



Past, present and future of industrial plantation forestry and implication on future timber harvesting technology

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Abstract Plantation forests are established, and expanding, to satisfy increasing global demand for timber products. Shifting societal values, such as safety, productivity, environmental, quality and social are influencing the plantation forestry sector. This is primarily driven through an ever increasing world population, which in turn influences the way nations view the value systems by which they live. More people require more resources—also forest products. Also, the availability of information is influencing the pace of technological development. These changes could result in a difference in the management of plantations that could affect the forest engineering systems of the future. This review aimed to summarize the current status of plantation forests; summarize future developments and

possible scenarios in forest plantation management for the various products; and assess whether these developments in a plantation environment could affect the harvesting systems used. Factors influencing the form of plantations include the type and nature of the plantation owner; the change in demand for different and new forest products; climate change factors, including the use of biomass for energy, carbon sequestration and trading; ecosystem services and other products and services; and sustainability certification of forest management. The impact and influence of these factors were summarised into a series of key drivers that will influence the technology used in harvesting machines, as well as the choice of harvesting machines, systems and methods. These drivers were the effect of variations in tree size, the expansion of plantation areas onto more difficult terrain, diversity in plantation design, increased attention towards site impacts and the increased use of biomass for energy. Specific information is provided regarding how the harvesting systems could be affected.

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Introduction

Due to the early abundance of natural forests, large scale plantation establishment only began in the 1960s (Szulecka et al. 2014). Pressure was increasing to reduce the deforestation rate of natural forests, which had become alarming. Plantation forests were, and continue to be, established to satisfy increasing global demand for timber products (FAO 2009, 2010, 2016), and they have the potential to supply the worlds entire wood needs (Fenning and Gershenson 2002; Siry et al. 2005). Modern industrial

plantations are usually well managed, produce better quality wood, and have very high growth rates and short rotation lengths, and embrace tree improvement technology (Campinhos 1999). Plantation area increases over the last two decades have been coupled to forestry industry internationalisation and a shift of industrial plantations to the southern hemisphere (Korhonen et al. 2014), thus helping in reducing the pressure on primary forest, modified natural forest (FAO 2016). Due to government promotions and grants, plantation areas have increased in some European countries as well (Assirelli et al 2016).

New technology and technology substitution influences the supply and demand of forest products. New products from wood biomass are emerging and certain conventional wood products are being substituted. As wood is by and large a commodity product, the forest sectors of different countries are linked by international trade and global environmental policies (Rauinkar et al. 2010). Forest management is thus a global business, which currently has changing forest ownership patterns. The land owners determine the management objectives and priorities. Owners of forest land are usually driven by financial returns, and forest management reflects this. Industrial plantations are affected by this more than other forestry types, such as woodlots and natural forests (Lacy 2006). However, the global forest sector has become more complex, interlinked and cross-sectoral. Aspects such as climate change, energy policies, nanofibre and biochemistry technologies, forest ecosystem services and changing values, are becoming increasingly influential (Hurmekoski and Hetemaki 2013).

All of these developments potentially impact the form of industrial plantations in the future. These changes could result in a difference in the management of plantations that could affect the forest engineering systems of the future. The main aims of this review are: (1) to summarise the current status of the forest plantation; (2) to identify the future development and possible scenarios in forest plantation management for the various products; (3) to assess whether these developments in a plantation environment could affect the harvesting systems used. In particular, this review will try to offer some preliminary answers to questions about the changing roles of forest plantations and their effect on the evolution of forest technology. To this end, the literature was searched using the “Google Scholar” search engine, along with the “Web of Science” and “Scopus” databases. Additional material was obtained directly from the Authors’ files, since all the Authors have a long-time experience with plantation forestry and forest technology. This experience was used for organizing, categorizing and interpreting the results of the search, eventually leading to the present review paper, which summarizes the extensive discussions conducted within the Author panel.

Industrial forest plantations

The expansion of plantation forestry

In the year 2000, plantations were only about 5% of the global forest cover, but produced 35% of global roundwood production (FAO 2011) on 0.33% of the global land area, and if all were managed properly could produce two thirds of global roundwood production (Christie 2008). By 2015, plantations reached 291 million ha, with an average annual increment of 1.84%, since 1990. The higher average annual increment has been recorded in North and Central America (2.51%), South America (2.38%) and Asia (2.17%) (FAO 2016). However, it is estimated that only half the plantations in Asia, Africa and Central America, are used for industrial wood production, with the remainder used for amongst others, watershed protection, fuelwood and desertification protection (Siry et al. 2005).

