Adjusting Expectations of Scale Based on Limitations of Supply: a Review of the Case for a Forest Bioenergy Strategy that Prioritizes Decentralization, Efficiency, and Integration

by

Derek Peter Wolf

A thesis submitted in conformity with the requirements for the degree of Master of Science in Forestry

Faculty of Forestry
University of Toronto

© Copyright by Derek Peter Wolf 2012
Adjusting Expectations of Scale Based on Limitations of Supply: a Review of the Case for a Forest Bioenergy Strategy that Prioritizes Decentralization, Efficiency, and Integration

Derek Peter Wolf

Master of Science in Forestry 2012
Faculty of Forestry
University of Toronto

Abstract

The limitations of renewable energy technologies require that pathways are carefully chosen such that renewable resources are used most effectively in addressing modern energy challenges. Optimized decision-making is particularly challenging for the forest bioenergy sector because of the multitude of potential pathways and because profit is highly sensitive to biomass procurement costs. I assessed energy wood recovery and procurement costs during semi-mechanized selection operations in the tolerant hardwood forests of Ontario. Logging contractors were able to recover unmerchantable sections of branches normally discarded during conventional operations, amounting to 1.3 to 2.7 dry tonnes of additional biomass per hectare. Supply chain scenarios are used to show that the biomass can be brought to market at a cost similar to mechanized operations. The need for prioritization of decentralization, efficiency, and integration with the value-added forest sector is discussed with reference to the relative scarcity and high cost of the forest resource.
Acknowledgments

I would like to thank everyone who made this degree possible, including my parents Jenifer and Peter Wolf, my supervisor John Caspersen, my committee members Tat Smith and Trevor Jones, Denis Cormier, Philippe Meek, and other members of the FPInnovations Forest Operations group, owner and operator of the Haliburton Forest and Wildlife Reserve (HFWR) Peter Schleifenbaum, HFWR members and University of Toronto Faculty of Forestry members who provided advice or helped with field work, logging operators at HFWR who provided advice and accommodated our requests during normal working hours, my previous supervisors and professors at Saint Mary’s University including Jeremy Lundholm, David Cone, and Hugh Broders, and finally Eadaoin Quinn for her love, support, insight, and catching positivity.
# Table of Contents

Abstract ........................................................................................................... ii
Acknowledgments .......................................................................................... iii
Table of Contents ........................................................................................... iv
List of Tables ................................................................................................ vi
List of Figures ............................................................................................... vii
List of Appendices ......................................................................................... viii
General Introduction ...................................................................................... 1

Chapter 1 – Review of Bioenergy Sector Development in the OECD .............. 9
  1.1 Overview of forest bioenergy in the OECD .................................................. 9
  1.2 Expectations for large-scale bioenergy and possible consequences ........... 13
    1.2.1 Modern energy policy and future expectations for bioenergy ................. 13
    1.2.2 Potential consequences of bioenergy policy .......................................... 15
    1.2.3 Potential causes of suboptimal bioenergy policy ..................................... 18
  1.3 The need to revise bioenergy policy ........................................................... 19

Chapter 2 – Forest Biomass Supply and the Role of Harvest Residue .......... 21
  2.1 Methods of forest biomass supply estimation ............................................ 21
  2.2 Forest biomass supply literature review .................................................... 22
    2.2.1 Global and regional forest biomass supply estimates .............................. 22
    2.2.2 National forest biomass supply estimates .............................................. 25
    2.2.3 Sub-national and local forest biomass supply estimates ......................... 26
  2.3 Constraints to forest biomass supply ......................................................... 28
    2.3.1 Land and market constraints and the value-added principle .................... 28
    2.3.2 Forest biomass from unused managed lands and natural disturbances ...... 33
    2.3.3 Forest biomass from existing forest supply chains ................................. 34
    2.3.4 The advantages of harvest residue ....................................................... 37
  2.4 Techno-economic constraints of harvest residue recovery  ......................... 38
    2.4.1 Techno-economic limits of conventional forest supply chains ............... 38
    2.4.2 The biophysical limits of the forest resource ......................................... 39
    2.4.3 The biophysical and techno-economic limits of harvest residue ............ 40
    2.4.4 Techno-economic progress in harvest residue recovery  ....................... 41
    2.4.5 Reconciling limitations of harvest residue with large-scale bioenergy ...... 43

  3.1 Introduction .............................................................................................. 48
    3.1.1 Harvest residue recovery in the OECD ............................................... 48
    3.1.2 Harvest residue recovery in mechanized partial harvest operations .......... 49
    3.1.3 Harvest residue recovery in semi-mechanized partial harvest operations .... 51
  3.2 Methods .................................................................................................... 53
    3.2.1 Study area and operational context ....................................................... 53
    3.2.2 Pre-harvest plot inventory .................................................................... 54
    3.2.3 Harvest trials ....................................................................................... 55
    3.2.4 Volume recovery estimation and statistical analysis .............................. 55
    3.2.5 Time-motion study of felling operations .............................................. 58
### 3.2.6 Supply chain productivity and delivered costs .................................................. 58

### 3.3 Results .......................................................................................................................... 60
- 3.3.1 Stand composition and tree marking ........................................................................ 60
- 3.3.2 Tree-level and stand-level harvest residue recovery ............................................... 60
- 3.3.3 Branch and product recovery .................................................................................. 62
- 3.3.4 Operational productivity ......................................................................................... 63
- 3.3.5 Costs ....................................................................................................................... 64

### 3.4 Discussion .................................................................................................................... 66
- 3.4.1 Volume recovery ........................................................................................................ 66
- 3.4.2 Supply chain logistics .............................................................................................. 67
- 3.4.3 Potential bioenergy pathways .................................................................................. 68

### Chapter 4 – Implications for the Managed Forests of the GLSL Forest Region in Ontario ...... 71
- 4.1 Bioenergy policy and research in Ontario ..................................................................... 71
- 4.2 Forest biomass supply and energy potential in Ontario ............................................... 72
  - 4.2.1 Provincial forest biomass supply and energy potential .............................................. 72
  - 4.2.2 GLSL forest biomass supply and energy potential .................................................. 72
- 4.3 Assessing the limitations, costs, and benefits of bio-electricity production in Ontario .......................................................................................................................... 74
  - 4.3.1 Technical and economic barriers to decentralized electricity generation .............. 74
  - 4.3.2 Costs and benefits of decentralized and centralized bio-electricity production .......... 77
  - 4.3.3 The high costs and marginal benefits of large-scale bioenergy ............................. 78
- 4.4 The case for a forest bioenergy strategy that prioritizes decentralization, efficiency, and integration .................................................................................................................. 79
- 4.5 Concluding remarks .................................................................................................... 86

# Literature Cited .................................................................................................................... 89

# Appendices .......................................................................................................................... 121
List of Tables

Table 2.1: Average direct employment per facility for various wood product manufacturing facilities and bioenergy production facilities.............................................................31
Table 2.2: Types and sources of forest biomass available for bioenergy production after imposing market constraints and value-added principles, ranked from least expensive to most expensive..................................................................................................................34
Table 2.3: Relationship between plant type and scale, annual biomass demand, and the land area required to support annual biomass demand with harvest residue (@ 10 dry tonnes per ha).................................................................................................................................44
Table 3.1: Comparison of recovery metrics for modified tree-length and conventional tree-length harvesting by size class..................................................................................61
Table 3.2: Branch recovery fractions by size class and treatment.................................................................................................................................63
Table 3.3: Costs of merchantable roundwood and residue for semi-mechanized single-tree selection operations employing the modified tree-length method with motor-manual felling..............................................................................................................65
List of Figures

Figure 1.1: Comparison of Canadian and American bioenergy production by sector.................11
Figure 1.2: Share of bioenergy in total national primary energy supply in ten OECD nations ..................................................................................................................12
Figure 1.3: Actual and expected contribution of bioenergy by type of energy in the European Union in 2004 ........................................................................................................14
Figure 1.4: Total global installed capacity of renewable electricity generating facilities ..........17
Figure 2.1: Current and future potential global primary energy supply from biomass ............23
Figure 2.2: Average market prices in northeastern North America for various forest products by value per unit roundwood..................................................................................29
Figure 2.3: Chart depicting aboveground mass of an individual tree and the fraction of the available mass that is recovered during a commercial harvesting operation and used to produce roundwood, harvest residue, mill residue, and conventional wood products ..............36
Figure 3.1: Mean basal area per hectare by size class, before and after harvest ......................60
Figure 3.2: Linear relationship between DBH and recovered tree-length volume for the modified treatment and the conventional treatment.................................................................62
Figure 3.3: Proportion of total working time that the chainsaw operator spent conducting various activities associated with felling and delimming/topping by treatment ....................64
List of Appendices

Appendix 1.1: Three-scale classification of bioenergy technologies .......................................................... 121
Appendix 2.1: List of potential forest products available with existing and future technologies .......................................................... 123
Appendix 3.1: Costing parameters for mechanized felling, motor-manual felling-delimming/topping, cable skidding, and slashing .......................................................... 124
Appendix 3.2: Costing parameters for self-loading logging trucks and chip vans .......................................................... 125
Appendix 3.3: Linear relationship between final delivered residue cost ($/dry tonnes) and distance travelled (km) for logging truck transport .......................................................... 126
Appendix 3.4: Linear relationship between final delivered residue cost ($/dry tonnes) and distance travelled (km) for chip van transport .......................................................... 127
Appendix 3.5: Box plots of volume per recovered tree in each treatment for four size classes .......................................................... 128
Appendix 3.6: R output for analysis of covariance of volume per recovered tree and DBH using log-transformed data .......................................................... 129
Appendix 3.7: Relative contribution of each operational phase to total procurement cost .......................................................... 130
Appendix 3.8: Assumptions and calculations used to determine number of households that could have electrical and heating needs supported with bioenergy facilities at various scales .......................................................... 131
Appendix 4.1: Forest biomass availability estimates for Ontario .......................................................... 132
Appendix 4.2: Forest biomass availability estimates for the GLSL forest region in Ontario before operational research trials .......................................................... 133
Appendix 4.3: Harvest residue recovery ratios and per hectare estimates for various silvicultural systems and harvesting methods .......................................................... 134
Appendix 4.4: Total annual area harvested commercially under the three silvicultural systems for all GLSL FMUs and estimates of annual potential residue recovery for all commercial harvesting activities in the GLSL forest region .......................................................... 135
Appendix 4.5: Comparison of the delivered cost per dry tonne of wood chips and wood pellets produced from harvest residue for a range of post-preparation transport distances .......................................................... 136
Appendix 4.6: Cost of various sources of forest biomass after preparation .......................................................... 13
General Introduction

Securing a sustainable energy supply through the encouragement of energy conservation and domestic energy production is a core principle guiding modern energy policy (IPCC 1990; EEA 2005; Casten and Schewe 2008; Liming et al. 2008; Omer 2008). Benefits of this approach are relatively certain and include increasing the lifetime of fossil and mineral fuel reserves for future generations, greater control over energy prices (Deese 1979), improvements in human health (Chow et al. 2003; Kampa and Castanas 2008), domestic economic development and job creation, and avoidance of international resource conflicts. Together with materials management policies that place emphasis on the recycling of by-products and wastes (McDougall et al. 2001), the promotion of energy conservation and domestic energy provides a responsible template for sustainable growth and climate management (Vitousek et al. 1997).

