatment etc. Its success requires that all operations be conducted with the utmost efficiency. Regeneration after harvest is obtained through resprouting, over an estimated 3 to 8 rotations before replacing rootstock. For that reason, SRC adopts only tree species with good coppicing quality, and especially: willows, poplars, eucalypts and black locust. Other options include ash, hazel, sweet chestnut, sycamore but with extended rotations or lower yield.

Plantations are established at a density between 3300 and 14,000 trees ha^{-1} in order to maximise yield (e.g. see the density in Figure 7). The diameter at 10 cm from the ground of stems grown under such planting scheme normally range from 2 to 8 cm. Depending on site fertility, clone selection and rotation age, yields can vary between 30 to over 100 fresh t ha^{-1}, which correspond to yields between 20 and 60 fresh t ha^{-1} $year^{-1}$. Wood moisture content is generally in the 50 to 60% range (wet basis), and therefore the actual yield in dry mass normally varies between 8 and 20 dry t ha^{-1} $year^{-1}$. Those figures refer to willow and poplar grown in the temperate region: faster growth rates are obtained for eucalypts in sub-tropical climates (Couto et al. 2011, Gonzalez et al. 2011), while other species like black locust offer slightly lower yields compared with willow and poplar, partly due to the difficulty with genetic selection that characterises locust (Grunewald et al. 2009).

Figure 7: Short Rotation Coppice stands are typically planted at extremely high stockings and managed more like an agricultural crop.

Species selection can constrain harvesting to months where the rootstock is dormant and free of leaves (Volk et al., 2020). Harvesting during the growing season ensures a high moisture content of the yield. Seasonality increases the cost of harvesting due to machine ownership costs being spread across a restricted annual volume.

Protection of the rootstock is of significant importance when harvesting for successful future crops. Harvesting during the growing season for hardwood crops can affect subsequent coppice growth. Damage to the stump during harvesting can do the same (see Figure 8). Damage such as that shown can be reduced by ensuring sharp cutters, correct positioning of push-bars and correct forward speed of the machine.

Figure 8: Example damage for coppicing crops which should be avoided to ensure high growth rates for subsequent rotations. Source: Compte-Rendu de Suivi de Chantier, 02/02/12 by Fraichot, J. & Ruch, P.. FCBA technological institute.

4.2.1 SRC in Europe

After early experiments in the 1980s, Europe launched an ambitious SRC programme in the early 1990's. Sweden started first, highly subsidising the production of coppiced willow plantations and to date it remains the European leader in the production of SRC, with more than 10,000 ha of land in SRC production. Within few years, Germany, Italy and the UK followed the example, establishing large SRC plantations subsidised by their respective Governments. That led to a few thousand hectares being planted in Germany and the UK, and over 5000 ha in Italy. More recently, plantations have been established in the Baltic countries, but not to such a large extent. In Austria and France many pilot programmes were launched, but SRC never reached a large-scale commercial stage. Changes in the food and energy markets over the past decade have crippled the profitability of energy plantations (Helby et al. 2006), and SRC only survives when additional revenue streams can be intercepted (e.g. phytoremediation, set-aside land, land earmarked for non-food crops etc.) (Lindegaard et al. 2016).

4.2.2 SRC in the USA

Starting in the late 1980s, several SRC projects were launched in the Mid West and North East USA, including the Willow Program at Siracuse State University (SUNY). The goal of the Willow Programme has been the development of shrub willow crops for commercial biomass production and alternative applications (Frank et al. 2022). There are currently about 500 ha of commercial willow crops growing in New York State and more are likely to be added in the near future (Volk et al. 2016). These commercial endeavours are happening with support of USDA BCAP and NEWBio. Alternative applications for bioremediation and ‘living snow fences’ are also being deployed across New York and the Northeast. Research and development of shrub willow crops has been supported by numerous funding agencies over the years including United States Department of Agriculture (USDA), United States Department of Energy (USDOE), New York State Energy Research and Development Agency (NYSERDA), Empire State Development Division of Science Technology & Innovation (NYSTAR), and the New York State Department of Transportation (NYSDOT).

4.2.3 Harvesting SRC

SRC can be harvested with different machines and techniques, but all harvesting systems share the following characteristics:

1. they must turn the standing trees (shoots) into chips; and,
2. they are designed for continuous harvesting

In general, SRC harvesting systems can be further divided into two subgroups: single-pass or multi-pass (Santangelo et al. 2015).

4.2.3.1 Single-pass Harvesting

This harvesting technique is based on a single machine that cuts and chips the stems in one continuous flow, much like the combine harvesters used in agriculture for corn, wheat or forage (Figure 7, page 20). In fact, many SRC single-pass harvesters are modified foragers (e.g. see Figure 9, and 11), where the original header designed for cutting and collecting grain is replaced with a purpose-built header for cutting and collecting small trees (Spinelli et al. 2009c). The original chopper can be modified or replaced with a dedicated one, depending on the case. With the cut-and-chip technique, stems are cut, chipped and blown into an accompanying trailer (Eisenbies et al. 2014). The major advantage of this technique is that all the work is done in a single pass with only one machine (plus the accompanying trailers). That simplifies operation planning, reduces relocation cost and increases utilisation of the base machine (which can be used for harvesting conventional agricultural crops). Agricultural tractors can also be fitted with cut-and-chip SRC harvester attachments, which can be carried on the tractor’s three-point hitch (then the tractor works in reverse - Figure 10) or towed as a trailer and work offset to one side. The productivity of a farm tractor-based SRC chip and cut harvester is in the range of 5-8 fresh tons of chips per scheduled machine hour. In contrast, the much more powerful modified forager (>300 kW) can reach a productivity between 20 and 40 fresh tons per scheduled machine hour. Forage harvesters also come in very large sizes and can be equipped with upsized SRC headers that can cope with the larger stems (butt diameter 15-18 cm) obtained from extended rotations (3-4 years), which are grown for producing better quality chips, with a higher fibre-to-bark ratio (Spinelli et al. 2011).

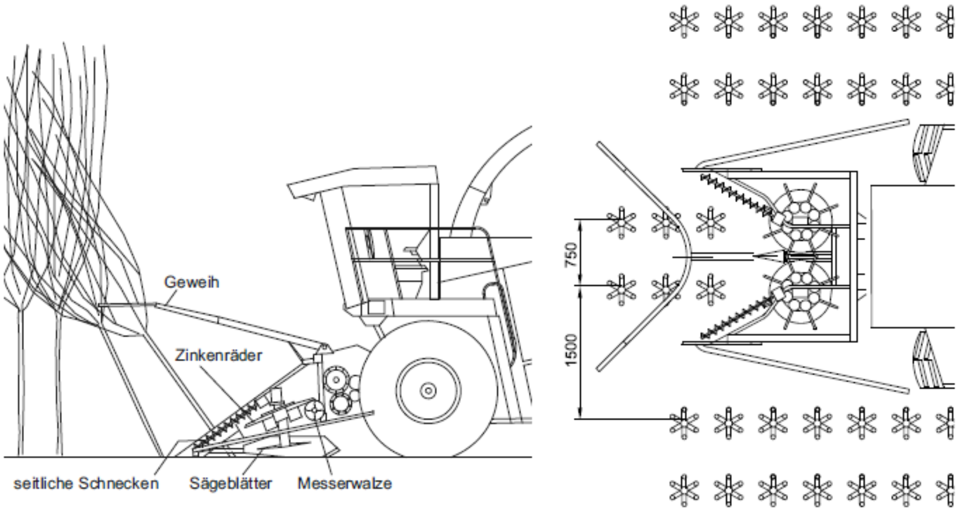

Figure 9: Modified combine harvester that fells and chips coppice <8cm in diameter in a single pass. Kaltschmitt & Stampfer (2024).

Figure 10: Agricultural tractor-mounted SRC single-pass Spapperi-brand harvester and chipper (right).

Modified forage harvesters offer high material capacity, consistent chip sizes, and are proven; however, they have the disadvantage of being very heavy (>20 t for the complete machine) and they chip the stems in a horizontal position; therefore they must lay down the cut stems in front of them in order to move it to the chipper, which may become difficult if the plantation is very dense and the stems are too tall. In contrast, tractor-based SRC harvesters are much lighter and many of them chip the stems in an upright position, which makes them most suitable for dense plantations and tall trees; their main disadvantage is poor durability and low productivity. To date, forager-based cut-and-chip harvesters are the most common and the most valued.

Figure 11: Single-pass harvesting SRC in moderately steep Italian terrain with a modified sugarcane harvester – likely an Austoft 7700.

4.2.3.2 Multi-pass Harvesting

Cutting, collection and chipping SRC are separate with multi-pass harvesting (Schweier and Becker 2012). There are many options: one machine can cut and windrow the stems, a second machine can collect them and move them to the field's edge while a third machine will chip them. However, in most cases only two passes are necessary. The most common systems are based on a dedicated cut-collector that cuts the stems, loads them on a trailer and moves them to the field's edge where the stems are chipped by a conventional chipper, possibly after some weeks for open-air drying. Otherwise, two dedicated machines are used: one cuts the stems, accumulates bunches, then lays them on the ground in orderly windrows (e.g. Figure 12), while the second collects the bunches, and conveys them to a chipper which discharges the chips to an integrated container (Civitarese et al. 2015). Again, some time may elapse between the first and second pass for air-drying.

Figure 12: The Salixmaskiner Rodster which cuts and accumulates bunches of coppice for mass handling.

Multi-pass systems are inherently more complex than single-pass systems and therefore they require planning effort. On the other hand, they offer advantages with a key benefit being the ability to delay the chipping of the harvested stems allows an opportunity for the wood to dry to a more desirable moisture content and/or to postpone their sale to a time when market demand is highest (Gigler et al. 2000). Delayed chipping has other benefits such as minimising dry matter losses in subsequent storage. Furthermore, using a powerful commercial chipper can result in good control over chip particle size distribution and is conducive to an overall high chip quality. Finally, subdividing the tasks between separate machines generally allows the use of smaller and lighter machines than a forage harvester. The point is relevant as the crop is often grown on wet soils (particularly when the crop provides a water filtration function) and is generally harvested in winter when the plants are dormant and have shed their leaves (see Figure 13). During boggy conditions, a lighter cut or cut-and-extract machine, possibly mounted on a high-floatation, low ground-stress carrier is more appropriate. If choosing the lightest option – a wide-track cutting machine – then extraction could be postponed until the soil has dried enough for accessing with adapted extraction equipment. Furthermore, cut-only or cut-and-collect harvesters can handle SRC crops with the highest stocking, as they can still handle and process those stems that have a diameter that is too large for the chippers that are fitted to most single pass cut-and-chip harvesters. The integral chipper is generally the limiting factor with the latter machines, and the industrial forestry chippers used in multi-pass operations can manage SRC stems most comfortably.

Figure 13:Harvesting in the winter dormancy period on flat sites also comes with the challenge protecting soil, roots and water.