In Africa and Asia, plantations have expanded most rapidly in countries with densely populated rural areas that experience rural to urban migration and have government policies that promote afforestation. In North America, South America and Oceania, plantations have rapidly expanded in countries with stable rural populations, low population densities, and large tracts of pasture land (Rudel 2009). South America is predicted to continue to increase its market share of plantation land in the form of industrial plantations. South America’s plantation area is expected to more than double, from 10.7 million ha at the turn of the century, to 26.7 million ha in 2050. Seventy-one per cent of the timber harvested in South America by 2050 will be produced by industrial plantations (Daigneault et al. 2008). Investment and expansion in *Eucalyptus* plantations and pulp mills is expected to continue (Phillips 2013).

Plantations from new regions, mostly from the semitropical areas of the southern hemisphere, are increasing in size and are playing an increasingly important role in supplying global timber markets (Sedjo 1999). The most fast-growing industrial plantations are located in the southern hemisphere. This is mostly due to faster growth rates that can range from 30 to 40 m³ per hectare per year compared to 10–15 m³ per hectare per year in the northern hemisphere (Siry et al. 2005). Due to competition for land, many of new plantation areas have been established on terrain that is difficult to access with conventional ground-based harvesting machines (Sandel and Svenning 2013). Plantation expansion will result in an increasing demand for harvesting machinery and systems and an assessment of the driving forces that will affect forest plantation is required to forecast the changes and developments in forest engineering sector. In addition, harvesting systems and

technology will be required to harvest increasingly steeper areas.

The importance of forest plantations

Demand for roundwood is predicted to reach six billion m³ by 2050, and will be the main driver for the expansion of industrial plantations (Barua et al. 2014). The reasons for this increased demand are varied, but include increased wood consumption by booming economies such as India, Brazil and China; increased population growth, illegal logging and land conversion for agriculture in tropical areas, which will result in the reduction of naturally forested areas and therefore an increased reliance on plantations. The reasons for the establishment of timber plantations are numerous and varied. Existing plantations were developed to satisfy a demand for certain wood products (Zhang et al. 2015). Traditionally, the primary reasons for plantations were to supply low cost wood fibre to the markets, which were sawmills or pulp mills. Roberts et al. (2004), cited in Niquidet and O’Kelly (2010), indicated that sawlogs constitute approximately 70% of a sawmill’s operating costs, and pulp logs, or sawmill chips for pulp, can comprise 40–60% of the operating costs for a bleached kraft pulp mill. Therefore the costs of fibre procurement are very important in the forest products business, resulting in a strategic focus on the sourcing of low-cost fibre to provide competitive advantage (Niquidet and O’Kelly 2010). As long as the demand for these products remains, the economic viability of these plantations remains (Cubbage et al. 2010).

China has been responsible for the largest expansions of plantations over the last century. China’s forests were badly damaged by excessive logging during the 1950s to 1980s. Policy changes in the 1990s have resulted in increases in China’s forest areas again (Dai et al. 2013). During the first decade of the new millennium, China implemented a Sloping Land Conversion Program (SLCP), which converted millions of hectares of marginal croplands to forests (Song et al. 2014). The primary objective of the SLCP was to reduce soil erosion (Wang and Maclaren 2012). China’s forest increased by 2.5 million ha per year between 1990 and 2005, a total of 49.7 million ha, mostly due to planted forest establishment (FAO 2012). However, much of the new forest areas are of poor quality, and China would need to improve forest productivity. Therefore, China’s newly established plantations are thought to neither contribute much to changing machine technology nor an increase in the global harvesting machine fleet.

The role of plantations as only being a source of roundwood for global markets has started changing. The future demand for forest products will most likely be met by plantations that have good conservation and biodiversity

standards, as well as respecting the needs and livelihoods of local communities (Innes 2013; Szulecka et al. 2016). Jepma et al. (1997) identified two major developments that have changed the focus and agendas of plantation forestry. The first is the recognition that afforestation and reforestation can contribute to the improvement of local socio-economic and physical conditions of people, especially in rural areas, as well as preserve biodiversity and act as a carbon store. The second is that all forests need to be managed sustainably. Burger (2009) indicates that managing forests simultaneously for wood, carbon sequestration, energy, biodiversity, flood control, water quality, recreation and habitat, is the twenty first century challenge for foresters who base their prescription on science. All these new roles can affect the forest engineering sector as related to the harvesting of forest plantations, by a greater focus on sustainable forest operations (Marchi et al. 2018). Harvesting systems need to cost-effectively harvest forest products and satisfy the other important values mentioned above, i.e. future harvesting machines and systems should consider the shifts in thinking related to the management of forest plantations.