Renewable energy technologies – including hydroelectricity, wind, solar, geothermal, and bioenergy – are an important component of this modern energy policy framework. Given the ubiquity of renewable fuels, including wind, sunlight, and biomass, which are present and available to some degree over the majority of the earth’s surface, renewable energy technology provides a means of sustainably increasing domestic energy capacity. Since most renewable energy pathways are carbon negative or neutral and have positive energy returned-on-energy-invested (EROEI) ratings (Bardi 2009), deployment of renewables also contributes to greenhouse gas (GHG) mitigation and energy conservation goals (Pacala and Socolow 2004).

The actual extent to which renewable energy capacity will contribute to future energy supply ultimately depends on the physical and biophysical limitations of renewable resources and the costs of using those resources to produce energy. Attempts to quantify global renewable potential have produced a vast range of estimates as a result of the coarse scales of analysis and differences in assumptions and methods used. For example, future global wind, solar, and bioenergy estimates range from 30 EJ to 2,500 EJ (de Vries et al. 2007; de Castro et al.
This range of estimates not only stands out in its gross imprecision and uncertainty but also in the enormous potential conveyed by the middle and upper portions of the range: current global primary energy supply is 500 EJ, 86.7% of which is derived from energy-dense fossil fuels (coal, oil, and natural gas) and uranium (IEA 2011a).

Over the past 30 years, a number of factors, including the high apparent potential of renewable energy, the inevitable exhaustion of fossil and mineral fuel supplies, and climate change concerns, have leveraged political and public acceptance of the deployment of renewable energy technologies. The majority of Organization for Economic Co-operation and Development (OECD) member governments and their respective jurisdictions (i.e. states, provinces) now call for an increase in the percent contribution of renewable energy to total energy supply, commensurate with a reduction in fossil fuel use. Non-hydro renewable electricity – including wind, solar, bioenergy, and geothermal – is expected to increase from 3% of total global electricity generation in 2009 to 15% in 2030, implemented via policy instruments (e.g. subsidies, taxation, cap-and-trade programs) and investments in transmission infrastructure (IEA 2011b). In the European Union (EU), where targets for GHG emission reductions and policies encouraging renewables are the most extensive in the world, the total contribution of renewable energy to secondary energy supply (in the EU-27) is expected to increase from the current level of 8.5% to 20% by 2020 (EU 2009; Carvalho 2012). As a final example, in Ontario, Canada, non-hydro renewables are expected to contribute 12.8% (10,700 MW) of total provincial electricity supply by 2030, an increase from the current contribution of 5% (OME 2010).

There is evidence that these renewable energy targets are unrealistic. Despite considerable policy, industry, and research attention since the 1970s, the global renewable energy sector has maintained a constant share in global energy supply as fossil and mineral fuel supply and energy demand have increased. For instance, between 1973 and 2009, the relative contribution of renewables to total world primary energy supply increased by only 0.8% percentage points. The majority of growth in primary energy supply during this period was driven by coal, uranium, and natural gas (IEA 2011a). As of 2009, fossil fuels and uranium represented 86.7% of total global primary energy supply, with the remaining supply constituted by biomass and wastes (10.2%), hydroelectricity (2.3%), and other renewables
The contribution of renewables to global energy supply becomes even more marginal when considering electricity only: non-hydro renewables contributed to only 4.6% of global electricity capacity in 2010 (REN21 2011).

Although the share of renewables is likely to increase with improvements in political will, policy development, and economies of scale and learning (Berry and Jaccard 2001), there are fundamental physical and biophysical explanations for the inability of nation-states to readily replace fossil and mineral fuels with renewables. Hydroelectricity – which is only available in regions with river systems that have not already been damned – is the only renewable energy technology that can consistently achieve facility capacities comparable to those of fossil fuels (1,000 – 20,000 MW). Consequently, 83% of total renewable power capacity in 2009 was provided via hydroelectric dams (IEA 2011a). Non-hydro renewable energy technologies, contributing to the remaining 17% of renewable electricity capacity, have facility capacities averaging 200 MW for wind and no greater than 80 MW for bioenergy and geothermal. It is difficult to foresee how technology development could increase this capacity threshold given the intermittency and relative scarcity of renewable fuels such as wind currents, photons, lithospheric heat, and biomass. Instead, continued replacement of fossil fuel and nuclear capacity with renewables will necessarily increase the total surface area of the earth that humans use to produce and distribute energy.

In addition to providing a physical barrier to leveraging economies of scale – a fundamental strength of conventional forms of energy – the small scale of renewable energy projects necessitates investment in additional supply chain and transmission infrastructure. For electricity generation, substantial investment in transmission infrastructure is required to connect expansive networks of smaller-scale electricity generation facilities, referred to as “decentralized” or “distributed” generation (Wolfe 2008). Subsidy programs or direct public investment are often necessary to cover these costs and other costs associated with facility establishment and competitive operation. Although subsidization is a normal part of nuclear and fossil fuel production systems (McCormick and Kabberger 2007), subsidies and subsidy projections for renewables have reached publicly- and politically-alarming levels in many regions. The high public cost of maintaining these renewable energy systems gives rise to concerns that public acceptance will waver over time (Frondel et al. 2008), especially in
North America where energy and fossil fuel prices have historically been low (Davoust 2008; Auditor General of Ontario 2011). Although the public burden of renewable energy policies can be mitigated through such means as phasing out the strength of subsidies over time (Mabee et al. 2012) or adjusting the details of policy incentives and regulations (Cory and Swezey 2007), the effect of such adjustments on the larger energy system is uncertain (Palmer and Burtraw 2005; Ford et al. 2007). The instability of expensive renewable energy subsidies has also recently been witnessed in the EU, where nations were forced to cut high-cost solar subsidies as an initial means of reducing public spending (REN21 2011). Energy prices will inevitably rise over the long term as fossil and mineral fuel supplies decline, but the rate of increase is likely to be increased in proportion to the rate of renewable energy deployment and this must be acknowledged as a source of uncertainty in the sustainability of renewable energy policy (Palmer and Burtraw 2005).

Environmental impacts of renewables, such as impacts of wind turbines and bioenergy on biodiversity (Kunz et al. 2007; Lattimore et al. 2009; Hesselink 2010) and impacts of wind turbine noise on human quality of life (Pedersen and Waye 2007), provide further barriers to renewable energy deployment, although technology (e.g. automated avian radar, Goldenberg 2009; acoustic deterrents, Johnson et al. 2012), harvesting guidelines, local ownership (Toke and Elliott 2000), and appropriate siting may provide some degree of mitigation. Negative economic externalities related to misallocation of scarce land and resources and the creation of conditions conducive to opportunism and system gaming also require attention. For instance, the allocation of land to renewable energy production will inevitably result in conflicts with other economic sectors and environmental services, including food production, fiber production, ecotourism, and biodiversity conservation (Field et al. 2008). In the case of forest biomass, there are also opportunity costs associated with allocating biomass to the production of bioenergy instead of higher-value alternatives that may receive more revenue and create more jobs per unit of woody biomass harvested and processed. With regards to the potential for opportunism and system gaming, carbon trading schemes, like the EU Emission Trading Scheme (EU ETS) and the now defunct cap-and-trade program under the Chicago Climate Exchange (CCX), are leading to the commodification of forest carbon, an “intangible commodity” that cannot be effectively monitored and verified (Adams 2010). The potential deleterious effects of carbon trading on the sustainability of economies and
institutions have already been evidenced in the demise of the CCX cap-and-trade program, which was ultimately due to an over-subscription to unverifiable carbon offset projects (Gronewold 2011).

To use Ontario as a case study of the incongruity between existing policy targets and actual potential, consider that \( \approx 10,700 \) MW of new non-hydro renewable electricity capacity is planned by 2030 (OME 2010). The maximum contribution forest bioenergy could make to this future non-hydro renewable capacity is only \( \approx 700 \) MW without energy crops (Zhang et al. 2010; McKechnie et al. 2011). If the current share of solar remains, the capacity of wind power – which is currently 1,500 MW (IESO 2012) – will require a \( \approx 6,000 \) MW increase by 2030 to meet the provincial target, contributing to 15\% of the total installed capacity in 2030. Assuming the current average wind farm size of \( \approx 100 \) MW holds, 600 additional wind farms would need to be constructed throughout the province to meet this target, carrying potential negative externalities and uncertainty regarding wind resource potential and the willingness of the public to subsidize (Auditor General of Ontario 2011). More fine-scale analyses of the potential for wind power at the municipal level in Ontario (McIntyre et al. 2011) and the experiences of European wind power sectors (Nogee et al. 2009) have demonstrated that wind resources can provide no more than 20-30\% of local or regional electricity supply in areas with favorable wind conditions. It is now apparent based on the current provincial generation mix (OPG 2012) and trends in natural gas exploration and markets that most of the projected future capacity deficit will be made up with increases in lower cost and more energy dense nuclear power and natural gas, not renewables.