The cutting step in multi-pass harvesting systems has been rapidly mechanised through the development of different models of cut and cut-and-collect machines, although those have been generally manufactured in low numbers. The very first cutting machines were derived from nursery equipment and were simple, consisting of a circular saw carried by a tractor and fitted with a push bar for directing the fall of the stems. These could only perform directional felling, which resulted in stem windrows, ready for subsequent bunching, extraction and chipping. Although very simple and cheap, those machines are not the most effective they often could not direct the fall of the tallest stems, with a centre of gravity higher up than the simple push bar installed on the machine. An improvement over that simple device is represented by slightly more complex machines, whereby a chain conveyor is placed behind the circular saw - similar to the *Bionic Beaver* earlier (Figure 6) - to grab the cut stems but to lay them down in an orderly manner. The conveyor can move cut stems to a windrow or an accumulation deck . The latter can be tilted at regular intervals, thus forming tidy bunches for later collection; otherwise, the machine can be driven to the field's edge and dump its deck load at a landing, ready for storage and chipping. Cut-and-collect units of this type are produced in many models and can be installed on a dedicated carrier (wheeled or tracked) or on a trailer for towing by a farm tractor. Many different models have been documented, among which probably the most popular and technologically mature is the *Stemster Mk III* (Figure 14), manufactured by *Nordic Biomass* in Denmark (Vanbeveren et al. 2018).

Figure 14: The Stemster MkIII by Nordic Biomass for cutting and accumulating large bundles of stems.

A further option may be a cut-and-bale machine, as the bundler built in the early 2000s as a prototype by *Salixmaskiner AB*, or the *Biobaler* - a commercial machine currently on the market (Savoie et al. 2013). Baling represents an additional step and incurs additional cost, but it simplifies product handling and storage, especially if the product cannot be stored at the field's edge, but must be hauled to a dedicated storage site some distance from the field (Guerra et al. 2013).

4.3 INTERNATIONAL LESSONS FOR NEW ZEALAND

Short-rotation plantations are quite an elusive target. All European cases have been supported by public subsidies. Even when the project was led by large industrial partners such as *IKEA*, *Egger* or *International Paper*, plantations were established on ex-arable land for which public support was available. The North American examples were not subsidised, but most were eventually discontinued, and the northeastern Oregon tree farms have long been returned to grain production. In contrast, eucalypt plantations in sub-tropical countries are not subsidised and they are widely successful – in fact a major player in the global fibre supply. Most (or all) such endeavours benefit from complete value chain integration, management by large-scale industrial companies and very favourable physical (climate and soil) and legal environments. New Zealand may position itself somewhere in between, especially for what concerns the physical environments for establishing such plantations, which is not as favourable as in sub-tropical countries.

In all cases, there is a constant tension between simplification of silviculture and harvesting, and better value recovery. In European SRC, there has been a constant trend towards increasing rotation lengths for a better product; both logs, but also chip – bark-to-fibre ratios (Camia et al. 2021). In Italy, for instance, poplar for energywood initially drove high stockings and short rotations (2-4 years) with a transition in more recent years to lower stockings and longer rotations to produce more valuable industrial roundwood products (Magagnotti et al. 2021). In the Pacific northwest, the initial 5-year rotation designed for the exclusive production of pulp chip was extended to add a certain proportion of small sawlogs that was expected to increase overall profitability (Stanton et al. 2002); all while making harvesting more expensive, due to the need for product separation. Those are very important considerations that should be made at the time of plantation design – or at least provisions should be made to keep design flexible enough that future adjustments can be made without excessive complication and cost.

SRC has never been seriously attempted on anything than moderately rolling terrain. Steep terrain is not suitable for a high-speed continuous harvesting system. In fact, technical solutions could be conceived and attempted – and they might even be successful, but they are unlikely to be cost-effective. If the target for New Zealand is moderately steep to steep terrain, then it may be best to disregard SRC and consider SRF only (and that will not be easy either).

Steep terrain may complicate the application of continuous harvesting systems, because gravity may negatively impact the operation of the tree conveying system(s). There are some technical hurdles to overcome to ensure a successful transition of the concept to steep slopes.

In New Zealand, a first conservative approach to short-rotation plantations may consist in establishing the same successful NZ pine plantation model, this time with a shorter rotation (15-18 years) and a higher stocking to produce the same large amount of fibre within a shorter time, while abandoning production of the most valuable structural log sorts. A simplified harvesting and log-making approach could be assembled, heavily based on mass-handling and designed to produce 2-3 products only (including biomass). Felling could be done with a feller-buncher, possibly one of the continuous-accumulation types originally designed in northern Europe for boom corridor thinning or eastern Canada's approach with hot saw feller-bunchers, extraction by a grapple or clambunk skidder (or a grapple yarder), delimbing/debarking with a chain flail and crosscutting with a slasher saw. The key success factors would be: mass-handling throughout, comparatively low-cost equipment and greatly simplified work systems. One such example is given in the sequence of images on the next page (Figures Figure 15, Figure 16 and Figure 17). It must however be carefully assessed whether shorter rotations and potentially lower harvesting cost offset the drastic reduction in crop value and the increase in establishment cost (more plants per hectare).

Figure 15: Simplified mass handling of SRF. Felling and extraction combined.

Figure 16: Simplified mass handling of SRF, harvesting to a trailer, then set out for collection for in-forest transport.

Figure 17: Mass handling for processing into the delivered product.

5 Machinery Options for Biomass Harvesting

The previous section highlighted some of the more successful international developments in biomass harvesting. The machines, systems and or technologies have each been developed to tackle productivity or product challenges, while their applications balance technical, safety and environmental needs.

The following subsections break down tree harvesting into the key elements of *felling* and *extraction*. It focuses on the existing machines and systems currently used in NZ, but also includes technologies that are (or are in development) on the international machine market. Most current NZ logging systems utilise multiple machines with specialist functions to complete the harvesting process, but some employ ‘all-in-one’ machines. Understanding the capabilities and concessions of the various options enables the application of the technology that best matches the constraints of the site and wider operating environment.

For biomass harvesting, comminution, or the breaking down of larger material (i.e. trees or logs) into biomass products (i.e. hog-fuel or chips) is a step that is out of the scope of this project. There are many publications on comminution systems, their advantages or disadvantages, productivities and costs (Asikainen & Pulkkinen, 1998; Garren et al., 2022; Ghaffariyan, 2010; Harrill & Han, 2012; Hoyne & Thomas, 2001; Kent et al., 2011; Malladi & Sowlati, 2018). Almost any comminution system can be coupled with the harvesting system.

5.1 FELLING

5.1.1 Manual Felling

Severing the tree stem from the stump can be carried out several ways in the modern forestry setting. Motor-manual – tree fallers using chainsaws remains the most versatile felling method available, enabling access to the most difficult terrain. However, it does not always deliver the lowest harvesting cost per tree, nor does it allow manipulation of the felled stems for optimising extraction. Unacceptable rates of fatalities and serious injuries from tree-felling have guided New Zealand’s commercial forestry industry to widely adopt mechanised felling methods on increasingly challenging terrain since the 2000’s (Visser et al., 2014). Future Forests Research conducted a research and technology development programme with the vision *“No worker on the slope, no hand on the chainsaw”*, reflecting logging contractor and forest owner sentiment at the time (FGR & MPI, 2018). As a general observation of most large-scale commercial forestry operations now, only the most machine-inaccessible crop-trees, or trees that are ‘too big’ for the mechanised felling equipment at hand are felled motor-manually.

Manual felling is completed by workers on foot, using chainsaws, which offers several benefits:

+ Low ground impact,
+ Low CO_2e emissions per tree felled,
+ Low investment in equipment (barrier to entry); and,
+ Versatility – applicable to all tree diameter and terrain scenarios

And drawbacks:

- High past serious injury and fatality rate (harvesting)
- Limited options for lowering the felling breakage rates of *large* trees, whilst also maintaining productivity & optimising layout for extraction.
- Productivity can be severely impacted by wind, tree quality (branching into gaps, lean), hang-ups, and undergrowth.

Formal training and certifications are required to carry out tree-felling work (NZFOA, 2016). The nature of these qualifications is subject to regular review. Felling hazards tend to increase with the height and age of the stand, so it is expected that younger, smaller trees carry a lower risk to workers than 'mature' trees (~27y/o). Workers felling trees with diameters <200mm at the butt are not required to complete a scarf and back-cut (Worksafe New Zealand, 2014), allowing for greater work rates.

Manual felling is commonly used in Nea Zealand waste thinning operations. Even without extracting the small, felled trees for sale, the cost-benefit is favourable. Waste thinning is somewhat comparable to a SRF scenario with Radiata pine, although clear-felling SRF stands should provide fewer difficulties for workers bringing trees to the ground, than for thinning-to-waste operations.

Despite direction towards mechanisation, manual felling is still be regarded as common in harvesting operations (Gilmore, 2022). Where a logging crew has a falling machine (and operator), manual felling is generally reserved for trees that are deemed inaccessible to machinery (various reasons) or too big for the machine.

Carbon emissions per tree felled by chainsaw was assessed as 0.11 kg CO_2e m^{-3} of roundwood produced in Austria in 2018 (Kühmaier et al., 2022).

5.1.2 Mechanised Felling

There are several unique solutions for mechanised felling in use across the world. New Zealand's typical approach to mechanised falling has evolved from an excavator-type[1] prime mover and a 'dangle'-type felling head with integrated bar saw (Figure 18), to now more steep-slope specialised, self-levelling prime movers which work on the same principles (Figure 19). This is a similar approach to operations in the mountainous Pacific Northwest (PNW) region of North America. The excavator-based machines offer ample power to fell and move large (often >2 tonne) trees while also being robust and manoeuvrable in challenging environments. Other prime-mover and felling head designs may also be applicable to the current harvest but are comparatively uncommon in New Zealand.

[1] While these machines are similar in appearance to earthmoving excavators, they are heavily modified for the felling work and are specialist machines. Differences include 'high and wide' track frames, heavy rollover, front/side impact and falling object protection, and unique geometries of the boom and stick (crane arm) for tree-felling.

Figure 18: 'Excavator-based' tree falling machine working on a moderately steep slope, with winch assist near Nelson.

Figure 19: John Deere 909KH falling machine. This type of machine with self-levelling capability has become the standard for falling trees in New Zealand's steep slope clearfell operations.

These excavator-based machines may be used to clearfell harvest ‘small’ trees (<1 tonne tree^{-1}) also; are particularly useful for shovelling & also producing bunches of small trees (e.g. Figure 20, below) for increasing the efficiency of the subsequent extraction operation, where completed with a separate machine. One limitation of the machines (and how they are operated) is the breakage of trees during falling and manipulation on the ground. While this is a problem with the handling of the tree, breakage is known to be exacerbated by increasing tree size (Murphy, 1982). Breakage therefore has been identified as a key area for improvement, to increase value recovery from the standing crop and reduce woody residues on cutovers (Prebble & Scott, 2019).

Figure 20: Trees felled, bunched and aligned by a winch-assisted falling machine for more efficient extraction by a cable yarder.