Species grown in forest plantations

Depending on site conditions and market demands, a variety of species are used in plantation forestry. The dominant genera include *Pinus*, *Eucalyptus*, *Populus* and *Acacia* (FAO 2009). The species selected for a certain site needs to have acceptable growth rates to make plantation forestry viable, and have wood properties acceptable to the markets they serve. The current expansion of *Eucalyptus* and *Acacia* plantations is primarily linked to global demand for pulp and paper (FAO 2009). Other species such as poplars, aspens and willows could also be planted in the boreal regions for short rotation forestry (SRF) and there does not appear to be any climatic, technical or environmental constraints for their use (Weih 2004). However, depending on the tree size, form, bark characteristics, products required, use of biomass, stand density, and many other factors, harvesting systems could well be affected and may require technological adaptation to suite the species and conditions.

Driving factors in forest plantation development

Overview

Innes (2013) describes the forest sector, including plantation forests, as a “sun-rise” industry. This is due to its ability to meet future needs with different land-use options and bio-products such as energy, chemicals and materials.

A shift is also needed to a wider variety of forest ecosystem services such as recreation, carbon offsets and water management. Phillips (2013) provides three main factors behind the global demand for forest products. The first is an improvement in the standard of living in countries such as China, Brazil and India. This allows their citizens to have more discretionary income, which is used to purchase items such as newspapers, magazines and packaged manufactured goods. The second is the major decline in print media and business forms in North America and Western Europe, resulting in major business realignment. The third is energy security and climate change, which is resulting in demand for bioenergy and bio-products from biomass. Moreover, with the arising of climate change, resource shortage and environmental protection awareness, wood is receiving increased attention by scientists, politicians, and economists as an important material for the development of bio-economy. Due to its environmental advantages over other building materials, the architecture, engineering and construction communities recognize wood as green, renewable and advanced material (González-García et al. 2011). Wood is also an advanced material affecting emerging high-tech fields and in particular three critical applications: green electronics, biological devices, and energy storage and bioenergy (Zhu et al., 2016).

Even though demand may be reduced for certain plantation commodity products, new uses for wood can satisfy human needs and improve their standard of living (Wang 2013). Therefore, the role of forests and plantations must be well understood in the future. Forestry managers also need to forecast technology changes that affect forest product demands and determine how current management practices will be influenced by this. While the growing demand for forest products is the basis for an expansion of forestry in general, the widespread success of plantation forestry in the past decades depends on some specific factors, and namely: the re-orientation of forestry investment, the efforts to mitigate the effects of climate change and the growing emphasis on non-wood products and services—the latter affecting plantation forestry both directly and indirectly. These specific factors are analysed in the following subsections.

Forestry investment

Globalisation and the strengthening of developing economies have resulted in a shift in forest products from the west to the east. The traditional regions that lead forestry were North America, Western Europe and Japan. These regions are losing their importance as consumers and producers and are being surpassed by developing countries such as China, India, Brazil and Indonesia. Timber will also increasingly be supplied from industrial plantations

located in regions such as Australia, the Southern USA, New Zealand, Asia and South America (Daigneault et al. 2008). Thus, the above-mentioned developed countries are examining their business models to produce novel forest products such as biochemicals (Hurmekoski and Hetemaki 2013), and this may influence the technology required by the modern forestry machine.

Timber Investment Management Organizations (TIMOs) first appeared in the USA in the 1980s, when institutions became interested in buying forest lands and forest companies were willing to sell them (Lacy 2006). TIMO's normally do not own the forest land; the land is owned by individual investors represented by the TIMO (Lonnstedt and Sedjo 2012). The main motivation behind these landownership changes has been improving financial performance through debt reduction, better utilisation of timberland assets, or tax efficiency. On the other hand, Real Estate Investment Trusts (REIT's) directly own forest land (Lonnstedt and Sedjo 2012). Forest products companies still maintain the security of their fibre supply through long-term timber supply agreements with the TIMO's (Lacy 2006). TIMO's have much shorter investment horizons than traditional forest owners. TIMO's normally reduce rotation age to realise a quicker return on the high establishment costs (Lacy 2006), with the resultant small trees possibly requiring different harvesting systems that can more cost-effectively harvest smaller trees.

Vertically integrated companies have different financial pressures compared with companies only owning the forest resource or the processing facility. Vertically integrated companies have less pressure to optimise the forest-growing part of their operations and they can put more emphasis on developing an accessible, high-quality, long-term resource. They may even subsidise their forest operations, as it is important to maintain the resource base, and achieve other important management goals such as being part of a community (Lacy 2006). Cabbage et al. (2010) even found that vertically integrated companies with high productivity plantation species would have much lower roundwood input costs than prevailing market prices, thereby improving profitability. This explains why many companies in South America remain vertically integrated, while companies in countries with longer rotations, such as the US or New Zealand, have tended to move away from land ownership. Lonnstedt and Sedjo (2012) indicate that many companies in Europe and North America have in recent years transferred their capital away from domestic forest land to high productivity and lower cost forest land in other global regions such as South America, Asia and South Africa (Laaksonen-Craig 2004). Out-grower schemes and small timber growers are increasing in certain parts of the world, including South America, Asia and Africa. This is one method of increasing timber availability and

overcoming increasing land prices (Kroger and Nyland 2012; Barua et al. 2014; Rudel 2009).