There is an obvious and formidable gap between the sustainable potential of renewable energy and the claims of potential enacted in legislation (Ragossnig 2007; Trainer 2010; de Castro et al. 2011; Tolon-Becerra et al. 2011). One explanation for this gap is that renewable energy targets are overestimates of total potential designed to elicit business interest, innovation, and investment (e.g. EU 2009). Indeed, investment in renewable energy technologies continues to increase on an annual basis (REN21 2011) and research and demonstration of renewable energy technologies is supported by most developed nations. However, the general lack of development of renewables at a global scale over the last 30 years (IEA 2011a) is evidence that the investment community has struggled with the
uncertainty of policy and challenging production economics of decentralized energy (Fuss et al. 2012, Siler-Evans et al. 2012). It is likely that targets and goals in most regions will need to be adjusted based on known limits to more accurately project the future composition of energy systems and to capture the confidence of investors and the general public. Policy goals should be attainable and informed with evidence and careful cost-benefit analysis, whereby the magnitude and certainty of benefits and costs of resource allocation for a range of options are assessed and compared based on the best available information.

While energy security and climate change motives cannot be separated, there is sufficient evidence from the contents of energy legislation, peer-reviewed scientific literature, and general public sentiment that concerns over climate change and the conclusion that it can be managed via mitigation (IPCC 1990; Pacala and Socolow 2004) have been the major drivers of energy policy and associated research over the last 10 to 15 years (e.g. EEA 2005). In 2007, the IPCC claimed that GHG emissions would have to be cut by 50-80% by 2050 to stabilize the atmospheric CO$_2$ concentration at a safe level of 450 ppm (currently >380 ppm) (IPCC 2007). National GHG emission targets, renewable energy policy, and applied scientific research are ultimately driven by these IPCC conclusions and the ensuing consensus that has emerged among key politicians and members of the general public (Curry 2011).

However, climate costs and benefits are by far the most uncertain of all the cost-benefit factors that must be considered in the development of responsible, evidence-based policy (Lomborg 2010). Human efforts to quantify, model, and project the magnitude and temporal oscillations of complex interactive effects of the earth system are inaccurate and incomplete (IPCC 1990; Lindzen 1992; Oppenheimer et al. 2007; Curry 2011; Curry and Webster 2011). The conclusions derived from the modeling of such a complex system and the costs of implementing those conclusions (e.g. GHG emission mitigation) should be fairly balanced against alternative related issues (e.g. long-term energy system stability, growing wealth inequality, political instability, education) that have a more certain effect on the lives of existing and future human populations. At a practical political level, many policy makers have found it difficult to reconcile the uncertainty of future climate benefits of renewable deployment and GHG mitigation with the certainty of near-term benefits of continued fossil
fuel exploitation and economic growth. The failures of Kyoto and Coppenhagen, and the continued development of the Albertan oil sands, attest to this.

Earthen fossil and mineral fuels are projected to become depleted over the next century if current global energy use trends continue (Shafiee and Topal 2009) and if novel fuels (e.g. thorium) and technologies (e.g. liquid fuel thorium reactors, nuclear fusion) are not developed. As part of a broader strategy to reduce energy demand and research and develop novel energy technologies, continued deployment of renewable energy is critical to long-term (century-scale) energy system planning and development. In transitioning to a more decentralized and efficient energy system, near-term (∼100 year) energy capacity deficits arising from the limits of renewable energy and continued growth of global primary energy demand can be cushioned by the growth of low carbon nuclear power and natural gas. However, overall, the costs, scarcities, limits, externalities, uncertainties, and biases that surround the renewable energy issue provide compelling reason for caution and skepticism in the actual contribution renewables can make to future energy supply. Stakeholders must be open to re-assess expectations and strategies based on the available evidence.

As a renewable energy technology with uncertain carbon neutrality (Ter-Mikaelian et al. 1995; Ter-Mikaelian et al. 2011; US-EPA 2011; Schulze et al. 2012), formidable fuel procurement logistics (Richard 2010), high opportunity costs (Moiseyev et al. 2011), potential harmful effects on biodiversity and stand productivity over repeated harvests (Lattimore et al. 2009; Hesselink 2010; Pare et al. 2011; Thiffault et al. 2011), limited potential (Nautiyal 1979), and a general lack of recognition by energy sector stakeholders not affiliated with the forest sector (e.g. Equinox Summit 2012), forest bioenergy can be regarded as the most uncertain and publicly contentious of the available renewable energy technologies. Forest bioenergy therefore represents a powerful case study for illustrating the strengths, weaknesses, and realities of renewable energy potential. In chapter 1, I will review the history of forest bioenergy development in the OECD and highlight the recent policy trend towards large-scale applications. The potential causes and consequences of this approach are reviewed and an initial case for an alternative approach that emphasizes efficiency and the biophysical and techno-economic limitations of the forest resource is made. In support of this alternative approach, chapter 2 concerns the issue of forest biomass
supply. A review of the forest biomass supply literature will begin with studies that occur at uncertain global and national scales and end with project-level studies that account for market and techno-economic constraints. Attention is then focused on these actual constraints of forest biomass supply and the importance of harvest residue, which represents the only consistently available and predictable forest biomass source that can be used for heat and electricity production in most jurisdictions without long term opportunity costs.

In chapter 3, I present a case study of the technical and economic availability of harvest residue sourced from single-tree selection operations typical of the tolerant hardwood forests of southeastern Canada and the northeastern USA. The volumes that can be made available are matched to the appropriate decentralized scale, which is generally limited to small-scale cogeneration or heating applications, unless supplemented with roundwood and/or mill residue or added to larger biomass supply chains that consolidate, densify, and distribute biomass from multiple sources. Finally, chapter 4 reviews the case for a renewed bioenergy policy in Ontario that includes heating applications (e.g. space heating, hot water heating) with reference to the empirical evidence presented in the preceding chapters. While bioelectricity and liquid bio-fuel production may be feasible in some regions, especially via integration and cogeneration, the economic benefits of heating applications and patterns of bioenergy success elsewhere are compelling points of evidence for the claim that encouragement of the development of such applications will lead to a more responsible, less costly, and more complete utilization of low quality forest biomass. Integrating bioenergy production with the supply chains serving the existing and future provincial manufacturing base will provide net benefits to the overall health of the forest sector and reduce the costs of heating, while making a marginal yet sustainable contribution towards fulfillment of modern energy policy goals like energy security, energy conservation, and GHG mitigation.
Chapter 1 – Review of Bioenergy Sector Development in the OECD

1.1 Overview of forest bioenergy in the OECD

The term “bioenergy” refers to usable forms of energy (heat, electricity, and transport fuel) produced from the thermal, chemical, and/or biological conversion of biomass, including woody biomass. The term “forest bioenergy” specifically refers here to bioenergy produced from woody biomass originating from natural forests, tree plantations, and short rotation woody crops. The typical energy density (lower heating value) of woody biomass is 19 MJ per kg, compared to 27 MJ per kg for lignite coal and 34 MJ per kg for bitumen coal (McKendry 2002). Conversion of this embodied energy into usable forms of energy (heat, electricity, and transport fuel) is facilitated with a number of bioenergy conversion technologies, ranging from rudimentary wood stoves to complex liquid bio-fuel production systems (also referred to as “platforms”) (IEA 2007). The range of existing and potential bioenergy conversion pathways can be subjectively divided into three scales (small-, medium-, and large-scale), corresponding to annual energy production capacity (Appendix 1.1).

The development of the modern bioenergy sector and the larger renewable energy sector began with the introduction of policies supporting energy security and renewable energy deployment in response to oil shortages in 1972/73 (Bonnor 1987). Before this time, bioenergy production in the OECD had been relegated to residential and commercial heating sectors and forest processing facilities in forested regions, which used small-scale wood combustion technologies like traditional stoves, fireplaces, and kilns for space and process heating requirements. Energy wood\(^1\) was primarily sourced in the form of sawmill residue (e.g. wood chips, sawdust, bark) or low-quality roundwood\(^2\) (e.g. firewood), which both arise at low cost and low effort from conventional forest supply chain processes such as forest

---

\(^{1}\) Energy wood refers to woody biomass used in the production of energy.

\(^{2}\) Roundwood refers to logs sectioned from tree stems and branches.
harvesting, transportation, and milling. The use of agricultural biomass and municipal solid waste in bioenergy production was negligible.

Renewable energy policies and related research organized under the International Energy Agency (IEA) since the 1970s have led to incremental growth in bioenergy production in the OECD. As a proportion of the total OECD fuel mix, biomass increased from 2.3% (4 EJ) in 1973 to 4.7% (11 EJ) in 2010 (IEA 2011a). Approximately 85% of all biomass currently used in the production of bioenergy in the OECD originates from existing forest supply chains, mostly in the form of sawmill residue, black liquor\(^3\), and urban wood waste (Ragossnig 2007). Growth of installed bioenergy capacity since the 1970s has been concentrated within the forest sectors of OECD countries, mainly cogeneration\(^4\) units in pulp and paper mills (Puttock 1989; Pingoud et al. 1999; Ralevic et al. 2008; Aguilar et al. 2011; Scarlat et al. 2011), with the majority of additional bioenergy growth occurring within the residential heating sector (Ericsson et al. 2004; Ralevic et al. 2008; Thornley and Cooper 2008; Aguilar et al. 2011). National commercial, electricity, and transport fuel sectors have also experienced marginal growth in bioenergy deployment (Figure 1.1). The majority of heat and electrical capacity increases within the forest, commercial, and electricity sectors have been achieved using standard steam-cycle units (boilers w/ or w/o steam turbine generators) which have been re-engineered to combust biomass. More recently, gasification technologies for heating and electricity applications have been demonstrated and commercialized (e.g. Nexterra 2012). In forested regions where residential heating has grown under policy incentives and high fossil fuel prices, traditional wood stoves and pellet stoves have been used (Christiansen et al. 1993; Aguilar et al. 2011; Scarlat et al. 2011).

---

\(^3\) Black liquor is an energy dense by-product of the Kraft pulping process that can be combusted in boilers to produce heat and electricity.

\(^4\) Cogeneration, also referred to as Combined Heat and Power (CHP), refers to energy pathways (bioenergy and non-bioenergy) that produce both electricity and usable heat.
Sawmill residue, black liquor, and low-quality roundwood (firewood) have been the main fuel sources for bioenergy production in the OECD. However, as bioenergy incentives have strengthened, procurement has gradually extended to include other low cost sources like agricultural residue, urban wood waste, and miscellaneous wastes, particularly in regions with bio-electricity sectors (Wiltsee 2000; Bain et al. 2003; Boralex 2003). Procurement logistics for these materials are simplified because biomass consolidation occurs as a by-product of the existing industrial base. Forest biomass that requires additional cost and effort to procure, such as branches, stem tops, and root systems, have also been used in regions with sufficiently strong incentives and market development (e.g. Nordic countries, mainly Finland and Sweden), as the full supply potential of lower cost sources has been surpassed by demand.