5.1.2.1 Excavator-based

See Figure 18 and Figure 19 on page 31. Well-regarded amongst New Zealand loggers for a number of reasons including power and manoeuvrability, the excavator-based felling machine is common across all terrains from flat to steep for clear-fell harvesting. Smaller models, often with low or zero tail-swing may be used for thinning operations, equipped with either felling, or harvesting heads.

For non-self-levelling models (Figure 21), with or without winch assist; they are 'consistently productive' to 20° terrain slope. Limiting factors are often engine lubrication, stability and operator comfort as the slope increases over 20°.

For self-levelling models, *with winch assist*, such as that shown on page 31 (Figure 19); these are 'consistently productive' to 35°, with improved weight balance and operator comfort on steep slopes, over non self-levelling models. The Best Practice Guideline for Winch-assist (Gilmore, 2022) defines a "realistic upper limit" for terrain slope as 42°, and an "absolute upper limit" as 45°. While working at these upper limits may be *feasible* for skilled and confident felling machine operators *in ideal conditions*, there are several reasons why the limits may not be (or should not be) achieved, including:

- the limits placed on equipment by their manufacturer,
- environmental effects – churning of soils has the potential to have a much higher cumulative effect during extreme weather on very steep terrain,
- safety – high reliance on winch assist cable tension for machine stability.

The Best Practice's slope guidelines (Gilmore, 2022) are also not specific to any one design of prime mover. Manufacturers specifications should preside, where stated.

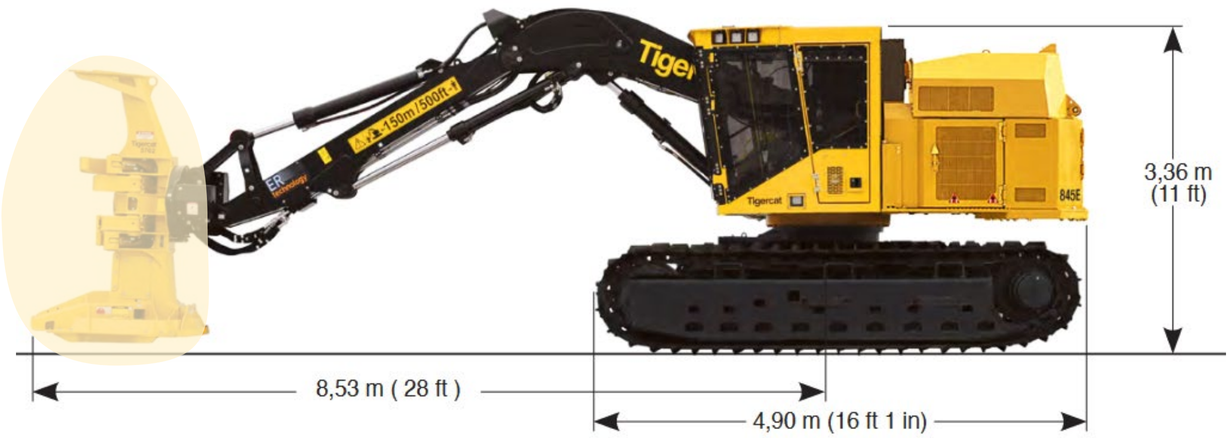

Figure 21: Tigercat 845E Feller Buncher. Non self-levelling machine. Source: 845E/L845E FELLER BUNCHER Brochure, accessed 1 August 2024 at https://www.tigercat.com/wp-content/uploads/2019/01/845E-L845E-EN1.1-0519-hi-res.pdf.

Emissions intensities of the typical diesel-powered excavator-based prime mover vary by a number of factors. In general as the rated power output of the engine increases, so do emissions. Smith and Shepherd (2022) established that aggregate emissions per cubic metre of logs produced by harvesting systems have increased for New Zealand harvest operations since a 2015 fuel use study by Oyier. Oyier's survey of logging contractors revealed a fuel use by felling machines ("harvesters" in the study), in ground-based operations averaged 0.37 l m^{-3}, with most respondents felling trees averaging 1.5 to 2.5 m^3 $tree^{-1}$. At a standardised CO_2 emissions conversion for diesel of 2.66 kg CO_2e l^{-1} (MfE 2022), this equates to 0.98 kg CO_2e m^{-3} as an indicative value for clear felling large trees. This corroborates with Roy & Rittich (2017) who measured fuel use intensities ranging from 0.35 – 1.28 l m^{-3} (0.93 – 3.4 kg CO_2e m^{-3}) from two modern machines that felled between 41 and 160 m^3 hr^{-1} over a four-month period.

Usage of the machine plays a large part in total emissions per unit harvested. Such variables include:

- Increasing slope steepness, increases emissions. Winch assist increases emissions (power requirement for tractive movement split across two machines).
- Tree size. Felling trees that are either side of the optimum size for the machine increases emissions per unit produced (slow production).
- Percentage of unproductive operating time.
- Other productive tasks such as bunching or shovelling, in addition to felling increases the machine's emissions per unit produced. However, when the tasks are optimised, this should reduce the aggregate emissions of the harvest system by improving the efficiency of extraction.

5.1.2.2 Wheeled feller-buncher

The wheeled feller-buncher (e.g. Figure 22, page 34) is a common prime-mover in the flat to gently rolling terrain of the Southern states of the USA. Production forests in the South vary from low stocking and large trees to high stocking and small diameter trees of mixed softwood and hardwood species. The design of the machine allows for fast travel speeds. It is called a feller-*buncher* because of the harvesting attachment. The typical felling attachment collects multiple cut trees in accumulating arms, before lowering bunches in piles for collection.

This prime mover must be driven up to each tree to be felled. While this can be done at relative speed, it means that compaction of forest soils is a key concern of its operation (Akay et al., 2007; Ampoorter, 2011; McMahon & Evanson, 1994; Parajuli, 2021). The manoeuvrability of the articulated machine is a drawback in selective felling scenarios also, particularly where high stocking rates are to be maintained. Three-wheeled designs with a single, rear, pivoting castor are an alternative (similar to the locally popular Bell Telelogger) which offers a near zero-turn radius. The three-wheeled configuration's popularity appears to have waned recently, however. As an example, *Delfab* in Michigan, USA still produce a three-wheeled, 130hp model.

Terrain slope limits are difficult to source for wheeled feller bunchers in scientific literature, the *Caterpillar* brochure for four-wheeled machines indicates a 20% or 30% (11-17°) limit, depending on model (Caterpillar, 2016). This is a fair representation of the easy-to-rolling terrains the machines are used on, in Southern USA. Pan et al. (2007) states that a *Valmet 603* three-wheeled feller buncher was observed operating on slopes from 0 to 28%, thinning trees up to 5” in diameter.

Figure 22: Wheeled feller-buncher with partially obscured tree felling attachment (Caterpillar, 2016).

Like excavator-based falling machines, the carbon emissions of wheeled feller bunchers are linked to the engine peak power output and the use case (terrain, stand, task, ground conditions). As an example of the criticality of the machine's use case, derived numbers from the Pan et al. (2007) time of motion study of the 130hp *Valmet 603* in small diameter (<5.0 inches) timber, produces an average of 5.6 kg CO_2e per green metric tonne harvested. Comparing to an old study by Logging Industry Research Association (LIRA) on a *Bell Super T Feller Buncher* felling 0.4 m^3 $tree^{-1}$ ponderosa pines, the 71hp machine managed a derived figure of 0.3 – 0.33 kg CO2e m^{-3} felled (Raymond & Hawinkels, 1988). Piece size and stand characteristics therefore play a major part in the emissions intensity of any machine's use.

5.1.2.3 Wheeled Harvester

The wheeled harvester is typical of fully mechanised Cut-To-Length (CTL) harvesting operations, varying in size from 4 to 8 wheels. They fell and process the trees into logs, at the stump and are usually paired with a forwarder for extraction. The relatively long machines (when compared to excavator-based prime movers) have a low centre of gravity, and no issue with tail-swing, which could otherwise be troublesome in thinning / selective cut scenarios. Although manoeuvrability is more restricted by comparison, this makes no material difference to the harvest pattern in selective harvest or thinning scenarios, with an 'out' row (100% harvested) for machine passage required, regardless. Models such as the machine shown in Figure 23 can be sold with a choice of crane arms, catering to different reach and lift requirements. As an example with reference to the machine in Figure 23, the heaviest crane arm option (the *HSM H4-15*) has a lifting capacity of 8.5 tonnes at 5m reach, 5.2 tonnes at 9m, dropping to 1.6 tonnes at 14.8m.

Figure 23: HSM 405 H steep slope wheeled harvester on show at Austrofoma 2023, Stuhleck, Austria.

Machines need careful checks to ensure alignment with NZ forestry Operator Protective Structure (OPS) rules. If not certified to a standard in accordance with New Zealand's Approved Code of Practice for Operator Protective Structures on Self-Propelled Mobile Mechanical Plant (OPS ACoP) (OSH, 1999) their use is illegal until modified and certified compliant. Modifications (even what might be considered minor) may also void the certification, requiring signoff by a qualified engineer.

For environmental performance, there are a number of conflicting studies on soil rutting, comparing wheels, band-tracked wheel-pairs (e.g. Figure 23) and tracks (Haas et al., 2016; Jansson & Johansson, 1998; Johnson et al., 1991; Liu et al., 2011; Murosky & Hassan, 1991), which indicates that soil impacts are nuanced and site-specific results are a combination of machine choice, harvest pattern, terrain and soil condition variables. Good practice to reduce rutting involves reducing peak ground pressure with band tracks (Bygdén et al., 2003), and placing logging residues ahead of the wheels as the machine moves through the stand (Ilintsev et al., 2020).

5.1.3 Felling Attachments

5.1.3.1 Cutter types

Several different concepts of cutters are available and used around the world. Most New Zealand systems have adopted the hydraulically-driven bar-saw (1 in Figure 24) in our systems that fell trees individually. The bar saw is attractive to loggers (and forest owners) because of its versatility, ability to actuate on demand and retreat to the protective saw box, small kerf (cut thickness), low damage caused to the butt of the tree, and allowance for fast changeovers of blunted chains.

Hot saws (2 & 3 in Figure 24) are continuously rotating saw disks which provide for fast cutting, and are particularly effective for smaller trees. In comparison to the bar saw, these have a larger kerf, and have high power requirements and are considered more robust. Options on the machine market currently include single-grip saws, and bunching saws. Where stems exceed maximum cutting dimensions of the saw, operators must either a) leave partially severed trees standing whilst they reposition for the final cut, or b) find another felling machine/method.

Shear heads (4-6 in Figure 24) offer an efficient solution for cutting small timber. Shear blades move slower and are more resilient to soil / stone dulling of the cutter(s). Several options integrate bunching functionality for improved productivity with the small-diameter trees that these are designed for. If felling large timber, damage to the cut-face such as crushing or splitting (i.e. compression damage) can result, making it generally suitable only for pulp or energywood timber production scenarios.