Climate change

Climate change is considered to be the result of human activities (IPCC 2007). Forest biomass was the fuel for the beginning of industrialization from the seventeenth to nineteenth centuries. Fossil fuels helped prevent the destruction of the world's forests by providing a lower cost alternative, and in doing so allowed a focus on higher value products and environmental services. Oil has become the main fuel of the modern economy (Hartl and Knoke 2014). However, the use of these non-renewable fossil fuels is now causing other problems (Schoene and Bernier 2012), namely the increasing concentration of greenhouse gases in the atmosphere that are causing global temperatures to increase to levels where the risks for human habitation are becoming unacceptable and possibly irreversible. Brown and Baek (2010) indicate the future will increasingly be shaped by policy interventions that strengthen energy security and mitigate global climate change.

Carbon markets have been identified as one of few financing mechanisms that can rapidly raise the capital needed to finance the REDD (Reducing Emissions from Deforestation and Forest Degradation) international mechanism in developing countries, as well as support conservation efforts and increase carbon stocks to limit climate change (Clarke 2010). Forests play an important role in the earth's carbon cycle, as they have the ability to withdraw or sequester carbon, and trees serve as a carbon sink while they are growing (Deal and White 2012). Therefore, forestry can be affected by policies that include payments for carbon sequestration or those that try to reduce the losses of forest areas to other land uses (Alig et al. 2010).

Climate change is a multifaceted and complex challenge for forestry policy and management. Droughts, rising temperatures, heavy rain, forest fires, cyclones and humidity could result in forests becoming more susceptible to threats such as pests and diseases (Singh et al. 2010), which could influence harvesting technologies due to changes in tree size, species, and the complexity of processing trees with stress related defects. Plantation forestry can contribute to the stabilization and reduction of levels greenhouse gases in the atmosphere by storing carbon in standing trees and wood products, substituting fossil fuels for energy, and substituting products that result in higher levels of greenhouse gas emissions (FAO 2016). Plantations for biomass also require low fossil-fuel inputs compared to other land uses; for example inorganic fertilisers, pesticides and fuel for machines (St Clair et al. 2008).

Greenhouse gas mitigation in the forest sector is possible by: increasing the standing volumes of trees by expanding the forest area, increasing the growth rates of existing forests, reducing the rate of forest loss and conversion to other land uses, increasing the use of long-lived forest products such as furniture to store carbon, using wood products to substitute other materials which cause more carbon to be emitted and using biomass energy to replace fossil fuels. The choice of which policy reduction tool will be used to reduce carbon emissions will be determined by the characteristics of each country (Sampson and Sedjo 1997). It is clear that many of the mitigation methods available to forest managers can influence tree harvesting. These effects are mostly related to increased tree size, increased plantation areas and the use of biomass for energy. The establishment of plantations could be one of the most effective ways to increase carbon storage, as planted forests take up and store carbon at greater rates compared to other world land covers (Parks et al. 1997). However, the uptake of using reforestation and afforestation as a carbon mitigation tool has been very slow.

The United Nations Framework Convention on Climate Change (2014) states that the Kyoto Protocol is an international agreement which commits participating countries to internationally binding emission reduction targets. The Protocol places a heavier burden on developed nations. Depending on the state of the specific country (industrialised, with economies in transition or developing countries; listed in annexes), CO₂ emitters receive a certain total of carbon credits. If they emit more CO₂ than allowed, they can use new technology to reduce emissions, or purchase additional carbon credits. Forest owners could potentially supply these carbon credits (Binkley et al. 2002). The reduction in global forests since the industrial revolution has contributed one third towards the increase in CO₂ emissions (Maclaren 2000, as cited in Adams and Turner 2012), which is second only to the energy production sector (Alig et al. 2010).