It is important to recognize that bioenergy production largely remains a small-scale, rural phenomenon. Globally, of the total 500 EJ of world primary energy supply, biomass and waste presently comprise approximately 50 EJ, 40 EJ of which is produced and used in
developing countries (IEA 2011a). Bioenergy production in developing countries predominantly occurs as residential heat for cooking and heating requirements, a symptom of limited historical access to wealth and electricity. In the OECD, where the remaining 20% (10 EJ) of global bioenergy production occurs, there is considerable variability among nation-states in the degree to which bioenergy has contributed to national energy supply and the goal of energy security, ranging from 0.8% in the United Kingdom to 17.9% in Finland (Gan and Smith 2011a) (Figure 1.2). Explanations for these differences include population size, proximity of populations to the forest resource, fossil fuel prices, and policy. Among OECD nations with strong forest sectors (Finland, Sweden, Austria, Canada, and the USA), there is a positive correlation between the deployment of small-scale community heating pathways (e.g. district heating and institutional heating in Finland, Sweden, and Austria) and the share of bioenergy in national primary energy supply (Lind 1979; Pingoud et al. 1999; Hillring et al. 2002; Ericsson et al. 2004; Madlener 2007; Madlener and Koller 2007; Thornley and Cooper 2008; Richter et al. 2009; Karha 2011).

![Figure 1.2: Share of bioenergy in total national primary energy supply in ten OECD nations (Gan and Smith 2011a).](image-url)
1.2 Expectations for large-scale bioenergy and possible consequences

1.2.1 Modern energy policy and future expectations for bioenergy

Modern expectations for renewable energy and bioenergy in the OECD represent a significant departure from what has been achieved to date. Climate legislation, visions of a future energy system fuelled primarily with renewables, and economic declines in the conventional forest industries are major drivers of this change. By 2020, the EU expects renewable energy to reach a 20% share in the total energy mix and liquid bio-fuels to reach a 10% share in the transport sector fuel mix (EU 2009). These targets are similar to the failed targets set in 2005 by the European Commission (EC 2005; EC 2006), which required that biomass supply increase by a factor of ≈5 for bio-electricity (assuming a 30% electrical conversion efficiency) and ≈15 for liquid bio-fuels (assuming an 80% liquid conversion efficiency) by 2010 (Ragossnig 2007; Figure 1.3). Jurisdictional bioenergy targets in North America exhibit similar bias in favor of electricity and liquid bio-fuel production (Galik and Abt 2011). For instance, the Energy Independence and Security Act of 2007 set the goal of a more than 3-fold increase in liquid bio-fuel production in the USA (Smith et al. 2012). Asian OECD nations are also incorporating aggressive bio-electricity policies: recent South Korean co-firing targets are expected to create a demand for wood pellets well beyond what existing global densified supply chains are capable of sustainably supporting (CanBio 2011).
Policy targets have been followed up in most jurisdictions with aggressive implementation measures. As of 2010, bio-fuel production and blending mandates, feed-in tariff (FIT) programs\(^5\), bio-electricity tax credits, carbon taxes, and renewable standards and quotas\(^6\) had been implemented in over 60 OECD jurisdictions (states, provinces, and countries) (REN21 2011). Electricity generation, which had been concentrated mainly in forest mills and stand-alone bio-electricity plants of scales no greater than 80 MW prior to the 2000s, is now being achieved through co-firing pelletized biomass at rates of between 1% and 20% in coal power plants (IEA 2011a). To date, co-firing has been tested in over 150 countries (Al-Mansour and Zuwala 2010), including plants in the EU (Hanson et al. 2009), Canada (Zhang et al. 2010;  

\[^5\] Feed-in tariff (FIT) programs pay a fixed rate for renewable electricity (including bio-electricity) that is higher than rates paid for conventional fossil and mineral fuel-based electricity. 

\[^6\] Renewable standards and quotas usually require that electricity providers source a specified percentage of their electricity supply from renewable sources.
Basu et al. 2011), the USA (Robinson et al. 2003), China (Dong et al. 2010; Hu et al. 2011), South Korea (CanBio 2011), Brazil (Hoffmann et al. 2012), and eastern European countries (Berggren et al. 2008; Kazagic and Smajevic 2009). Aside from achieving GHG and sulphur oxide reductions by displacing coal (Zhang et al. 2010; Gustavsson et al. 2011), benefits of this approach include utilization of existing labour and capital infrastructure, thereby displacing a portion of the total investment in new renewable electricity generation capacity that would otherwise be required in the near term while avoiding interference with the status quo. Liquid bio-fuel production is also being incentivized by most OECD nations, with Canada and the USA providing subsidies for ethanol and bio-diesel production. Low carbon transport fuel policies in California already favor the production of liquid bio-fuel over electricity or heat (Tittmann et al. 2010).

1.2.2 Potential consequences of bioenergy policy

Incentivizing bio-electricity and liquid bio-fuel production could have unintended consequences. Augmenting and sustaining the biomass supply needed to meet current targets for these medium-scale and large-scale pathways will be expensive (i.e. increased energy prices, increased use of public funds) and challenging, requiring an unprecedented level of coordinated investment in biomass production systems and supply chains. Bioenergy sector growth to date has been based on the utilization of industrial waste (e.g. black liquor, sawmill residue, urban wood waste), a supply source that is reaching its limits in most regions (Bain et al. 2003; Levin et al. 2011). The production economics of electricity and liquid bio-fuel pathways are optimized at the largest possible scale and low conversion efficiencies of between 20% and 35% require 2.5 to 10 times more biomass per unit of usable energy produced compared to heating or cogeneration pathways, which have conversion efficiencies of between 70% and 90%.

The relatively high demand per unit of energy produced for electricity and liquid fuel applications contrasts with the relatively low supply potential of the forest resource. The only potential sources of energy wood in the near term are managed forest lands, forest supply chains, and associated waste streams, sources that cannot support a level of heat, electricity, or liquid fuel production beyond \( \approx 10\% \) of jurisdictional renewable energy targets or total energy supply, including in the EU (Caula 2011; Moiseyev et al. 2011), North America
(Mabee et al. 2011a), USA (Buchholz et al. 2011; Galik and Abt 2011), Canada (Nautiyal 1979), and Ontario (Zhang et al. 2010; Mabee et al. 2011b; McKechnie et al. 2011; McKechnie 2012). Furthermore, there are considerable logistical and economic challenges associated with consolidating unused biomass from managed forest lands in volumes of sufficient size for economical energy production (Richard 2010). Monocultures of fast-growing woody and herbaceous plant species that produce low-quality biomass over short rotations, termed “short rotation woody crops” or “energy crops”, are critical to realizing targets, but have not yet been established in most regions and have highly uncertain land-use, socioeconomic, and environmental tradeoffs.

The relative scarcity of available biomass is also evidenced in the current level of global bioelectricity capacity and the scale thresholds of existing bio-electricity plants. Bio-electricity only constitutes 4.7% of total global renewable electricity capacity, or 19.9% of total global non-hydro renewable electricity capacity (REN21 2011; Figure 1.4). With regards to the scale thresholds of individual plants, business and operating experience in the bio-electricity industry over the last 30 years has found through trial and error that facilities cannot exceed capacities of 50-80 MW when restricted to local and regional biomass supplies because of biophysical limits (Nicholls et al. 2008; Shahi et al. 2011; Johnson 2012). The average scale of stand-alone bio-electricity plants in Canada and the United States – which are predominantly fuelled with sawmill residue and urban wood waste – is ≈25 MW (Bain et al. 2003; Boralex 2003) and the largest stand-alone bio-electricity plant in North America is only 60 MW (Mabee et al. 2011b). Nuclear and fossil fuel stations commonly scale at 200 MW and can reach 110,000 MW capacities (IEA 2011a). In Europe, where co-firing is most extensively practiced, co-firing rates range between 1% and 20%, but average only 2.8% on an electricity generation basis (WIP Renewable Energies 2009) because of the lack of available biomass supply and lower energy density of wood pellets. In fact, local and regional supplies have been exhausted under European co-firing incentives, requiring the importation of pellets from outside the EU, including North America (Heinimo and Junginger 2009; WIP Renewable Energies 2009). The limits of local and regional forest biomass supply arise from fundamental biophysical, market, and techno-economic constraints.
The realization that volumes are not available in sufficient supply to meet modern targets is leading to concerns in most regions of the OECD that the emerging bio-fuel and bio-electricity sectors could lead to competition for merchantable roundwood normally used in the production of pulp and paper, composite, and solid wood products (Lundmark 2006; Galik et al. 2009; Plieninger et al. 2009; Spelter and Toth 2009; Thek and Oberberger 2009; Abt et al. 2010; Conrad et al. 2010; Schwarzauer and Stern 2010; Tromborg and Solberg 2010; Moiseyev et al. 2011; UNECE/FAO 2011). Re-allocation of wood fibre from conventional industries to bioenergy can have questionable trade-offs: Moiseyev et al. (2011) estimated that meeting 8% of the EU renewable energy directive (EU 2009) with bioenergy would require reallocation of woody biomass from pulp and panel industries and a corresponding 20-25% decrease in the production of pulp and panel products. Potential conflict among competing bioenergy pathways has also been observed in the USA, with
proponents of the bio-electricity industry standing against bio-fuel and pellet industries because of overlapping raw material demands (Leefers 2011).

1.2.3 Potential causes of suboptimal bioenergy policy

As a complex issue, development of informed, optimal bioenergy policy has encountered a number of challenges, many of which are unique to forestry. Perhaps most important has been poor communication among stakeholders in the forest bioenergy sector, many of whom are new entrants to the forest industry and thus unfamiliar with existing structures and functions. Lack of standardization of methodology and terminology has been a problem common to forest sector research and communication (Robinson and Honer 1974; Groot et al. 2005), and the forest bioenergy issue is no different (Gan et al. 2008; Benjamin et al. 2010; Stupak et al. 2011). The term “bioenergy” includes a broad range of technologies and conversion pathways at various scales. The woody biomass used to fuel bioenergy production is referred to in the literature with a number of synonyms like “biomass”, “energy wood”, “lignocellulosic fuel”, “primary forest fuel”, “woodfuel”, and “fuel wood”. When this confusing bioenergy terminology is coupled with complicated and imprecise biometric, silvicultural, and operational terminology, it is often unclear to politicians and other groups not strongly affiliated with the forest sector as to where the forest biomass fuelling the bioenergy sector actually originates and what the energetic and ecological implications of procuring this biomass might be.