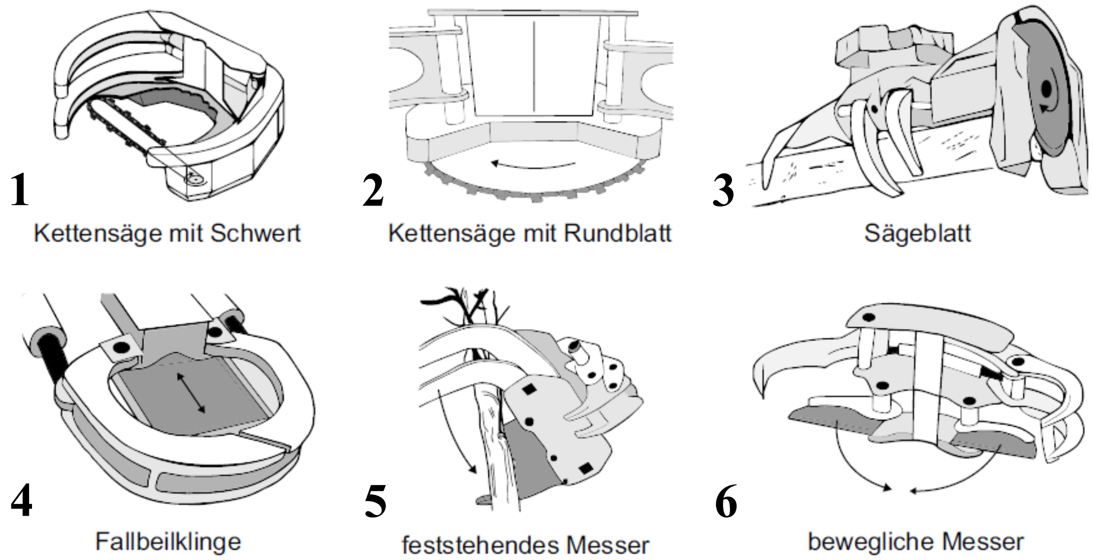

Figure 24: Felling attachment types. Source: Kaltschmitt & Stampfer (2024). (1 Barsaw, 2 Circular saw ('hotsaw') 3 retractable hotsaw, 4. Guillotine blade 5. Fixed knife 6. Shears)

5.1.3.2 'Dangle' heads versus 'Fixed'

Most felling and processing in New Zealand is currently carried out with 'dangle'-type felling, or processor heads (Figure 25). These have a pivot that allows the grapple and saw assembly to rotate freely from the chassis on demand. This ensures that as the tree and grapple pivot together, no unnecessary load is imparted on the hydraulic system (or crane arm). The flexibility enables more delicate manipulation of felled stems when shovelling and lowers the related timber breakage. Dangle heads are used because of the large trees harvested in New Zealand and the body of knowledge built up around their use. The drawback, that has encouraged some loggers that are harvesting smaller trees to trial 'fixed' heads (Figure 26), is the high frequency of felling breakage, when the trees rotate in a dangle head and hit the ground at speed (Prebble & Scott, 2019). Although felling breakage is most prevalent in large trees (Murphy, 1982), current machines struggle to lower the fall speed of 2+ tonne trees, particularly on steep slopes. Highly mechanised small timber harvesting in WTH systems globally has trended toward fixed felling heads, allowing more precise manoeuvring of the cut trees around leave trees (remaining crop trees) minimising potential for unintended damage.

Figure 25: Example of a dangle-type harvester head. The specialist, dangle-type felling heads are built to a similar format, but without log processing capabilities. Dangle heads are designed to return to an upright position for felling with assistance from a pair of hydraulic rams.

Figure 26: Example of a fixed felling head. These can pitch and roll, with more restraint on the movement of the tree(s) in the grip than dangle heads.

5.2 WINCH ASSIST

While mechanised felling capability on steeper slopes has been improved by design aspects such as self-levelling, a major advance is the application of winch-assist technology (Visser & Stampfer, 2015). As the name suggests, a separate winch (typically mounted on a supporting machine) provides a pulling force to allow machines to navigate steep terrain effectively (Figure 27). This has allowed ground-based machinery to operate on steep slopes, increasing productivity and lowering harvesting costs. New Zealand has been instrumental in the design, development and application of these systems to the steepest slopes, and is their use is now supported with its own Best Practice Guideline (Gilmore, 2022).

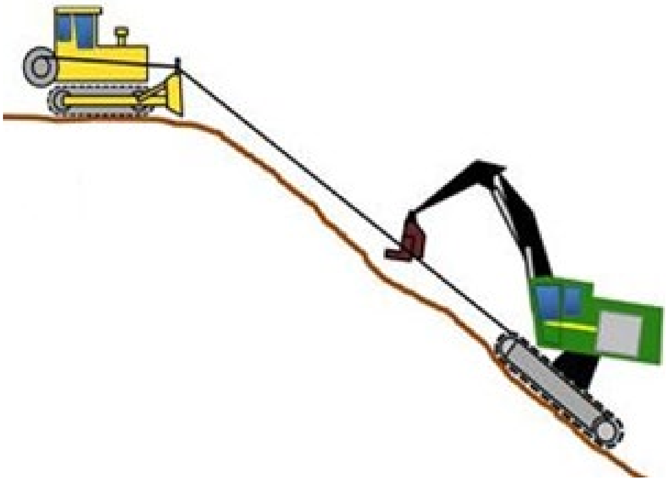

Figure 27: One example of a winch assist steep slope felling system used in New Zealand.

Slope limits cannot be readily found for many machines, and it is typical of manufacturers to not detail a slope limit (Berkett & Visser, 2012). Berkett & Visser (2012) state that slopes ranging from 30-40% (17-22°) are a realistic upper limit for wheeled and tracked machines. Machine traction, soil bearing capacity and erosion potential become limiting gradeability[2] factors (Heinimann, 1999). The addition of winch assist alleviates these issues, allowing for use on steeper slopes. Without manufacturer information, harvesting slope limits for ground-based machinery may be simplified with the following interpretation of the work by Heinimann (Figure 28). With winch assist, purpose-built steep slope ground-based machinery may operate consistently in the 'Very Critical Area' (31-39°) when soil and climatic conditions allow, and harvesting is planned sympathetically to the risk of machine instability. Figure 29 goes further to show that for the same machine (e.g. the tracked harvester), soil strength has a major bearing on the gradeability of the machine. As the soil strength increases, the gradeability of the machine increases until a plateau around the machine's inherent limit.

[2] Gradeability as presented here is the steepest slope that a machine can climb with tractive movement under a given set of conditions.

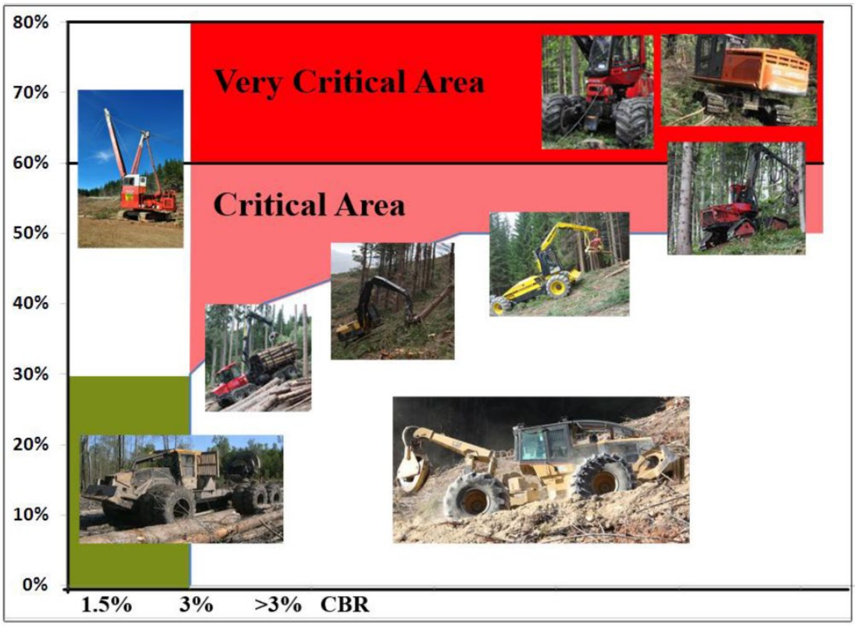

Figure 28: Safe operating range of ground-based harvesting machines related to terrain slope (%) and soil bearing capacity, as measured by California Bearing Ratio, interpreted from Heinimann, (1995). Source: Berkett & Visser (2012).

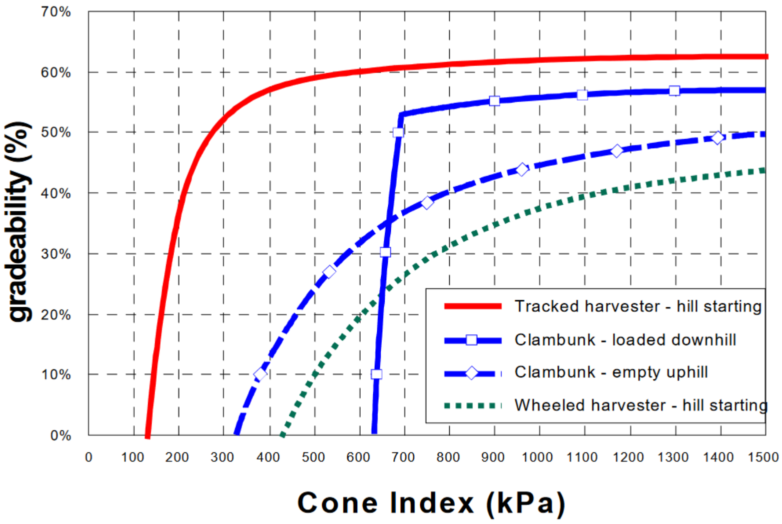

Figure 29: Calculated gradeability chart for wheeled and tracked machinery against soil strength (Cone Index measure). The clambunk (skidder) is wheeled. Source: Heinimann (1999).

5.3 EXTRACTION

Extraction generates the most options for machinery and configurations. A combination of terrain, harvest type, cost per unit harvested largely dictates the choice of extraction system at a high level. The transition to mechanisation has enforced a need for all extraction systems to be highly productive to offset the high cost of the added machinery.

Extraction systems are separated into three broad categories:

1. **Ground-based extraction** is to move the tree out of the stand with a machine (or animal) that uses tractive effort to move the timber across the ground (e.g. Figure 30).
2. **Cable-based extraction** is to move the tree out of the stand by means of a stationary machine that provides power to a system of wire ropes and attachments (e.g. Figure 38).
3. **Aerial extraction** is to move the tree out of the stand using a machine that provides aerodynamic or aerostatic lift.

All methods of extraction can be attributed to one of these. The increasing capabilities of winch assist (Figure 27, page 38) means that (mechanised) ground-based extraction can now be used on steeper slopes with lower requirements for earthmoving for skid trail construction than was previously achievable (Pedofski & Visser, 2020). This means that there is now more overlap than ever between 'cable-based' and 'ground-based' terrain. Because of cost, helicopter logging is only used in niche applications, and is typically associated with the extraction of higher value native trees, or the removal of plantation trees in very sensitive locations (Visser & Dronfield, 2023).