Forestry can contribute to carbon storage by avoiding deforestation and carrying out reforestation and afforestation (Christie 2008). This forestry sequestration approach is often favored by policymakers as it is easy to relate to carbon emissions and it is an inexpensive strategy (Khatun et al. 2010; McKenney et al. 2004; Michetti and Rosa 2012; Tavoni et al. 2007). Richards and Stokes (2004) categorized two types of forestry practices which can increase sequestration, being plantation area increase and secondly, improved forest management. Forest carbon became a marketable commodity in the year 2000 as part of afforestation and reforestation projects under the Clean Development Mechanism (CDM). Article 3.4 of the Kyoto Protocol has increased the value of all forests by the market value of the sequestered carbon. CO₂ prices can create

incentives for landowners to increase forest inventories and therefore carbon stocks, and to prevent deforestation (Alig et al. 2010). Forest owners may need to start managing forests for carbon, and not only for the traditional timber, non-timber forest products, and social and environmental services (Schoene and Bernier 2012; Pohjola and Valsta 2007). Emissions Trading Scheme (ETS) policies are developed with the objective of reducing and mitigating greenhouse gas (GHG) emissions. The cost of lowering emissions is reduced by trading between emitting and sequestering parties. The European Union was the first to apply ETS to GHG emissions, which came into effect in 2005 (Adams and Turner 2012).

Forestry related carbon can be significantly increased by expanding forestry areas and increasing rotation lengths (Alig et al. 2010). Harvested wood products can play a role in carbon storage by providing GHG sequestration benefits. Longer rotation lengths also increase the amount of stored carbon in forest products due to the larger proportion of sawlogs that can be produced (Nepal et al. 2012; Susaeta et al. 2014). As the price of carbon increases, the shift moves from the production of logs to the production of standing biomass (Manley 2012). The increase in rotation length results in larger trees at harvesting and an increased yield per hectare (Pohjola and Valsta 2007). The implementation of schemes that reward potential or current forestry investors or landowners for sequestering carbon has been limited. Christie (2008) attributes this to mechanisms developed being unmanageable for forestry due to the long investment cycles and the risks involved; but still maintains that there is potential for forestry.

Ecosystem services and other products and services

The role of forests and plantations for the provision of products and services, besides roundwood, is increasing (Janse and Ottitsch 2005; Szulecka et al. 2016), and the market for new and improved bio products is growing (Innes 2013). This is due to increased wealth, changing sensibilities and possibly reduced supply (Binkley 2005). The Millennium Ecosystem Assessment (MEA 2005) divides the services offered by forests into four categories. These are:

- provisioning services—e.g. food, fibre, genetic resources, biochemical, natural medicines, pharmaceuticals and fresh water,
- regulating services—e.g. air quality regulation, climate regulation, water regulation, erosion regulation, water purification and waste treatment, disease regulation, pest regulation, pollination and natural hazard regulation,

- supporting services—e.g. nutrient cycling, soil formation and primary production, and
- cultural services—e.g. aesthetic values, spiritual and religious values, and recreation and ecotourism.

Historically, markets have been unable to capture the many non-product benefits of forests (Stephens and Grist 2014). Market-based instruments for ecosystem services are used to change the behavior of natural resource managers and land users so that they maintain or protect ecosystem services (Pirard 2012). This approach combines the abovementioned forest services to provide financial incentives to achieve conservation goals (Deal et al. 2012). Market based mechanisms for ecosystem services could even assist to overcome some of the investment hurdles for industrial plantations (Stephens and Grist 2014). Stephens and Grist (2014) expect the importance of plantations for environmental services to increase in the future.

Driving factors in future plantation management

Timber and pulpwood

Demand for conventional forest products was great during the twentieth century, but has stabilised since the turn of the century due to factors such as product substitution with metals and plastics and the effect of the digital era. Demand increases will still occur, but will be more subdued (FAO 2005; Binkley 2005), as the price of roundwood is capped by the prices of substitute materials (Eriksson et al. 2017). A change in the markets for conventional forest products could result in changes to the species, form, tree size, level of processing, quality requirements and other product requirements, and this could influence the technology required to harvest these trees.

The demand for paper (printing, writing and newsprint) has been increasing for over 100 years. At the turn of the century, several developed countries in North America and Western Europe started to experience demand decline (Hurmekoski and Hetemaki 2013). The demand for pulpwood is significantly influenced by substitute product technology developments (Tromborg et al. 2000). China poses the largest growth for all paper and packaging products (Phillips 2013). Increased recycling has reduced the global demand for virgin fibre (Lonnstedt and Sedjo 2012). Because China already recycles at high levels and does not have enough timber domestically to meet its packaging needs, it is expected to import recovered paper from the United States and Western Europe. This will drive up the prices of recovered fibre to a point where it will need to import liner or bleached pulp from countries with

softwood forests, such as USA, Canada, Australia, New Zealand, Brazil and Chile (Phillips 2013). It is evident that large increases in global wood demand are unlikely, even with large consumption increases in China (Lonnstedt and Sedjo 2012).