Further confusion arises from the misleading claims of potential made by advocates of bioenergy. A great number of the forest biomass supply estimates published in peer-reviewed literature have used coarse scales and methods, leading to unrealistic estimates of the potential for forest biomass to contribute to energy supply. Such estimates support the tendency among politicians, businessmen, engineers, environmentalists, academics, and other stakeholders without a forestry background to apply centralized energy systems thinking to investigations and expectations of the potential for forest bioenergy to solve or create modern energy and climate problems (Wilson et al. 2012). For instance, mechanical, chemical, and biological engineers have published studies exploring the feasibility of distributing liquefied biomass in existing pipeline networks (Pootakham and Kumar 2010), establishing and operating 300 MW bio-electricity plants (Mobini et al. 2011), sustaining bio-fuel, bio-
chemical, bio-material, and bioenergy production in large “biorefineries” with genetically-engineered energy crops (Ragauskas et al. 2006), and replacing the entirety of jurisdictional coal supply with biomass sourced from land areas greater than 9 million hectares (Hocatoglu et al. 2011). Such scenarios are highly unlikely because of the biophysical, technical, economic, and environmental limitations of natural forests, forest operations, and energy crops (Field et al. 2008; Ralevic et al. 2010). These pathways represent long-term possibilities, contingent on the establishment and maintenance of large expanses of energy crops and on the management of associated environmental externalities.

The recent focus on the potentials of bioenergy without explicit acknowledgement of limitations is symptomatic of the tendency for the human species to ignore basic biophysical and physical limitations of economic activity (e.g. Cleveland et al. 1984). This tendency has become pronounced within the forest industry and forest-dependent communities in recent years because of the poor economic conditions brought on by the global economic downturn and the prevalence of mill closures and job losses. The survival of the industry and its stakeholders is threatened, with job creation and development needed immediately by those who are economically dependent on the industry (e.g. Eastern Ontario Model Forest 2005). Although establishing bioenergy capacity may interfere with the conventional solid wood and fiber industries, as well as future value-added markets, regions that have experienced mill closures and work force losses would welcome the revenue and employment benefits of increased harvesting activity and bioenergy production. This can lead to myopic policy that favors bioenergy at the expense of an optimal long-term value-added strategy that may provide greater, more sustainable net benefits via solid wood products, engineered wood products, bio-chemicals, and/or bio-materials in the long run (FPAC 2010; Lazar 2010).

1.3 The need to revise bioenergy policy

Careful cost-benefit analysis that one might expect from governments exercising evidence-based decision-making does not seem to have fulfilled the role that it should in policy development. Rigorous supply studies have clearly shown that the electricity and liquid bio-fuel targets set by OECD nations and respective jurisdictions are unrealistic and unattainable without the development of regional and/or international densified biomass supply chains that are derived from energy crops, a resource that remains unproven at the large scales
required. Pursuing a more gradual decentralized strategy that prioritizes the growth of high-efficiency heating applications and smaller-scale cogeneration when supplies are sufficient – as has been done in the most successful bioenergy producing European nations like Finland, Sweden, and Austria and which is actively promoted by the European Union (EU 2009) – may be more appropriate given the limitations of the resource. More importantly, heating pathways have the potential to reduce the costs of bioenergy production, both in terms of public costs of subsidization and taxation (Dasappa et al. 2003; Samson et al. 2005; McKenney et al. 2011), GHG mitigation costs (Wilson et al. 2012), and opportunity costs of re-allocating forest biomass from existing and future value-added manufacturing pathways. Additional benefits of this revised policy strategy include an improved contribution of bioenergy to energy sector goals of energy efficiency and sustainability and to forest sector goals of renewed value-added manufacturing (Egeskog et al. 2009). This is an approach that has been advocated by many North American forestry practitioners, researchers, industry members, and students who have experience with the forest sector and its forest bioenergy subset (Etcheverry et al. 2004; Samson et al. 2005; Richter et al. 2009; Ghafghazi et al. 2010; GreenPeace 2011; Hall 2011; Pare et al. 2011; Yablecki et al. 2011; Cockwell pers. comm.; Cormier pers. comm.; Desrochers pers. comm.; Ryans pers. comm.; Schleifenbaum pers. comm.).

In moving forward, it may be helpful to understand how North American bioenergy policy has reached its present stage of development, in which electricity and liquid bio-fuel production is emphasized over heating pathways. In addition to human biases, self-interest, bounded rationality, economic necessity, and contingencies of geography and history, biomass supply research – an evidence-based, empirical discipline – has tended to omit important details that strongly affect the actual amount of biomass that can be mobilized for bioenergy production. This has helped to maintain an illusion of abundance that has detracted from realistic goal-setting in forest bioenergy policy (Lundmark 2006). In the following chapter, the forest biomass supply literature is reviewed, beginning with coarse-scale studies and ending with fine-scale, project-level studies. The chapter concludes with a review of the market and techno-economic constraints to forest biomass procurement with specific reference to harvest residue.
Chapter 2 – Forest Biomass Supply and the Role of Harvest Residue

2.1 Methods of forest biomass supply estimation

One of the first steps in developing bioenergy policy and projects is to quantify the available biomass supply and the actual contribution this supply can make to energy supply and demand. Biomass supply studies – which seek to quantify biomass supply from various sources at various scales – have therefore remained a significant component of the bioenergy literature that has accumulated in peer-reviewed journals like “Biomass and Bioenergy”, “Bioresources”, and “Bioresource Technology” since the 1980s. Studies occur across all scales from global to local and vary considerably in methods, assumptions, and accuracy.

Many published estimates have included the use of models that automate compilations and calculations (e.g. Dornburg et al. 2010). However, regardless of whether or not a model is used, the general approach to assessing the biomass potential of a fixed forested area is a simple step-wise procedure (Smith et al. 2009). First, the total land area available for procurement is estimated using forest inventory, maps, and/or Geographic Information Systems (GIS). Second, the amount of biomass per unit area is estimated using surveys, ground plots, and/or remotely-sensed data, combined with biometric models and conversion factors (Aldred and Alemdag 1988). Third, deductions from the total amount of biomass available are made for higher-value products (e.g. roundwood for solid wood products and/or fibre products), handling losses, and, sometimes, cost. This procedure results in a final estimate of the amount of forest biomass that can be made available for bioenergy production.

The accuracy and reliability of the final estimate will depend on the scale of the analysis (global, regional, local), the resolution of the datasets used, the rigor of the models and conversion factors used, and the degree to which the analysis rests on assumptions about land use, biomass yield, and technology development (Berndes et al. 2003; Smith et al. 2009). Coarse scales and methods of estimating future global or regional biomass supply are inherently inaccurate and confounded by incomplete information, as is the case in
macroeconomics and other large-scale data collection and analysis procedures that attempt to model past, current, and future states of large, complex systems (e.g. Giampietro 2008). Generally, as the scale of the supply analysis decreases and the time horizon of the analysis shortens, the accuracy of biomass availability and energy production estimates increase.

2.2 Forest biomass supply literature review

2.2.1 Global and regional forest biomass supply estimates

The ambition of modern bioenergy policy can be attributed in part to the prevalence of biomass supply studies that espouse the potential for bioenergy production at uncertain geographic scales. Estimates of global biomass potential for the years 2050 and 2100 range from 0 – 1,500 EJ (Berndes et al. 2003; Dornburg et al. 2010), the upper limit of which is three times larger than current world fossil fuel-based energy supply. These estimates have been refined to between 100 and 500 EJ (Berndes et al. 2003; Smeets and Faaij 2007; Dornburg et al. 2010) in subsequent iterations that constrain land availability for energy crops, yet remain 2 to 10 times larger than the current global biomass primary energy supply of 50 EJ (IEA 2011a). Regional biomass supply studies in the EU have estimated a potential contribution of between 12 EJ and 28 EJ by 2030 (EEA 2006; Ericsson and Nilsson 2006; de Wit and Faaij 2010), but these studies also suffer from coarse scales, assumptions of energy crop establishment, and associated uncertainty (see below). Consider that the estimate of 28 EJ is over 9 times higher than the current 3 EJ of primary energy supply of biomass in Europe (EEA 2006) and over twice as high as the current primary energy supply of biomass in the entire OECD (10 EJ).

Most of the variability and ambition in estimates of future global bioenergy potential is attributable to herbaceous and woody energy crops, which constitute the majority of total biomass supply in most published reports on the topic (Berndes et al. 2003; EEA 2006; de Wit and Faaij 2010; Dornburg et al. 2010; Figure 2.1). There are a number of complex, interdependent factors that influence the actual amount of available land that can be gradually phased into energy crop production, including competition with other economic sectors, environmental impacts, and economic costs (Field et al. 2008). In the long term, land uses that win out over others will be determined by unpredictable contingencies of economy,
politics, and human population growth. This is especially true for unstable developing countries, which are assumed to support most of the global energy crops in published studies, densifying and selling the harvested biomass to developed countries (Berndes et al. 2003; Dornburg et al. 2010; Nijsen et al. 2012). Uncertainty of biomass yield per hectare as a result of differential latitude, climate, soils, fertilizer inputs, and species also serves to confound the reliability of energy crop-based estimates (Field et al. 2008). Interest of plant scientists and biotechnologists in creating genetically engineered energy crops (e.g. Ragauskas et al. 2006) is also contentious from the standpoint of environmental ethics and the actual benefits that the costs of such engineering might provide to energy systems in the long run.