A consideration for biomass harvesting systems is where in the system the biomass is planned to be comminuted. This is divided into two broad classes:

1. **Whole biomass harvesting:**
   Where biomass is felled and extracted to infrastructure, without comminuting the material.
2. **At-stump comminution:**
   Where felling and comminution is done in the cutover, and the extraction to infrastructure requires the comminution of the harvested material.

This is the high-level subdivision separating the many biomass felling and extraction systems that have been trialled across the world (Kanzian et al., 2008).

5.3.1 Ground-Based

Ground-based extraction is tailored to the product being extracted and the terrain. The philosophy is the same as any logistics; to maximise the tonnes-per-hour of machine use. This involves maximising payloads and ensuring all parts of the extraction cycle are as fast as reasonable, given the conditions. WTH and CTL have diverged, with extraction machine designs tailored to the product type (stems or logs).

Figure 30: Ground-based extraction with a grapple skidder.

5.3.1.1 Whole tree extraction

WTH with ground-based machinery has trended towards 4 or 6 wheeled grapple skidders (Figure 31) as the extraction machine of choice. These are well suited to clearfell WTH and can be productive to several hundred metres from the landing (Spinelli et al., 2019). The movement of material is efficient because much of the mass of the 'load' is borne by the ground. The grapple provides lift to the stem-ends, to reduce sliding resistance. Grapple skidders are most efficient when timber is presented in optimised bunches, which is usually done by the felling machine, or occasionally with a dedicated excavator-based bunching machine. Wheeled skidders can travel overland through the cutover until around 30% slope (productively). To negotiate steeper slopes, they may be used on carefully planned paths with winch-assist (Visser & Spinelli, 2020), or else earthmoving is required to create dedicated skid tracks.

Figure 31: Wheeled grapple skidder.

There are a couple of minor variances in skidders. Clambunk skidders have an upright grapple that must be loaded, either by another machine (e.g. Figure 32) or with an integrated crane (Figure 33). Clambunk grapples are usually capable of larger payloads because of the improved lift and weight distribution. Another variance is the *cable* skidder (now infrequently used in New Zealand) which enables the operator to self-accumulate a full drag. The process is much slower and requires manual effort to pull out the cable and securely attach to stems. In the push for higher productivity and safer work, cable skidders have fallen out of favour, but do enable accumulating loads within a reasonable distance of a track without the aid of another machine.

Figure 32: A clambunk skidder with dual wheels, used for logging on extremely soft terrain in southern USA

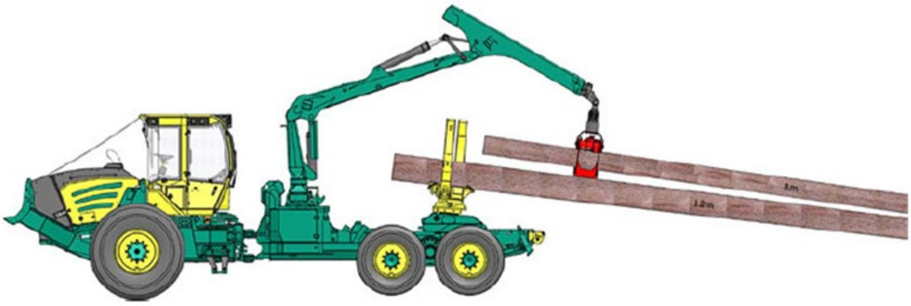

Figure 33: Self-loading multi-purpose forwarder, with a clambunk grapple attachment instead of log cradle. Source: Kaltschmitt & Stampfer (2024).

Konrad Forsttechnik and *Ecoforst* have recently co-developed a semi-autonomous winch assist clambunk skidder (*T-skidder*) for extracting on steep slopes (Figure 34). The two machines (i.e. winch-assisted skidder and winch assisting unit) work in tandem to skid stems up steep slopes along GNSS[3] waypoint routes. The *T-skidder* is intended to be remote controlled around the loading phase, then set off on its GNSS route back to the unload site, with constant communication with the *T-winch* about tension requirements for traction. As of publication there is no official indication of a release date, however the *T-winch* is used by logging contractors in New Zealand for winch-assisting a variety of manned machines.

Figure 34: Ecoforst T-winch (left, green) providing winch assistance to the semi-autonomous Konrad T-skidder (right, yellow).

Steep slope shovelling with excavator-based machines is also used successfully in New Zealand and America. Shovelling can be direct to the landing/processing area (Californian example with small clearcuts on easy-moderate terrain) or to a track, where a skidder will complete the stem's journey to the landing. Local anecdotal experience suggests that felled trees can be reasonably shovelled uphill through the cutover for up to two tree lengths before productivity losses become significant. Downhill shovelling is far more productive, reducing the earthmoving requirements for a site (for skidder tracks), or eliminating the use of a cable yarder. Alternatively, shovelling may be employed to move stems towards a cable yarder's corridor for pickup.

[3] Global Navigation Satellite System

Whole tree extraction from production thinning or selective harvesting operations must be done with care to limit damage to residual trees, inviting disease and timber defects to the remaining crop. For this reason, CTL is generally used in thinning scenarios.

5.3.1.2 Cut-to-Length Extraction

Most CTL extraction worldwide is done with forwarders (Figure 35). Forwarders are preferred for self-loading ability and their robustness to variable terrain conditions. Winch assist enables forwarders to be used on slopes approaching 80% (39°) in ideal conditions (experienced operator, good traction, smooth terrain, straight cable alignment), however this combination of conditions may be rare.

Most manufacturers have a range of prime-mover and boom options so that a machine can be scaled appropriately for the log-hauling task. Smaller lightweight 4-wheeled machines are used for thinning or SRF harvests with small trees, progressing to the largest 8-wheel machines for harvesting large trees (Figure 35).

Figure 35: Wheeled forwarder self-loading logs in a patch cut harvest.

5.3.1.3 Agricultural Tractors

Wheeled agricultural tractors are regularly used in forest harvesting in Europe due to their versatility (inside and outside of forestry) and the ability to be used profitably in low-production scenarios. Machines such as the German-made *Pfanzelt Pm Trac* (Figure 36) are purpose-built for forestry, and promoted as multi-purpose skidders, forwarders, chippers, mulchers, energywood harvesters, or power-units for small tractor-mounted cable-yarders. The machines are limited to being used on formed tracks and flat-to-gently rolling terrain only. Many agricultural tractors such as the *Fendt* and *Valtra* brands are converted to forestry use also with added machine and operator protection, and there are many marketers of forestry attachments for tractors across Europe. Some manufacturers such as *Werner Forsttechnik* in Germany specialise in the full conversion of farm tractors into forestry machines, which also includes guarding, general upgrading and certification.

Figure 36: Pfanzelt Pm Trac with detachable crane and forwarding trailer. Source: pfanzelt.com, August 2024.

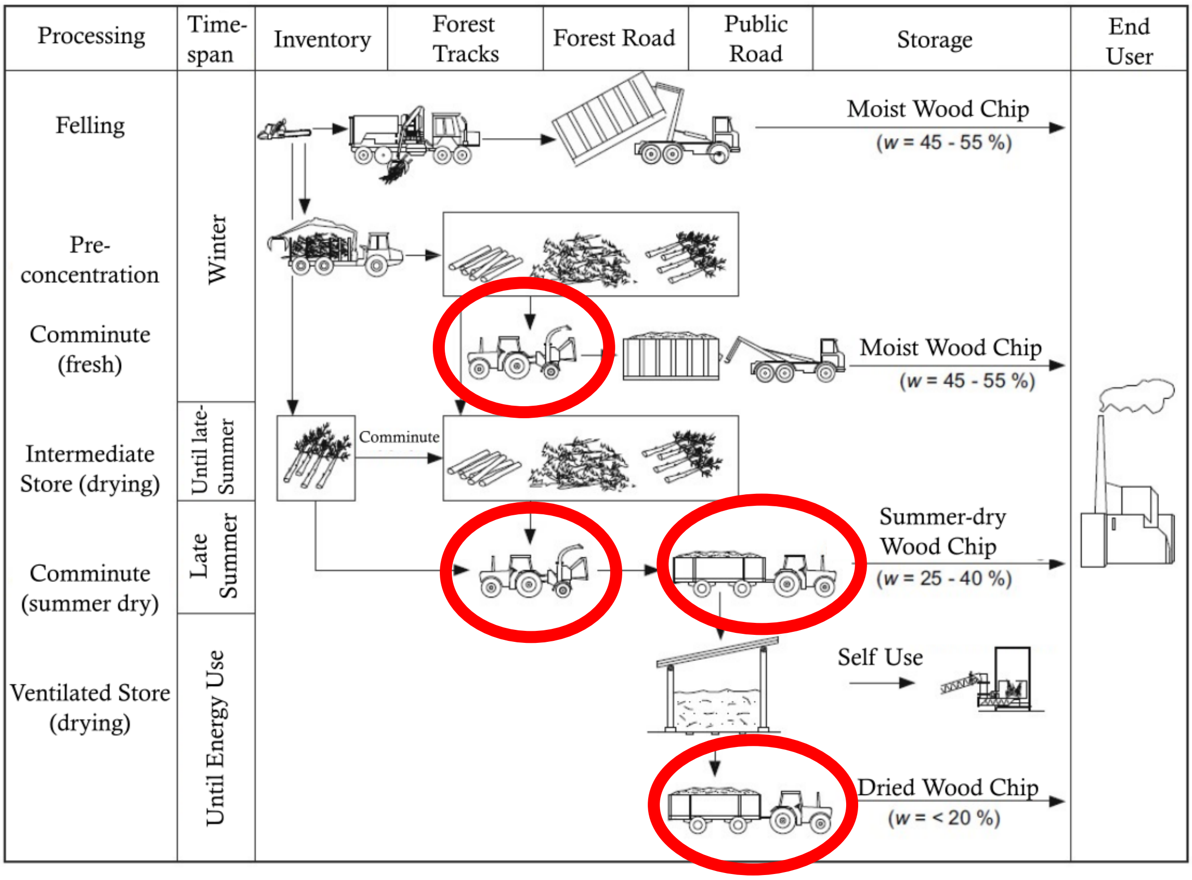

Figure 37: European style short rotation crop biomass recovery options, depending on season. Note the extensive use of agricultural equipment to reduce operational costs. Source: Kaltschmitt & Stampfer (2024)

Agricultural tractors also require a level of guarding that meets the OPS ACoP if used in New Zealand forests. Depending on the use case, machines may require retro-fitting and an engineer's certification to meet the required standards. Multi-use machinery may be attractive to a contractor in the New Zealand context, particularly with seasonal, or cyclical, market-driven demand for work as may be required for SRC harvests.