The pulp and paper industry is able to produce products that go beyond paper. Christie (2008), comments that there is great commercial potential for some of the by-products of the paper manufacturing process. These include products from lignin (natural binders and adhesives, sub-bituminous coal, sulphur-free solid fuel and chemical products), hemicelluloses/polyoses (thickeners, adhesives, protective colloids, emulsifiers, stabilisers, sugar substitutes, furan resins, chemical products and nylon) and cellulose (softeners, solvents, lubricants, chemicals, polymers, fuels and organic acids).

Biomass for energy

Energy supply will be one of the primary challenges in the future (Christie 2008). Renewable energy production has increased due to high fossil fuel prices, improved renewables technology, government policies and increasing global energy demand (Zhang et al. 2014; Tromberg and Solberg 2010). Woody biomass use for energy production is expected to increase due to wood being a climate-friendly and renewable energy source, with part of the biomass coming from mill residues and lower-quality wood (FAO 2016). Industrial plantations will be the main tool used for biomass and bioenergy production (Cubbage et al. 2010). The promotion of renewable energy in Europe is predicted to drastically increase the demand for woody biomass (Lauri et al. 2012), resulting in a scenario where demand exceeds supply (Jonsson 2013). There is already evidence that forestry activities are increasing to meet the larger demand for woody biomass (Buonocore et al. 2014; Ince et al. 2011). Flaspohler and Webster (2011) predict that as the value of the forests providing bioenergy feedstock increases, more land will be converted to fast growing tree plantations to meet the demand for cellulose. Harvesting machines will be required to be cost effective in biomass harvesting, and a larger machine population would be required for the expanded areas.

Studies by Kraxner et al. (2013) showed that under a high global demand for bioenergy, biomass would mostly be sourced by converting unmanaged forests into managed forests, or from new fast-growing plantations, or by optimizing the use of existing plantation land. Plantations are better suited than natural forests for biomass production as they are logically laid out, established on high productivity land, have good infrastructure, and are harvested by technologically efficient systems. Also, everything from the stump to the needles can be used and has a potential value

(Talbot and Ackerman 2009). Besides burning biomass for energy, cellulose from wood is also an economically viable source of ethanol biofuel (Potter and Loffler 2010).

Biomass harvesting and transport system costs will have to be reduced if biomass based bioenergy is to compete with coal or natural gas in the long term (Sims and Venturi 2004). Gonzalez et al. (2011) provide the key cost drivers of dedicated bioenergy crops as being establishment, maintenance, harvesting, transportation and storage. With low fossil fuel costs, only harvesting residues would be used for energy (Moiseyev et al. 2013). A carbon price of at least €20 per ton of CO₂ emissions from fossil fuels is needed to increase wood based energy production. When carbon prices are below €50 per ton, the energy wood can consist of forest residues, black liquor, bark and recycled wood. At a price of €50 per ton, wood for energy begins to compete with wood used for conventional forest products. At a carbon price of €110 per ton, one third of the wood used for energy could also have been used for conventional forest products (Lauri et al. 2012). With ambitious bioenergy targets, there is unlikely to be sufficient land available for both bioenergy plantations and longer-rotation forests. This would result in competition between the two land uses (Hedenus and Azar 2009).

The term “biomass harvesting” is a very generic term referring to any part of the tree destined for energy production. This could include both above and below ground biomass. However, biomass harvesting can require distinctly different machines and systems depending on the location, form, part of the tree, species, volume per hectare, client requirements and distance to the market (Puttock 1995). Certain plantations could be established for the sole purpose of harvesting biomass for energy. Literature refers to these as short rotation energy wood plantations or short rotation coppice (SRC). However, even these short rotation plantations can range from harvesting very small trees at very high stand densities (SRC) to larger trees with lower stand densities (SRF) (Gonzalez et al. 2011). The very small tree scenario may require an agricultural type harvester (Spinelli et al. 2009, 2011), while the larger trees may require a more traditional roundwood harvesting system (Leslie et al. 2012; Spinelli and Hartsough 2006; Spinelli et al. 2012). SRC is seen as a method of producing large volumes of biomass for energy in a short period of time in a way that does not compete with other biomass products from forests (Schweier and Becker 2013). Machine and systems development is still taking place for these site specific scenarios, and requires comprehensive research to guide these developments (Rummer et al. 2010).

Landowners currently seem reluctant to establish SRC, even on marginal lands where conventional crops show low productivity. This is due to the uncertainty regarding the

income that will be derived. Other factors that contribute to a slow uptake include a lack of expertise, a reluctance to invest in a long-term, inflexible crop, political uncertainties, biological risks due to pests and diseases and high investment costs (Schweier and Becker 2013; Di Corato et al. 2013; Tan et al. 2015). Kantavichai et al. (2014) indicates that most authors believe that harvesting residues will not be sufficient for large scale biofuel projects, and plantations dedicated to energy production will be required. The negative effects of using harvesting residues also need to be considered.