The uncertainty surrounding energy crops is compounded by more practical considerations like the poor economics and high risk associated with growing and maintaining energy crops over 10 year rotations. Farmers in Ontario have remarked that energy crops do not make business sense relative to agricultural crops because of the longer rotations which reduce payback periods and increase susceptibility to crop failure (Working Forest 2011). If the energy crop sector has a substantial private component, economic trade-offs must also be
factored into future supply projections, as producers may have incentive to divert woody biomass to composite or engineered wood products in future market conditions. The uncertainty that arises from these factors and assumptions of land availability, crop production, and economics is evidenced by the high variance in projections of global energy crop potential in the literature, which range from 27 – 1,100 EJ (Hoogwijk et al. 2003; Field et al. 2008), reduced to 50 – 250 EJ (Berndes et al. 2003), 120 – 260 EJ (Dornburg et al. 2010), 120 – 300 EJ (van Vuuren et al. 2009), and up to 340 EJ (Nijsen et al. 2012) in subsequent coarse-scale iterations. Regional estimates for the EU have published energy crop potential ranges of between 1.7 and 12.2 EJ (EEA 2006; de Wit and Faaij 2010).

Despite these uncertainties, energy crops will need to be phased into production eventually if the long-term depletion of earthen fossil and mineral fuel-based energy supply is not offset by a combination of alternative energy sources and a reduction in overall energy demand. There are a number of benefits associated with energy crop establishment, particularly on degraded lands (Nijsen et al. 2012) and when applied locally to meet the demands of heat and/or electricity facilities. When situated close to the conversion facility, energy crops can be competitive with fossil fuels for heating applications (McKenney et al. 2011). Higher value roundwood procured from sustainably-managed natural forests can remain as a high revenue-generating product with associated employment benefits of manufacturing. At larger scales, the costs of establishing millions of hectares of energy crops in Canada could be exceeded by the benefits of having a transport fuel supply source that could be sustained in perpetuity. However, the degree to which energy crops contribute to future energy supply remains highly uncertain and therefore does not form a realistic reference for policy aimed at increasing near-term bioenergy capacity.

Forest biomass that can be made available from existing managed forest lands and associated supply chain and waste stream derivatives is a much more certain supply source. Unlike energy crops, recovery of forest biomass originating from managed lands is not limited by land availability: the land is already sustainably allocated, planned, and actively managed in most cases. Forest biomass available for bioenergy production from managed lands, supply
chains, and waste streams includes mill residue, unused roundwood, harvest residue\textsuperscript{7}, thinning residue\textsuperscript{8}, and, to a lesser extent, roundwood and residue available from naturally disturbed stands. Projections of the maximum primary energy potential of biomass from these sources globally and for the EU (excluding natural disturbances) are far lower than those of energy crops, ranging from 30 to 180 EJ (Smeets et al. 2007; Dornburg et al. 2010) and 1.4 to 12.9 EJ (de Wit and Faaij 2010), respectively. Again, although more certain than energy crop estimates, the coarse scale of global and regional studies results in a vast range of estimates.

2.2.2 National forest biomass supply estimates

National biomass supply studies have further refined estimates for forest biomass availability from energy crops and managed lands, supply chains, and waste streams by making more reliable deductions for protected areas, inaccessible areas, handling losses, and product allocation. Many results have been optimistic: Perlack et al. (2005) estimated that over 33% of transportation fuel demand in the USA could be met with biomass from forest residues, agricultural residues, and future energy crops. Studies of national biomass supply in Canada have estimated that 18-27% of national energy supply could be met with biomass from forestry, agricultural, and municipal solid waste (BIOCAP 2003). As with global and regional studies, most of the national estimates for Canada and the USA assume that the majority of the future supply will come from agricultural lands and energy crops (Perlack et al. 2005; Kumarappan et al. 2009), indicating that a significant shift in biomass supply – which is currently dominated by biomass from natural forests – will be required.

Estimates of maximum forest biomass potential tend to decrease with time, as subsequent studies make additional deductions for material that has a low probability of being available for bioenergy production, or that is not available in the near term. For instance, in contrast to the estimate of 33% reported by Perlack et al. (2005) for bio-fuel production in the USA,

\textsuperscript{7} Harvest residue refers to unused trees and tree components arising from commercial forest operations.

\textsuperscript{8} Thinning residue refers to small-diameter trees arising from precommercial and commercial thinning operations.
Mabee et al. (2011a) recently estimated that the maximum contribution forest and agricultural residue from existing managed lands could make to ethanol production for transportation was only 5.3% in the USA and 13.7% in Canada. Although the lack of inclusion of energy crops in the Mabee et al. (2011a) study contributes to most of the disparity, part of the disparity is attributable to the exclusion by Mabee et al. (2011a) of mill residue and unused roundwood (i.e. net annual increment), which together contributed 53% of the total forest biomass supply estimate in the Perlack et al. (2005) study. Assuming that volumes of mill residue and unused annual increment will be available for transport fuel production ignores current and future alternative mill residue markets and the techno-economic barriers and biodiversity concerns associated with harvesting surplus forest growth. Procuring these supplies for bioenergy production would negatively affect existing markets for alternative products (e.g. composite products, landscaping, animal bedding) and, in the case of the unused annual increment, would require bioenergy market prices to rise well beyond current and historic levels.

2.2.3 Sub-national and local forest biomass supply estimates

Although confounded by a coarse scale of analysis, the national-level Mabee et al. (2011a) estimate is consistent with the more rigorous analyses of biomass potential from managed natural forests at sub-national and local scales. As mentioned earlier, these studies have indicated that available supplies are only sufficient to meet no more than ≈10% of jurisdictional demands for electricity and liquid fuel or renewable energy (Zhang et al. 2010; Buchholz et al. 2011; Caula 2011; Galik and Abt 2011; McKechnie et al. 2011; Moiseyev et al. 2011; McKechnie 2012). The rigor of smaller scale analyses arises from the consideration of additional constraints on biomass supply, including local markets, forest structure, ownership, supply chain logistics, transport distance, technical specifications of machinery, and economics. Each of these aspects vary in space and time and impose limits on the amount of biomass per unit area of managed land that can be delivered to a given conversion facility at an acceptable cost. It is in resolving the local and regional details of these limits of biomass availability and cost that actual volume availability for bioenergy production can be reliably determined and used to inform policy (Richardson et al. 2006).
Ensuring a sustainable supply of biomass is highly dependent on local factors. Stasko et al. (2011) summarize this well: “Competition from such incumbent industries (forest product industries) for forest biomass is localized and influences both availability and market values. Forest density and terrain impact the logging costs, and the spatial distribution of forests determines the cost of transportation to the plant gate”. Project-level supply studies account for these local effects. There have been numerous published studies that have analyzed biomass supply and bioenergy production at local, project-level scales, usually incorporating spatially-explicit methods via GIS (e.g. Masera et al. 2006; Noon and Daly 1996; Ranta 2005; Viana et al. 2010; Emer et al. 2011; Yoshioka et al. 2011; Zhang et al. 2011) and/or optimization models parameterized using local data (e.g. Shahi et al. 2011). Many local studies have included development of cost-supply curves, which define thresholds of biomass availability at a set market price based on estimates of delivered cost (e.g. Nicholls et al. 2008; Parker et al. 2010; Tittmann et al. 2010). Theoretical plant optimization models have also contributed to the literature, evaluating the extent to which universal biophysical and engineered factors such as biomass availability, conversion efficiency, and capital and operating costs affect facility scale, final costs, and energetic output (e.g. Gan and Smith 2011b; Kim et al. 2011; Leboreiro and Hilaly 2011).

Systematic understanding of energy wood supply at the fine-scales explored in project-level and theoretical optimization studies can be facilitated by dividing constraints into three main functional groups: constraints imposed by land availability and ownership (“land constraints”), constraints imposed by existing forest product markets and principles of value-added manufacturing (“market constraints”), and constraints imposed by the technical and economic aspects of harvesting, processing, and transporting forest biomass to the conversion site (“techno-economic constraints”). Constraints of land availability and ownership, including parcelization on private lands (e.g. Germain et al. 2006; Sampson and Decoster 2000; Butler and Ma 2011; Markowski-Lindsay et al. 2012), dictate the total area and locations that can be harvested in a given area. Market constraints include competing markets for forest biomass and the trade-offs inherent in pursuing one pathway at the expense of another. Identification of market constraints serves to define the sources of forest biomass that could potentially be made available for bioenergy production from the available land area and forest resource. The actual fraction of this potential supply that can be recovered and
delivered to market at profit is determined by techno-economic constraints, such as forest structure, terrain, road network quality, density, and tortuosity, and supply chain infrastructure. Only once land, market, and techno-economic constraints have been identified and resolved can the production facility be appropriately scaled and informed policy developed. Note that environmental constraints (e.g. nutrient imbalance and susceptible biodiversity) can further limit energy wood supply on some sites (Thiffault et al. 2011).

2.3 Constraints to forest biomass supply

2.3.1 Land and market constraints and the value-added principle

Although some jurisdictions have regulated wood use by banning bioenergy producers from using merchantable roundwood (Ericsson et al. 2004; Simon and Kimmerer 2011), the problem of determining which forms of biomass can be used in the production of bioenergy has been dictated by forest markets in most cases. Forest markets pay up to 100 times more per volume/mass equivalent for structural lumber, pulp and paper, and composite board than for energy wood (Hamilton pers. comm.; Figure 2.2). This prevailing market state is largely set by demand: there are no cheap or GHG neutral alternatives for wood in the residential construction, pulp and paper, and composite sectors. In contrast, energy markets have at least ten different choice fuels. As a consequence, over 90% of all forest biomass harvested in the OECD (roundwood and residue) is used in the production of solid wood and fiber products (Jahn and Preston 1976; Araya and Katsuhisa 2008; OECD/IEA 2011).
Figure 2.2: Average market prices in northeastern North America for various forest products by value per unit roundwood equivalent (Hamilton pers. comm.).

The differential market value of forest products ultimately controls the structure and function of forest management regimes and supply chains, and this has important implications for the bioenergy sector. Primary forest products like veneer, lumber, and pulp and paper can be sold on the market at prices that cover the high costs associated with merchantable roundwood production and procurement, including land ownership and rent, forest management, planning, silviculture, operations, and transport. Lower-value secondary forest products like composites\(^9\) and bioenergy (including firewood) usually cannot cover these costs and therefore must make use of the by-products of merchantable roundwood production, procurement, and manufacturing from the land area upon which these activities are carried out. Definitions of what constitutes merchantable roundwood – which is sectioned from tree stems and rarely large branches (Zakrzewski 2011) – differ based on mill requirements and

\(^9\) Composites include plywood, oriented strand board, cross-laminated lumber, particle board, medium density fiber board, etc.
tree growth form but is generally limited to roundwood of sufficient straightness with a minimum end diameter greater than 10 cm and a length greater than 1.3 m (OMNR 2008; Van Deusen and Roesch 2011). Roundwood meeting these requirements can be transported by truck and milled to the standards of solid wood and fiber products. Note that merchantability standards are lowered in pulp and paper operations that chip roundwood before transportation.