5.3.2 Cable-Yarders

Cable yarding is considered best practice for extracting timber from steep terrain and can be used in either WTH or CTL harvests. The aerial system of cables can allow good lift to timber, minimising or eliminating soil disturbance during timber extraction with the necessary infrastructure in place.

Cable yarders come in a range of sizes to suit a pricing point and productivity intentions. New Zealand's tower and swing yarder fleet (e.g. *T-mar*, *Madill*, *Thunderbird*, *Skagit*, *Berger* branded machines) represents some of the most powerful machines available globally, and therefore have high productivity demands of them.

Figure 38: A cable yarder (specifically a 'swing' yarder) extracting a stem to a forest road with a mechanical grapple..

The newer excavator-based yarders (such as the locally built *Harvestline*, Figure 41, page 48, *Alpine Shovel Yarder* & *APEX Smart Yarder*) are mid-sized and offer a solution that can be deployed quickly on short corridors (Abeyratne, 2021). European mid-sized solutions are truck-mounted, trailered, or self-propelled tower yarders (Figure 39) that are designed to be set up on a road or landing.

Figure 39: Italian-built Valentini V850, self-propelled, remote-controlled & semi-automated tower yarder.

Smaller yarders also come from the European market which are carried and powered by agricultural tractors (Figure 40). These are designed for small timber, or to extract logs only in a CTL harvest. Features (such as a haulback drum) depend on the model, but in general these are designed for simple, uphill operation.

Europe's smaller harvest areas on steep slopes lead to an extensive use of manual tree falling, and manual breaking out; something that New Zealand's operations have actively trended away from. Safety issues associated with breaking out in Europe have been partially mitigated with remote-control technology. In many yarder/carriage offerings now (such as that shown in Figure 39), the head breaker-out takes over control of cable movements (yarder driven) *and* the carriage functions with a remote control during the hook-up and breakout phase (*APEX* – a local manufacturer also has this feature), then sets the carriage to auto-return to the yarder. The yarder then automatically manages cable tensions and line speeds (stopping for errors/exceptions) according to the pre-programmed instructions. The yarder operator who is usually working the mechanised log processor, will then take back control of the yarder's movements at the end of the inhaul for the final drop of the drag and set the carriage to auto-return to the previous breakout position. European semi-automation allows the right workers to be in control at the right time and inbuilt programming minimises the chances of overloading or damaging usage.

Figure 40: Austrian-built Koller 301-T Tractor-mounted yarder for thinning and small timber harvesting operations. Source: Koller K 301-T Product Catalog.

Mechanisation in New Zealand has directed a shift away from manual breaking out, and towards grapple carriages to remove people from the slopes. There are several possible reasons for this choice, rather than semi-automation and remote control which European loggers have opted for instead. With restricted lateral cable movements possible, many tower yarder operators have adapted to now integrate mechanised winch-assist felling, bunching in corridors, and/or 'feeding' grapples with excavator-based machines (Howden, 2023). The net result of removing breaker-outs (and by association also manual fallers) is fewer exposed workers, higher emissions, more soil disturbance, but an unexplored effect on cutover woody residue volumes.

Hybrid power and full electrification of cable yarders or carriages is underway in several markets. *Alpine Logging Equipment* in New Zealand have for many years offered a grapple carriage that recovers energy as hydraulic pressure with its movement along cables. *APEX Equipment* offer a grapple carriage that recovers energy from cable movements, and stores that in batteries for grapple function. *HULK*, a European startup, have developed a fully electric dropline carriage (for manual breaking out) that self-drives along a standing skyline cable, without needing drive power from a yarder. The *HULK* is in the late stages of commercial development, before market release. *Koller* (the Austrian cable logging equipment manufacturer) demonstrated a hybrid-electric *K410* tower yarder concept with electric *ECKO* slack-pulling carriages at the 2023 Austroforma machine show. These all promise lower emissions per tonne of timber harvested.

Yarder operations are complex to plan as a result of the terrain they are used in. A combination of yarder, terrain, infrastructure and crop type need to be known for cable planners to be able to assure feasibility. Yarding machinery (particularly medium to large equipment) is a significant investment, and acquisition of a new 'system' requires assurance of a consistent programme of work to de-risk the venture.

An estimated 750 logging crews work in New Zealand’s commercial forests; around 320 are cable-harvesting crews and the remainder are expected to be ground-based crews (Harrill & Visser, 2019a, 2019b). Cable-harvesting crews typically also have access to ground-based machinery (e.g. a skidder, Figure 30) to provide some versatility and consistent production (needed for the high operation costs), particularly while the cable yarder is shifted and set up in new harvest areas or is set aside for maintenance.

For a logging contractor, the choice of extraction system to specialise in is a major investment decision, most particularly for a ‘small’ business with 1-2 harvesting crews. The skillset required of the machine operators is quite different and significant capital is required – particularly so for a ‘typical’ Pacific Northwest-style swing yarder or tower yarder owner. Winch assist now allows ground-based crews to expand into steeper terrain than would have been reasonable previously and as a result ground-based crews have more harvesting work available. Conversely yarder crews can now divest their yarders and offer a more cost-effective operation on ‘straightforward’ cable-harvesting terrain (where the environmental and infrastructure constraints allow).

Environmental effect of harvesting remains a determinant of extraction system used. Cable yarding is still regarded as ‘best practice’ for extracting trees from difficult or sensitive terrain (Harrill et al., 2019; Visser & Harrill, 2017). Cable yarding is nearly unlimited by terrain steepness, however infrastructure, cable corridor planning (lift feasibility), worker safety, productivity estimates and residual slope stability risk define where cable yarding *should* or *can* be carried out on a given site. The infrastructure needs of ground-based and cable-based harvesting are often quite different for the same harvest setting and, in many cases, whether winch-assisted or not, cable yarding requires less earthmoving in sensitive areas. The recent local development and market uptake of the more affordable excavator-based yarders (Figure 41) may indicate some recognition of that (Raymond & Hill, 2018; Visser et al., 2024).

Figure 41: A New Zealand-built 'Harvestline' excavator-based yarder and operator (Abeyratne, 2021).

European models of steep slope extraction challenge New Zealand’s harvesting norms and have seen a low uptake in the local logging market (Shepperd & Visser, 2021). The reasons can only be speculative with few examples of European yarders used in New Zealand in the modern era. European cable systems offer a more adaptable solution to terrain constraints such as convex terrain profiles by the widespread use of standing skylines together with intermediate supports, at the expense of extraction productivity.

The setup of European standing skyline systems often requires tree-climbing and rigging at more than one point along the cable corridor, making the setup of each cable corridor more laborious. New Zealand's setups have single spans (no intermediate supports) and yarders generally have high line speeds, while clearcuts allow for rapid line shifts to new hauling corridors. The productivity benefits of the New Zealand systems are therefore clear. New forest regimes or harvest constraints which compromise logging productivity could lead to greater adoption of European-style extraction systems, with favourable market signals and/or confidence around their safe operation. The risk is combining productivity compromises with low-value harvest products, so regime changes or new harvesting constraints (or a combination) must be carefully analysed before implementation.

5.4 COMBINATION EQUIPMENT

The Harwarder is simply a forwarder with a robust crane arm and harvesting head. The Harwarder is designed to complete the functions of both a harvester, and forwarder in CTL harvesting operations. The concept was first developed in the 1950's, called the '*Bush Combine*'. *Hemek*, *Valmet* and *Ponsse* (Figure 42) are brands that have produced harwarders since the 2000's, with *Valmet* even integrating an innovative rotating log cradle to eliminate double handling (log-make directly to the cradle) (Wester & Eliasson, 2003). Kärhä et al. (2018) detail that the harwarder is more efficient than a harvester/forwarder system in small timber harvests (stems ranging from 0.11-0.17 m^3 $stem^{-1}$) or low intensity harvests, and lowers the relocation cost between harvest areas. When timber is larger, the two-machine system is more profitable. Von Bodelschwingh (2003) additionally notes that for the machine operator, the multiple tasks required to harvest with a harwarder breaks the "monotony" of machine work, potentially a benefit for retaining skilled workers, reducing staff turnover.

Figure 42: Ponsse Buffalo Dual forwarder (harwarder). Source: Laitila & Väätäinen (2020)

Forwarder-mounted biomass bundlers were a niche product developed and widely tested in Europe during the 2000's-2010's. The concept is to collect the branches after CTL logmaking in the forest, baling them densely into log-form for transport with existing machinery. The concept and application were sound, with *John Deere* producing the *1490D* bundler (Figure 43) for several years which saw application in Europe and America. Spain-based manufacturer *Monra Forestal* produce a forwarder-mounted unit called the *ENFO 2000 Woodpac*, which reportedly reduces biomass volume "up to 80%", making bales 60-80cm in diameter. Headwinds for slash bundling internationally include concerns of over-harvesting slash from forests (nutrient loss), and narrow margins on the low value product.

Figure 43: Forwarder-mounted biomass bundler. Source: Kaltschmitt & Stampfer (2024)

In a similar concept, the extremely versatile forwarder prime mover has also been fitted with chippers with or without high-lift discharge bins for processing stem and branch waste as they move through flat to gently rolling cutovers. One such example is the *BRUKS 806.3* Mobile drum chipper which is designed to be retrofitted to medium-large forwarders. The power demands of chippers require a separate, dedicated engine. Productivity is heavily dependent on the balance of time feeding the chipper and that spent moving, emptying a full chip bin or waiting for support from chip shuttles (usually agricultural tractors with towed bins – e.g. Figure 37, page 44) to take chip to the roadside.

Other forms of modified agricultural machinery, designed for coppice crop harvesting have been detailed in Section 4. In essence, due to the small stem size of coppice crops, agricultural tractors with towed harvesters, or modified forage harvesters are often more appropriate, aggregating stems in a continuous harvesting pass, rather than on an individual basis such as regular forest harvesting.

6 Specific Scenarios – System Options

In this chapter we consider various forest and harvesting scenarios, and then reflect on the principles that might lead to the best machinery selection.

6.1 THE EFFECT OF FOREST STOCKING RATES

As a general relationship for a plantation forest, stocking (number of trees per hectare) has an inversely proportional relationship with the size of each tree; that is the denser the plantation, the smaller each tree is for a given age. As the individual tree size reduces, mechanised harvesting systems depend more and more on mass handling for gains in efficiency.

At one end of the tree-size spectrum, current New Zealand tree crops grown for a combination of clearwood, veneer, structural and industrial log types offer a tree size where felling must be done on an individual tree basis because of machine/harvesting environment limitations. Extraction systems such as grapple skidders and large cable yarders are not as impacted by the individual tree size so can handle several stems at once. Logmaking must create log products that meet strict customer specifications in New Zealand and is therefore a significant constraint that ensures logmaking is completed one tree at a time.

At the other end of the spectrum is SRC with extremely small stem diameters, the harvesting machine is proportionally (/comparatively) much larger than the individual stem and is therefore able to fell on a continuous basis. There is also no need for product differentiation. The entirety of the above-ground tree is made into chip, which eliminates the individual assessment and segregation of the highest value portion(s) of the stem.