Sustainability certification of forest management

Certification through schemes such as the Forest Stewardship Council (FSC) and Programme for the Endorsement of Forest Certification (PEFC) has become the means by which producers and consumers can verify the authenticity of a supplier's claim. It is a non-governmental approach to ensure adherence to legislation, rules, policies and procedures. It is now a requirement of entry into many markets that wood products be certified as having originated from a well-managed forest (Goulding 2005). Forest certification has progressed alongside sustainable forest management (SFM) to measure compliance to this agenda. It is clear that forest certification has made a positive difference to forest management, and in fact drives technological change for certain aspects at a pace that might not otherwise have been achieved. The harvesting systems of the future will need to be able to operate within the boundaries of society's expectations.

Potential effects of future developments on forest harvesting technology and systems

Overview

The literature clearly indicates that industrial plantations will continue to expand, especially in the tropical and subtropical areas of South America, South East Asia and Africa. This will result in an increased global population of harvesting machines. The question is what will be the characteristics of the new machines that will be deployed in plantation forestry to match the increased needs while reflecting the new trends in plantation forest management and techniques. Until now, the paper has described these new trends, which are: change in tree size (towards bigger or smaller trees), increased complexity in forest structure and/or product basket, expansion towards marginal areas and reduction of environmental and social impacts.

Tree size

The productivity of conventional single-stem harvesting technology is directly proportional to tree size, and is especially low in pulpwood-size plantations (Lambert and Howard 1990). Therefore, any reduction in tree size caused by a shift towards shorter rotations will result in a marked efficiency loss. When that is the case, the mass handling is the best solution, because it can largely offset the small stem size constraint (Adebayo et al. 2007; Spinelli et al. 2014). Mass handling is normally obtained by deploying feller-bunchers, grapple skidders and chain-flail delimiters debarkers-chippers, which can achieve a remarkably high efficiency even when negotiating small trees (Spinelli et al. 2018). Therefore, moving to shorter rotations will favor multi-tree technology, and in general whole-tree harvesting over cut-to-length harvesting. On the contrary, extended rotations would favor single-tree cut-to-length harvesting, and drive machine selection towards large models, reflecting current trends already visible in the harvesting of managed natural forests (Nordfjell et al. 2019).

Complexity

The trends towards obtaining multiple products from the same stand and operation will have an impact on both technique and technology. In terms of technique, that will favor integrated harvesting, as a way to maximize the efficiency of wood procurement (Spinelli et al. 2019). In that regard, one may speculate about two main scenarios.

In Scenario one, plantations are grown for the sole production of biomass. In that case FT is the obvious choice, but depending on the prevalent tree size, the market will react with an increased use of chip-and-cut forager type units, as used in Europe (relatively small trees), or with an expansion of feller-skidder-chipper operations as used in pulpwood in the Southeastern U.S.

In Scenario 2, plantations are grown for a main crop of products other than biomass, but a certain amount of biomass is also recovered. In that case, depending on tree size, harvesting will be conducted according to the cut-to-length (CTL) system (large trees) or the whole-tree (WT) harvesting system (small trees). In the former case, new systems will be developed for recovering residues left in the compartment, such as enlarged-space forwarders, compactor forwarders, bundlers and balers, terrain chippers etc. (Guerra et al. 2018). In the latter case, new agile chippers or bundlers will be introduced for handling landing residues (Spinelli et al. 2015). Furthermore, the possible expansion of biomass recovery may tilt the scales in favour of CTL or WT depending on the overall harvesting efficiency calculated over the main products and the energy assortments.

In any case, increased complexity in product type and stand characteristics is bound to decrease efficiency, and coping with that may favour resorting to operator-assist tools, especially when it comes to merchandising (Tolan and Visser 2015).

Expansion

Besides the obvious effect of surface expansion on machine fleet size, an increase in plantation area will have indirect effects in terms of site characteristics. Since the most favourable land has already been occupied by farming and urban development projects, plantations can only expand to marginal sites (Nahuelhual et al. 2012). In particular, technological marginality may originate from two main causes: excessive slope gradient and insufficient compartment surface. Accessing stands on steep terrain requires cable technology, which is already being introduced to plantation forestry (Engelbrecht et al. 2017). Therefore, the expansion of plantation area towards hill country is likely to promote the spreading of cable yarders or cable-assist devices, while also impacting the development of specific technology solutions that may best match the conditions offered by plantation forests (Visser and Stampfer 2015).