The low-value forest bioenergy sector has been relegated to the use of unmerchantable material that arises as a by-product of merchantable roundwood production, procurement, and manufacturing activities like commercial forest operations, silvicultural activities, and milling. This specifically includes mill residue, which arises as a by-product of forest product manufacturing, harvest residue and thinning residue (collectively referred to as “forest residue”), which arise as by-products of commercial harvesting and silvicultural activities, and low-quality roundwood arising from commercial harvesting that does not meet merchantability standards or for which markets do not exist.

Increases in the strength of energy wood markets under modern renewable energy policy and related climate concerns may alter this traditional state of forest sector structure and function, leading to a diversion of low-quality merchantable roundwood from existing pulp, paper, panel, and composite markets (Lundmark 2006; Galik et al. 2009; Plieninger et al. 2009; Spelter and Toth 2009; Thek and Oberberger 2009; Abt et al. 2010; Conrad et al. 2010; Schwarzbauer and Stern 2010; Tromborg and Solberg 2010; Moiseyev et al. 2011; UNECE/FAO 2011). The potential for bio-electricity and bio-heat markets to jeopardize the interests and capital of conventional forest industry stakeholders and beneficiaries has been a long-standing concern within the forest industry (Puttock 1987; Hakilla and Nousiainen 2000; Ericsson et al. 2004; Leefers 2011). This concern reflects the self-interests of existing incumbents but can also be argued on macroeconomic grounds to represent a threat to an optimized value-added manufacturing strategy that maximizes revenue, employment, and wages over time (FPAC 2010; Lazar 2010). In the near-term, in the absence of policy instruments that make bio-heat and bio-electricity markets competitive with fiber markets, the lack of alternatives for solid wood and fiber products will maintain the existing difference in market value and revenue potential where such markets exist. In regions where the
conventional industry is failing, many forest sector proponents advocate focus on future value-added markets for a diversity of bio-chemicals, bio-materials, and bio-fuels (Appendix 2.1), because of the greater revenue potentials these products might receive when sold on local, regional, and/or international markets. The less capital- and labour-intensive bio-heat and bio-electricity sectors may also generate fewer jobs per m³ than manufacturing-intensive value-added pathways (FPAC 2010; Greenpeace 2011; MNDMF 2011) (Table 2.1). Note that Table 2.1 does not reflect employment per m³ of wood processed, which is, for example, often higher for sawmills than pulp mills.

Table 2.1: Average direct employment per facility for various wood product manufacturing facilities and bioenergy production facilities (FPAC 2010; Greenpeace 2011; MNDMF 2011).

<table>
<thead>
<tr>
<th>Plant/facility type</th>
<th>Direct jobs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulp and paper mill</td>
<td>300-350</td>
</tr>
<tr>
<td>Biorefinery (bio-fuel and bio-chemicals)</td>
<td>300-350</td>
</tr>
<tr>
<td>Sawmill</td>
<td>50-210</td>
</tr>
<tr>
<td>Composite mill</td>
<td>50-80</td>
</tr>
<tr>
<td>Bio-fuel plant</td>
<td>50-80</td>
</tr>
<tr>
<td>Pellet plant</td>
<td>10-100</td>
</tr>
<tr>
<td>Stand-alone bio-electricity plant</td>
<td>20-40</td>
</tr>
<tr>
<td>Community heating plant</td>
<td>3-5</td>
</tr>
</tbody>
</table>

Artificially increasing energy wood prices via policy and causing the diversion of merchantable roundwood from solid wood and fiber products to bioenergy production reduces the ability of solid wood, fiber, and future value-added markets to meet societal demands for those products and may reduce total sector employment and revenue. By this logic, if revenue- and employment-maximization remain basic development goals, the use of merchantable roundwood in bio-heat and bio-electricity production can only occur in regions where merchantable roundwood is not fully utilized by the existing industry and where the prospect of future value-added markets for merchantable roundwood (e.g. engineered wood products, bio-materials, bio-chemicals) is low. The emergence of sufficiently-intense bio-electricity subsidization programs in North America are low-probability caveats to this argument because of the high public costs entailed (Frondel 2008; Auditor General 2011). However, climate era bioenergy policy in the EU and other nations (e.g. South Korea) is leading to exponential growth in the international wood pellet and liquid bio-fuel trade, of
which Canadian sawmill residue is a major supply source (Junginger et al. 2008; Heinimo and Junginger 2009; Junginger et al. 2011). Continued commodification of wood pellets and liquid bio-fuels under strengthening incentives could conceivably lead to competition for merchantable roundwood in many regions. Again, this can be regarded as a low probability development under rational, evidence-based policy because of long-term opportunity costs and energy efficiency losses entailed.

Bio-electricity and bio-heat producers will therefore continue to be limited to unmerchantable forest biomass not used in the manufacturing of value-added forest products, including mill, harvest, and thinning residue, low-quality roundwood from existing operations, and – a more recent consideration – low-quality roundwood and residue from entire stands left unused by the industry (also referred to as the “unused annual increment” or “unused annual allowable cut”) or from entire stands affected by natural disturbances. The use of these various forms of unmerchantable material in the bio-heat and bio-electricity sectors will still produce wealth, create jobs, and provide sustainable energy if properly regulated, as has occurred in Finland, Sweden, and Austria (Pingoud et al. 1999; Hillring et al. 2002; Ericsson et al. 2004; Madlener 2007; Madlener and Koller 2007; Thornley and Cooper 2008; Richter et al. 2009; Karha 2011). Supporting heat and/or electricity pathways that utilize unmerchantable material can increase the revenues of forest contractors, create jobs for boiler technicians, reduce heating fuel costs for building owners and tenants, and contribute to GHG mitigation (Madlener and Koller 2007). Furthermore, jobs will be shifted from conventional fossil fuel or nuclear generation, which have large foreign supply chains, to local and regional domestic supply chains.

The ability of the bioenergy sector to establish and maintain energy wood supply chains and to realize associated revenue, employment, and energy benefits will depend on the biophysical availability, economic availability, and predictability of the sources over time. Economic availability and predictability are particularly important factors affecting the establishment of new bioenergy capacity because attraction of the required investment hinges on demonstrating that the required biomass supply can be met over the lifetime of the facility at acceptable cost (Richardson et al. 2006; Becker et al. 2011). The biophysical availability
merely quantifies the amount of biomass present in a given area without making deductions for market and techno-economic constraints.

2.3.2 Forest biomass from unused managed lands and natural disturbances

Low-quality forest biomass from unused managed lands and natural disturbances has a relatively high biophysical availability in many regions. In Ontario, for example, 30% to 40% of the total area of sustainably-allocated forest land and associated standing volume is left unused by the industry because of lack of markets, low stand value, and/or high access costs (Zhang et al. 2010; McKechnie et al. 2011). This resource, including both low-quality roundwood and residue, constitutes approximately 80% of total biomass supply estimates for the province (Zhang et al. 2010; Mabee et al. 2011b; McKechnie et al. 2011). Canadian researchers are also beginning to consider forest biomass from natural disturbances (e.g. Kumar 2009; Hosegood et al. 2011), which have significant biophysical potential given the large swaths of managed forest land that become affected by natural disturbances annually and the recent mountain pine beetle (*Dendroctonus ponderosus*) outbreak in British Columbia and Alberta.

However, there are fundamental economic barriers to successfully procuring forest biomass from unused managed lands and natural disturbances for purposes of bioenergy production. A large fraction of the total cost of forest operations, including overhead, fixed, and variable costs, must be borne by the low-value energy wood because the resource lacks the quality required by value-added manufacturers and/or because no value-added markets for the resource exist within economical transport distance. Overhead and variable costs also tend to be higher than normal because road networks are either not in place or require maintenance work after years of not being used. If these high costs become manageable under continued bioenergy market development or direct subsidization, the issue of ensuring that the supplies can be made available over the lifetime of the facility must be addressed. In unused managed stands, a long term supply of roundwood and residue can be guaranteed contractually with potential long-term opportunity costs as the quality of future rotations improves under silviculture. Natural disturbances, however, cannot be predicted with sufficient accuracy because of the inter-annual and inter-decadal variability in their extent, intensity, and location.
2.3.3 Forest biomass from existing forest supply chains

Although it is conceivable that biomass from unused managed stands and natural disturbances could be mobilized with subsidization and drastic increases in market prices for bioenergy, near-term recovery of energy wood will continue to be restricted to low cost biomass originating from managed forest lands that are used by the existing solid wood and fiber industries. Specific energy wood types include unused mill residue, urban wood waste, unused low-quality roundwood, and harvest residue that can be made available from conventional supply chain activities like solid wood and fiber product manufacturing and harvesting (Table 2.2). This material goes unused by the industry because of market factors and/or quality standards and can be made available at low cost by using existing supply chain infrastructure, machinery, and labour. Overhead costs like stumpage, planning, inventory, supervision, land rent, office building rent and maintenance, road construction and maintenance, and other miscellaneous costs are already part of the normal operating expenses of the contractors, companies, and/or government agencies involved. Note that thinning residue can also be considered as a by-product of conventional forest supply chains and management regimes but is not dealt with here.

Table 2.2: Types and sources of forest biomass available for bioenergy production arising from existing forest supply chains, ranked from least expensive to most expensive.