It is clear therefore that there are several factors, other than stocking and usually customer/product-driven that might dictate a certain harvesting system selection. Stocking only has an indirect effect on machine choice.

In general:

1. Tree size is inversely proportional to stocking.
2. Large trees need to be felled individually.
3. Small trees, destined for low-value products must be felled and handled extremely efficiently, with minimal waste (e.g. breakage).
4. For mechanisation, machine size needs to be appropriate to the ‘unit’ of harvesting, i.e. falling machine is appropriate for felling 2-tonne trees individually, or accumulating several 0.3-tonne trees in bunches.
5. Product differentiation, which is progressively more attractive as tree size increases, increases harvesting complexity and related product segregation costs.
6. Product differentiation needs either:
    a. Individual assessment and processing, or
    b. Eased customer specifications to enable mass processing; i.e. chain-flail delimbing and mass cross-cutting into logs (see: ‘slasher saw’, Section 4.1.4.2).

6.2 SHORT ROTATION COPPICE

SRC has only been carried out at scale on flat to gently inclined terrain internationally, and usually with the help of government incentives, and sometimes with co-benefits (e.g. water filtration). Combine harvesters or agricultural machinery have demonstrated acceptable performance in SRC plantings and are attractive choices due to the seasonality of SRC harvests, enabling machinery owners to satisfy regular agricultural demands in other parts of the year.

In general:

1. One-pass harvesting SRC at scale is efficiently done with modified combine harvesters, creating a high moisture content chip products.
2. Multiple pass SRC harvesting with agricultural tractors and implements adds complexity but allows for improved management of the product's moisture content, and therefore increase its value.
3. Existing SRC owners internationally have not targeted steep slopes as a rule and so adoption of the regime on steep slopes in New Zealand will incur significant risk where other, cheaper sources of biomass are available.

6.3 HARVESTING AGROFORESTRY

Agroforestry may take an array of forms based on the needs of the property owner, farming system and landscape. It can be assumed that agroforestry prioritises pasture production. Widely spaced trees may be used to add soil stability, supplementary fodder (depending on species choice), runoff mitigation and/or shelter to paddocks. Low (tree) stocking rates and/or partial harvests will comparatively lower the productivity and profitability of any harvest in any terrain. The drive to make a high-value sawlog product to offset the high harvesting unit price is therefore significant. If logs are produced, paired harvester & forwarder, or harwarder systems are likely to be the safest and most viable harvesting systems for these agroforestry systems. Farm infrastructure often requires machinery that can forward timber some distance from the harvesting site to an access point for road transport, and the sensitivity of the forwarder or farm tractor + forwarding trailer around farm infrastructure such as gateways and culverts makes each a decent choice. The farm tractor + forwarding trailer additionally can be operated on public roads (chaining-down log packets is likely required), and at relative speed, thereby increasing the possible forwarding distance where required.

No one harvesting approach will be 'the model' for agroforestry systems unless relative consistency emerges, on a district or regional basis for tree management. One such model is the example of widened shelterbelts on flat to rolling terrain. Shelterbelts planted as 4+ rows of a common commercial forest species can offer some pastoral benefits, while also being logged with conventional machinery and techniques and sold to existing markets. A relatively consistent approach on a regional basis allows contractors to invest in the appropriate machinery and offer a consistent service to tree owners.

In general:

1. Small harvest areas or low harvesting volume throughput make agroforestry harvests more inefficient than for commercial forestry, making full mechanisation less viable.
2. Farm infrastructure and systems need to be considered, with occasional long forwarding distances and/or seasonal harvesting requirements.
3. Agricultural tractors are widely used for forest harvesting in Europe but may need additional safety guarding if used in tree harvesting in New Zealand. This is however dependent on application, so compliance checks should be sought.

6.4 MULTI AGE-CLASS FORESTRY

Harvesting multi-age class forestry (also known as 'continuous cover' or 'shelterwood' regimes) is demonstrated locally in Woodside Forest in the Canterbury region (Novis et al., 2005). The management of some Coastal Redwood stands in California are another example of the practice (Giusti, 2004). The selection strategies differ, but the intent is relatively similar. At each entry for harvesting, the mature (or selected) portion of the crop in any given area is felled and extracted, leaving mixture of immature and near mature crop behind for later harvest. Harvests usually aim to recover at or near to the volume growth increment of the stand. European examples vary from 5-to-15-year cycles for selective harvests.

Harvesting a continuous cover forest must be sympathetic to the remaining crop to ensure the long-term growth productivity of the stand. Manoeuvring machinery, felling mature trees within a stand and extracting whole trees (or logs) while only doing "acceptable damage" (Novis et al., 2005) is more difficult than clearfelling, leading to the general necessity for high road densities and higher logging costs per cubic metre harvested. For the Woodside example, the cost is somewhat overcome by the improved returns from harvesting only high value timber (Evison et al., 2024). For European steepland cable logging scenarios, loggers are familiar with the need to protect established seedlings during harvest operations to expedite the growth of the following crop (by more than a decade in many instances).

Fully mechanising the harvesting in multi-age class forests may remain a challenge due to the low production rates offered by selective removal. With the benefit of rolling to steep terrain, valuable redwood timber and economies of scale, the Mendocino and Humboldt Redwood Companies, California use large cable yarders for cable extraction when harvesting a significant fraction of the standing crop on less regular harvesting schedules, however in meeting the silviculture goals, parts of the harvest operation, including falling and breaking out remain manual.

In general:

1. Selective harvesting using a mixture of manual and mechanised methods in multi-age-class forestry is proven on easy-to-moderate terrain with high road density.
2. Creating a valuable log product mix can offset decreased harvesting efficiency.

6.5 TRADITIONAL PLANTATION PRODUCTION THINNING

Production thinning has been practiced with varying enthusiasm over New Zealand's history with plantation forestry (McConchie & Terlesk, 1990). Today, about 13% of the national estate is production thinned (MPI, 2024). It is primarily a silvicultural treatment, intended to improve the quality of the remaining crop and so a narrow margin or a small cost is often acceptable to the forest owner, as detailed by the 55% of area that is currently manually thinned to waste (a cost). Today's small, paired harvester and forwarder harvesting systems are common (Taylor, 2021) and offer the best chance of economic viability, enabling:

a) Harvesting on flat-to-rolling terrain,
b) Acceptable stand damage with only cut logs extracted.
c) Straightforward load accumulation to ensure each cycle is as optimal as the log product mix allows.

Extraction of thinnings by cable yarder was practised in New Zealand prior to 1990. High equipment costs and damage to remaining crop trees led to abandonment of the idea (McConchie & Terlesk, 1990). Steep terrain will always be the first to become unviable in challenging log market conditions due to the higher machine operating costs.

In general:

1. Production thinning is sensitive to several external factors including:
    a. Distance to market,
    b. Market prices offered,
    c. Machine operating costs,
    d. Stand characteristics / thinning intensity, and
    e. Harvesting efficiency.

With these addressed, more waste-thinning area will become attractive to production thin, opening up significant volumes of biomass for sale opportunity.

7 Biomass Harvesting System Recommendations

This literature review has outlined that harvest ‘systems’ are not static options. Rather, a harvest system is the sum of parts, and each part can be tailored to the constraints posed by the terrain, crop, and intended product mix. Recommendations for a harvesting system should only be ever relative to a set of goals and criteria. For example, a vertically integrated company that grows and harvests its own fibre may have different goals and view of market risk, than an independent forest owner that grows to supply a free market; even if each of these owners occupy the same type of land. That is, the vertically integrated company will focus on choosing a harvest system meets the quality and productivity expectation of for making the final product, whereas an independent biomass grower make need additional flexibility in harvest system choice to react to market external demands. A plantation management company that has a primary focus on growing trees for the higher value sawlog market, but also has forest resources aligned with biomass products, will possibly seek to utilise their existing ‘mature tree’ harvesting capability and modify its practices rather than invest in additional biomass specific equipment.

The “which harvest system is best?” question should be reframed to: “what harvest system will deliver the quantity and quality of product mix that maximises the post-harvest returns of my forest?” as a better reflection of the interconnected nature of silviculture, markets and harvesting systems.

In terms of choosing a harvest system, there will be two over-arching considerations, being (1) ensuring worker safety & health and (2) complying with both national and regional level environmental regulations.

Regarding ***worker safety & health***, specific considerations for a biomass type harvest system, as presented earlier in this report, will still be guided by the machine options, technology and skills available. While smaller tree sizes allow for more manual options to be considered, the productivity focus for efficiency through scale will strongly lend itself towards the safer, mechanised harvesting options. Current long term trends in New Zealand plantation harvesting have been to reduce worker exposure hours in ‘high risk’ manual tasks where possible, and so reversing that trend will require some wider discourse about priorities.

With regard to ***environmental regulations***, a primary focus is invariably the protection of water quality. This involved ensuring the harvest is well planned and the operations carried out in such a way as to minimise the overall level of soil disturbance – especially on slopes. Specifically short rotation crops lend themselves to higher intensity harvest practices (more machine movement to harvest the higher number of trees in a given space), and also short rotation crops require more frequent harvesting, increasing pressure on environmental performance. Biomass forests will have a strong link to carbon sequestration and/or the overall goal of emissions reduction, the choice of harvest system design should also take into consideration the relative overall carbon footprint.

With safety and environmental standards ensured, the harvest system should be optimised with regard to ***economics*** (time and money) ***crop recovery rate*** (percentage recovered, minimal breakage). With the caveat that there are these many considerations, the following sections with supporting tables provide examples of harvest system selections as differentiated by: (1) Short rotation forestry (clearfell), (2) short rotation coppice and (3) traditional plantations.

7.1 SLOPE AND LOG SORT EFFECT ON SHORT ROTATION FORESTRY

Short rotation clearfell forestry is further divided by terrain class and product mix in terms of 'log sorts'.

With regard to slope categories:

< 30% is considered relatively flat / rolling where under normal conditions all modern ground-based operations could operate effectively.

30 – 50% is hilly and getting steep, where purpose built steep slope machinery can operate, but ground-based systems with winch-assist can work comfortably and productively, especially on wet or unstable slopes.

50 – 70% is a reasonable upper range for usual winch-assist, but also very much cable logging territory.

> 70% is very steep, where typically a harvest system might revert to using manual fallers, and cable yarder extraction.

With regard to log sorts:

Chip only – means the whole tree can be simply limbed (and debarked, depending on product requirements) and everything is directed to a single product sort ('biomass')

2 log sorts – means that a higher value butt log might be recovered when the quality (typically diameter and length) is suitable, the remaining upper portion of the stem is 'biomass'.

>2 log sorts – More than two log sorts starts to trend towards more conventional harvesting systems, where the stem value is carefully optimised by making multiple quality sorts of different values, and then biomass starts to become a 'by-product'.

Table 1: Recommendations of SRF harvesting systems to be considered by terrain and log product mix (as a proxy to tree dimensions).