Concerning small-size compartments, a smaller compartment area is going to generate an increase in machine relocation cost which may erode operation profitability (Väättäinen et al. 2006). Therefore, an increase in the share of plantation area grown over small individual lots is likely to favor integrated multi-task machines such as harwarders, whereby one single machine can perform the tasks of more individual units, thus reducing the frequency and cost of machine moves (Kährä et al. 2018).

On this same note, one may also want to consider the progressive opening to market production of large surface of existing (and new) Chinese plantations, which will have to be regenerated at some time in the near future. They represent a very large share of the global forest surface, and their coming into production—although as a secondary goal—may have a strong impact on forest technology development. Very little is known about the work conditions offered by these forests, but the few existing works on this specific subject point an interest for mechanization, even if small scale—at least for the moment (Hoffmann et al. 2018). The Authors prefer not to speculate on this very subject, since the volume of available information is too small compared with the potential impact. However, readers must be made aware of the large potential impact that the Chinese plantations might have on future technology developments.

Environmental and social impact

Environmental awareness has grown over time, decreasing the tolerance for site disturbance (Abbas et al. 2018), and that is certainly going to affect equipment choice and design (Spinelli et al. 2010; Edlund et al. 2013). While a description of the specific technology solutions remains highly conjectural, there is every reason to believe that an increased attention to reduce site impacts will support the use of high-flotation multi-axle and/or wide-tire vehicles, as well as cable technology in general. In fact, proper planning is even more effective than equipment choice, and one may expect a rapid success of low-cost intelligent solutions, supported by remote sensing, UAV surveys and accurate site mapping. That is the domain of precision forestry, which is already a crucial component of forest plantation management and may soon extend to fine-tuning harvesting operations with the purpose reducing site impacts (Holopainen et al. 2014).

On the social side, the future expansion of the plantation area together with the affirmation of a strong safety culture will favor mechanization over semi-mechanized and motor-manual operations, since the latter are inherently more dangerous (Bell 2002; Tsioras et al. 2014). At the same time, mechanization may improve the social profile of forest workers, contributing to their professionalization (Bayne and Parker 2012).

All in all, the picture is positive: the environmental impacts resulting from the new trends in plantation forestry can be minimized, while the social impacts are generally positive—to start with.

A schematic representation of the above discussions has been summarised into a series of key drivers that are expected to influence the technology used in harvesting machines, as well as the choice of harvesting machines, systems and methods (Table 1).

Conclusion

As the human population grows and increasing pressure is placed on natural forests, intensively managed plantations will become essential to meet current and future needs, and to support the new bio-economy. The majority of changes that will take place in industrial plantations will influence harvesting machines and systems in some way. Plantations managed for conventional products and residues for energy will require systems that can harvest both products. Dedicated energy forest harvesters will require the most development if harvesting costs are to remain at acceptable levels. Where plantations are used for carbon sequestration, it is evident that tree size will increase and this will affect harvesting systems in that the machines

Table 1 Key drivers affecting the technology used in harvesting machines for forest plantation

Drivers	Description
Variations in tree size	Possible reductions of tree size may favour the application of full-tree harvesting over CTL, the former being much less sensitive to tree size as a result of mass handling. The contrary is true if larger tree sizes will prevail
Diversity in plantation design	Technology will become more versatile, also through a wider use of optimisation software on modern machines to provide fast and accurate adjustments of machine settings to react to rapidly changing conditions
Increased use of biomass	This may have important implications for technology choice and technology development, leading to integrated harvesting or exclusive biomass production. Comminution technology will become increasingly popular
Expansion of plantation areas	Growers to expand over steeper terrain, with a dramatic effect on technology choices. As one moves over the 35% slope gradient threshold, there is a strong reason for adopting cable technology in the form of cable yarders and/or more modern winch-assist or tethered ground-based equipment
Increased attention towards site impacts	This may lead to an increased use of CTL to the expenses of FT, even where FT would still be competitive. This may also result in an increased used of multiple-axle units, favouring 8-wheeled harvesters over 6-wheeled ones, 10-wheeled forwarders over 6- or 8-wheeled ones and 6-wheeled skidders over 4-wheeled ones

need to have sufficient power and size. Pulp for paper and packaging or biochemical products will be similar to current pulpwood trees and in the absence of other influencing factors such as biomass use or carbon sequestration, will have little effect on current harvesting systems. With TIMO's, the rotation length could decrease resulting in smaller trees and the resultant complications for machine selection and productivity. However, even if the plantations retained their current characteristics, other very important safety, productivity, environmental, quality and social drivers will affect the technology used in the future. It is, therefore, clear that harvesting technology, machines, systems and methods will be influenced by a number of driving factors, being variations in tree size, expansion of plantation areas, diversity in plantation design, increased attention towards site impacts and the increased use of biomass.

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