<table>
<tr><th rowspan="2">TERRAIN CLASS</th><th colspan="3">PRODUCT MIX</th></tr>
<tr><th>Chip only</th><th>2 log sorts</th><th>>2 log sorts</th></tr>
<tr><td>0 – 30%
(0-17°)</td><td>WTH
Excavator-based felling machine.
Fixed head bunching hot saw.
Grapple skidder to roadside.</td><td>WTH
Excavator-based felling machine.
Fixed head bunching hot saw + prelim. tree size segregation.
Grapple skidder to landing.
Chain flail + slasher saw.</td><td>CTL
Small wheeled harvester.
Forwarder to roadside.</td></tr>
<tr><td>30 – 50%
(17-27°)</td><td colspan="2">CTL
Excavator-based harvester (w-w/o winch assist) + multi-stem processor head.
Forwarder (w-w/o winch assist) to roadside.</td><td>CTL
Excavator-based harvester (w-w/o winch assist).
Forwarder (w-w/o winch assist) to roadside.</td></tr>
<tr><td>50-70%
(27-35°)</td><td>WTH
Excavator-based self-levelling falling machine (w- winch assist).
Fixed head bunching bar saw.
Cable yarder with grapple.
Buffering capability at the landing for chipper throughput needs to be considered.</td><td rowspan="2">WTH
See left.
Add processing with chain flail and slasher saw.</td><td rowspan="2">WTH
See far left.
Add processing with mechanised processor.</td></tr>
<tr><td>> 70%
(>35°)</td><td>WTH
Manual felling.
Cable yarder with slackpulling carriage (manual breaking out).
Buffering capability at the landing for chipper throughput needs to be considered.</td></tr>
</table>

7.2 STOCKING EFFECT: AGROFORESTRY AND COPPICE

Stocking can also influence harvest system choice. Two specific scenarios are presented here with distinctly different tree stocking, being a very low stocking associated with agroforestry, and a very high stocking associated with coppice. They are also related to slope classification. Specifically:

- **Agroforestry** – tree owners are likely to favour pastures being minimally damaged and so whilst skidding may be efficient, it is also damaging to pastures and farm infrastructure. Hence there is a implicit need to select the system with the lowest possible impact on the pasture.
- **Coppice** – results in a very high number of ‘trees’, but these are not individual trees but sprouts from a common stump. Each stump many have multiple harvestable sprouts. The main challenge with harvesting coppice is that our regular harvesting heads can struggle to grab and cut these sprouts.

Table 2:Recommendations of harvesting systems to be considered for agroforestry and SRC based on terrain slope classifications

<table>
<tr><th>TERRAIN CLASS</th><th>Agroforestry
(<200 stems ha^{-1})</th><th><b>Coppice
(>>2000 stems ha^{-1})</th></tr>
<tr><td>0-30%
(0-17°)</td><td rowspan="2">CTL
Wheeled harvester.
Forwarder or agricultural tractor + forwarding trailer.</td><td>CONTINUOUS HARVESTING
Single-pass.
Agricultural tractor with 3-point linkage mounted harvester/chipper.
Choose unit appropriate to stem size.
Agricultural forwarding tractors towing high-lift tip bin trailers.</td></tr>
<tr><td>30-40%
(17-22°)</td><td>CONTINUOUS HARVESTING
Single-pass.
Slope-capable agricultural tractor with 3-point linkage mounted harvester/chipper.
Agricultural forwarding tractors towing high-lift tip bin trailers.
Technical challenges may require R&D solutions.</td></tr>
<tr><td>40-70%
(22-35°)</td><td>CTL
Wheeled harvester.
Forwarder
Winch assist where site conditions require.</td><td rowspan="2">Not recommended</td></tr>
<tr><td>>70%
(>35°)</td><td>Not recommended.</td></tr>
</table>

7.3 GOALS WITHIN TRADITIONAL PLANTATIONS

With the potential future changes to market demands for products from New Zealand's traditional plantations, and/or increasing demand (and value) for woody biomass, consideration has also been given to the changes of current harvesting systems. To improve biomass recovery and productivity the following minor system changes or foci should be investigated further, with respect to the crop harvested:

- **Fixed felling and bunching heads for 'small' or 'very small' trees**
  - The lower breakage rates found when felling small trees is already returning benefits for some. For 'very small' trees, bunching heads should (depending on work pattern) reduce the total amount of slewing compared to bunching each stem individually, increasing work rates as a result.
- **Regime change on 'difficult' harvesting terrains (reduced harvested tree size)**
  - Clearwood regimes offers high value logs, but individual trees typically also have greater dimensions, making them more predisposed to breakage during felling. Structural or short rotation biomass regimes are likely to reduce breakage rates through the harvest of smaller trees.
- **Clean presentation of biomass grades.**
  - Biomass customers can be particularly sensitive to product that is contaminated with soil and stones. Careful planning and handling of the stem from stump to truck is therefore a must. This extends (where necessary) to landing design if extraction from residue piles is planned, and the work patterns on landings to reduce the chances of contamination.
- **Ensuring machines are not 'oversized' for task.**
  - This review has highlighted the importance of the concept of mass handling for maintaining efficiency as tree size decreases – or reducing the machine size to suit.
- **Consider biomass as an alternative to industrial log grade supply.**
  - Relaxed log specifications for biomass supply (when compared to industrial specifications) may allow faster log production and a marginal increase of fibre volume being sold. Domestic and export market fluctuations will define the economic decision at any given time, but research will need to be conducted into the likely volume difference to aid the calculation of the breakeven price differential between biomass and industrial logs.

8 Conclusion

This report provides a detailed literature review to support the development of woody biomass harvesting practices. The New Zealand plantation industry has prioritised growing trees for industrial use (i.e. logs, pulpwood), and the residue material used for energy is secondary. While the recovery of residues from current forestry practices presents a low-cost opportunity, the scope and scale of producing renewable energy will remain relatively small unless product is redirected to biomass markets or plantations are established and grown with the priority being the production of woody biomass.

For considerations of harvesting woody biomass specifically, it is important to recognise that a harvesting system is the sum of its parts, where each part is chosen to carry out a task with the highest possible efficiency whilst also meeting the constraints. Many of the constraints on the harvest system are actually as a result of terrain, silviculture, and a forest owner's intent for the crop given the market conditions at the time.

Harvesting forests for biomass can be investigated in many ways. New Zealand plantation forest owners are already demonstrating an intent to extract 'biomass' log grades from structural or direct sawlog (clearwood) regimes. But other regime options involve planting at high (SRF), or extremely high (SRC) stockings, lowering the value of the product, but also increasing the volume growth from a site when compared over the same timeframes. These regimes enable and require a simplification of harvesting to ensure the harvesting cost (especially the cost of mechanisation) does not make the regime choice unprofitable.

This literature review presents a number of solutions from around the world to the challenge of mechanising the harvesting of small or extremely small-dimensioned timber. The recommendation is that New Zealand does not pursue a 'one-size-fits-all' approach for biomass harvesting. This is particularly due to the exposure (or lack of exposure) of forest owners to markets for log products. Product differentiation complicates and adds cost to harvesting, but allows for sale options. Mass handling principles may still be applied however, even with log product differentiation, and so where small trees are being harvested, bunching felling heads, mass debranching/debarking and crosscutting at lower specification could be the key to lower costs per cubic metre harvested.

9 Glossary

Term	Description
Break(ing) Out	The first few movements of stem or logs as they are lifted from their stationary position on the ground during extraction.
Breaker Out	A person who hooks up stems (usually with wire rope chokers) for extraction.
(Cable) Yarder	A yarder is a machine that has one or more winches for powering the movement of wire ropes used for cable logging.
Carriage	A machine or attachment the moves along a system of wire ropes for transporting stems or logs in a cable logging system.
Chain flail	A machine of contained spinning chains that knock bark and branches off either singular or bunches of stems.
Clearfell	Large areas 100% harvested of trees.
Comminute	To pulverise, or reduce to smaller parts (used in connection to making chips or hog fuel)
Coppice	Coppice is the new shoots that a tree generates from a cut stump.
Crosscutting	Making a cut perpendicular to the long axis of a stem.
CTL	Cut-to-Length: a harvest system where the trees are processed into logs 'at the stump' where they are felled.
DBH	Diameter at Breast Height (of a standing tree)
Delimber	A machine that cuts the branches off a stem.
Drag	One or more trees that are or have been extracted.
Feeding Grapples	A machine bunches and delivers stems directly to a grapple.
Forage harvester	A harvester typically used for agricultural grain crops.
Forwarder	A machine that collects cut logs and transports them from one place to another - usually from 'the stump' to a landing or roadside.
Harvester	A machine that fells and processes trees into logs.
Harwarder	A machine that does the job of both a harvester and a forwarder.

Hog fuel	Low quality industrial woodfuel made by smashing timber with rotating hammers at high speed.
Intermediate Support	A tree that is rigged to hold the standing skyline aloft some distance between the yarder and the tail-tree (end of the corridor).
Kerf	Width of a cut.
Land Expectation Value	A discounted cashflow calculation of the value of bare land in perpetual timber production.
Landing	A dedicated staging area for harvested trees and/or processing.
LED	Large End Diameter (of a cut log)
Monocultural	A crop of a single species.
Piece Size	Refers to the size in tonnes or cubic metres of the unit of work, usually a tree.
Processing	The action of turning a whole tree into product(s) such as logs.
Regime	A categorisation of similar silviculture practices.
Rotation	The lifecycle of a single age-class forest.
Sawlog	A log that is destined for a customer of solid timber products.
SED	Small End Diameter (of a cut log)
Self-levelling	Where the cab of the machine can operate at an angle to the undercarriage or chassis, improving operator comfort.
Shovelling / Shovel logging	Shovel logging uses an excavator to swing logs in a non-tractive manner to a landing or road-side for processing or further extraction. This method of shifting stems poses as an alternative to other conventional ground-based and cable extraction methods using skidder/forwarders and skylines respectively" (Deans, 2013)
Silviculture	Operations conducted to influence the growth and composition of a forest for particular outcomes.
Slash	Residues of forest harvesting, specifically branches, cones and needles.
Slasher saw	A machine consisting of a large cradle and actuating bar saw for crosscutting bunches of logs.
SRC	Short Rotation Coppice: a tree crop that is established at the densest spacing and harvested at the shortest rotations, and

	therefore is regenerated by coppicing to offset a very high establishment cost.
SRF	Short Rotation Forestry: a conventional tree crop, which is established at higher stocking and harvested on shorter rotations than a common forest plantation.
Stocking	Density of trees per unit of area (usually hectares).
Structural	Timber destined for a use as solid wood for framing and similar uses.
Thinning	A silvicultural treatment. Selective felling of trees in a forest.
Waste thinning	Thinning, where the felled trees are not recovered for sale.
Winch assist	Where a machine's traction is assisted with a system of cables and winches.
WTH	Whole-tree Harvesting: a harvest system where trees are transported some distance away from where they are felled before being processed.
Zero tail-swing	An excavator-based machine that can rotate without extending the counterweight outside the footprint of its tracks.
Zero-turn	A turning radius that is effectively zero.

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