<table>
<thead>
<tr>
<th>Type</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mill residue: black liquor, bark</td>
<td>Pulpmills supplied with roundwood and/or chips from commercial harvesting</td>
</tr>
<tr>
<td>Mill residue: sawdust, shavings, bark</td>
<td>Sawmills supplied with roundwood from commercial harvesting</td>
</tr>
<tr>
<td>Urban wood waste</td>
<td>Urban waste management yards and landfills</td>
</tr>
<tr>
<td>Unused low-quality roundwood</td>
<td>Commercial harvesting</td>
</tr>
<tr>
<td>Harvest residue</td>
<td>Commercial harvesting</td>
</tr>
<tr>
<td>Thinning residue</td>
<td>Thinning operations</td>
</tr>
</tbody>
</table>
There are important differences in the biophysical and technical availability of unused roundwood, mill residue, and harvest residue procured from existing forest supply chains that originate from commercial harvesting operations on managed forest land. Roundwood, which is produced from stems and large branches, has a much higher biophysical and technical availability compared to harvest residue because it represents the majority of the aboveground mass of individual trees (Zavitkovski et al. 1981; Alemdag 1984) and is more easily handled. Harvest residue, such as branches and stem tops, constitutes the minority of the aboveground biomass of individual trees and is associated with handling losses because of its small, irregular form. As a result, harvest residue only represents a maximum of $\approx 25\%$ of total recoverable biomass, or $\approx 40\%$ of total roundwood production, when recovered during commercial forest operations (Cormier and Ryans 2006; Smith et al. 2009). The rate at which mill residue is produced is also lower than that of its solid wood co-product: in sawmills, approximately 60% of the roundwood that enters the mill ends up as final solid wood products, with the remaining 40% of roundwood ending up as mill residue (Ericsson et al. 2004) (Figure 2.3).
Figure 2.3: Chart depicting aboveground mass of an individual tree and the fraction of the available mass (on average) that is recovered during a commercial harvesting operation and used to produce roundwood, harvest residue (for three silvicultural systems), conventional wood products, and mill residue (adapted from Smith et al. 2009).
2.3.4 The advantages of harvest residue

Estimates of unused low-quality roundwood produced as a by-product of commercial forest operations for solid wood products are particularly high in recent years because of the general decline in forest sector activity. Levin et al. (2011) estimated that between 504,000 and 1,008,000 dry tonnes of unused low-quality roundwood (normally used in pulp or firewood production) is available for bioenergy production in eastern Ontario as a result of pulp and paper mill closures. However, the actual amount of unused roundwood available over the lifetime of a bioenergy conversion facility or pellet mill will depend on uncertain market constraints, including whether value-added manufacturing facilities are re-opened or established in the near future in the vicinity of the roundwood supply that is currently unused. Accurate prediction of low-quality roundwood availability is further confounded by variation in roundwood quality among stands as a result of differential history, infection, mortality, and aging. In uneven-aged forests, for example, low-quality roundwood production ranges from 30% to 70% of total roundwood production (Levin et al. 2011; Hamilton 2012). Mill residue is more readily predicted as a fraction of roundwood milling but also suffers from local market effects and is generally regarded as being fully-utilized in most regions (Bain et al. 2003; Levin et al. 2011). While biomass supply from these sources will be predictable in some regions with contract agreements over the lifetime of the facility, availability is dependent on local market and biophysical factors, confounding accurate prediction at regional or national scales (Stasko et al. 2011).

Although limited in biophysical availability compared to roundwood, harvest residue is available at relatively low cost and is predictable in supply, inferable from conventional forest inventory (Hauglin et al. 2012) and roundwood production (Cormier and Ryans 2006). The high predictability of harvest residue is related to the species-specific central tendency of tree growth form and the fact that alternative markets are generally absent in all regions. Benefits of using harvest residue extend to other forest sector incumbents as well. In most cases, focusing on the utilization of harvest residue can strengthen the value-added strategy to forest policy and management, avoiding competition for roundwood and improving the economics of commercial roundwood harvesting (Puttock 1995) and various silvicultural activities designed to improve the quality of the resource for value-added manufacturing.
(Smith et al. 1985; Hudson 1995; Gullberg and Johansson 2006; Munsell and Germain 2007; Abbas et al. 2011). Harvest residue has therefore been understood to represent a universal energy wood supply source for bioenergy production since the 1970s.

2.4 Techno-economic constraints of harvest residue recovery

2.4.1 Techno-economic limits of conventional forest supply chains

Given the relative weakness of bioenergy markets, the forest industry has been challenged in bringing harvest residue to market at a sufficiently low cost: if the material cannot be supplied to market at a cost per unit that remains below revenue per unit, supply fails and bioenergy production fails. This issue of cost is obviously central to roundwood supply chains as well, but is particularly important for harvest residue due to the lower recoverable volume per unit area and lower market value. The effect of cost on residue supply has been illustrated at coarse scales through the use of cost-supply curves (Bain et al. 2003; Lundmark 2006; Kumarappan et al. 2009; de Wit and Faaij 2010). Kumarappan et al. (2009) estimated that the percentage of available biomass in Canada and the USA that could be brought to market at profit in 2009 energy market conditions was only 25% and 66%, respectively. Again, although a useful exercise, the coarse scales involved fail to resolve the specific techno-economic constraints of individual supply chains that will further limit the fraction of available harvest residue that can be brought to market cost-effectively.

The delivered cost of forest biomass (roundwood and residue) is a function of individual supply chain components (e.g. machinery and labour) and the interactions among these components, the environment, and the material being handled, processed, and ultimately delivered to market in acceptable form. The term “techno-economics” is often used by engineers to describe this interdependency of biophysical, technical, and economic factors. The techno-economics of forest supply chains (not including conversion facility parameters) can be systematically understood by dividing the system into three main interdependent components that determine final recovery and cost: 1) the biophysical limits of the resource, i.e. the volume/mass of material per unit area, 2) the fixed costs and technical ability of the employed machinery to handle, process, and deliver the material to market, and 3) the rate at which the various machines handle, process, and deliver the material to market, termed
operational productivity or efficiency (Ralevic et al. 2010). Biophysical limits of the resource and the fixed costs and technical limits of the employed machinery combine with contingencies of terrain, weather, and the competence, skill, and morale of managers and operators to influence operational productivity, variable costs, and final delivered cost and quality (Cormier and Ryans 2006; Ryans 2009; Ralevic et al. 2010). Overhead costs such as road construction and maintenance, stumpage, and rent also contribute to final costs but can be regarded as a separate cost domain.

2.4.2 The biophysical limits of the forest resource

The most important factor influencing the techno-economics of a supply chain is physical or biophysical, that is, the volume/mass of material available per unit area. The denser the material in space, the less time and cost incurred collecting and consolidating the material for delivery. Forestry is unique among resource extraction sectors in this regard, a particularly important realization for bioenergy proponents interested in replacing fossil and mineral fuels with biomass. Fossil and mineral fuels exist in homogenous form in relatively dense, unvarying deposits in the earth’s crust. Coal densities in coal beds in the Netherlands, for example, are between 1,000,000-11,000,000 tonnes per square kilometer (100 hectares), to depths up to 1,500 m (de Jong 2004). Forest biomass, on the other hand, is heterogeneous in form, has a lower energy density per unit mass, is distributed loosely over the earth’s surface, and varies in time. Forest biomass density (roundwood and residue) per square kilometer is roughly 200-2,000 tonnes for mature stands in temperate forests (Lim and Treitz 2004) and 1,000-5,000 tonnes for mature stands in tropical forests (Tajchman et al. 1996; Bryan et al. 2010), equivalent to less than 0.005% of the areal density of coal. Furthermore, only a small fraction of this available standing biomass can be recovered to bioenergy markets because of environmental, market, and techno-economic constraints.

The low biophysical availability of the forest biomass resource imposes limits on the techno-economics of forest supply chains. Relative to other resource extraction industries, the loose and uneven distribution of the forest resource leads to a relatively low density of recoverable biomass per operating area (“harvest block” or “cutblock”) and a low density of operating areas over the managed landscape. Transportation costs are particularly high because the volumes required to leverage the economies of scale afforded through railway or marine
shipping cannot be consolidated at the location of extraction (Forrester et al. 2006). Instead, roundwood or comminuted biomass must be trucked from disparate landings and harvest blocks to a mill or terminal yard. As a result, the upstream portion of the supply chain (forest operations and transportation) is particularly sensitive to cost, representing 33% to over 60% of total production costs, regardless of product type (Pulkki 1991; Boralex 2003; Spelter and Toth 2009; Thek and Obernberger 2009; He and Zhang 2011). Cost minimization in the upstream portion of the supply chain has therefore been a central concern of profit maximizing producers (industry), governments, forest engineers, and other stakeholders interested in establishing and sustaining forest supply chains.

2.4.3 The biophysical and techno-economic limits of harvest residue

In providing forest biomass to solid wood and fiber product manufacturers, forest supply chains have traditionally been configured to handle and process roundwood only, or in the case of some pulp and paper operations, chipped roundwood. The relatively large size and symmetry of roundwood provides techno-economic benefits for procurement of an otherwise loosely distributed resource, such as improved handling, improved machine productivity, and increased bulk density (and energy density) during transportation. Interest in recovering smaller diameter and/or irregularly shaped material (e.g. harvest residue) for bioenergy production has presented techno-economic challenges to this existing configuration. Compared to roundwood, harvest residue like unmerchantable stem tops and branches are distributed more loosely in space, and are smaller in size, greater in piece number, and more asymmetric in dimension, making cost-effective handling difficult after being sectioned from the tree.

Forest contractors interested in recovering harvest residue for bioenergy markets during conventional roundwood operations are further challenged by the low market prices for energy wood in most regions. Maintaining delivered costs below the market price generally depends on maximizing recovery of residue per unit area harvested, increasing the bulk density of the material before transportation, minimizing transportation distance, and minimizing the number of actions taken on the material by integrating residue handling, processing, and transport with pre-existing supply chain infrastructure and processes (Ryans 2009). Most importantly, because residue is worth less than roundwood and is produced in
smaller quantities per unit area harvested, residue recovery cannot reduce the production of merchantable roundwood, as this will reduce profit (Ryans 2009; Benjamin et al. 2010). This is a significant barrier to residue procurement, especially given the increasingly challenging economics of forest harvesting as fuel costs rise and mills close (Stuart et al. 2008; Drolet and LeBel 2010). In Finland and Sweden, where energy wood markets are of sufficient strength, residue is usually recovered after the initial roundwood operation, avoiding potential interference with roundwood production if residue piling during the preceding roundwood operation is efficient (Peltola et al. 2011).

2.4.4 Techno-economic progress in harvest residue recovery

Successful cost-effective integration of harvest residue recovery with commercial forest operations has mainly been limited to the forest sectors of Sweden and Finland where local and regional bioenergy markets have developed under favorable energy policy and pre-existing district heating infrastructure (Lind 1979; Pingoud et al. 1999; Hillring et al. 2002; Ericsson et al. 2004; Thornley and Cooper 2008; Karha 2011). There remain few examples in Canada and the USA (Desrochers pers. comm.). Early interest in forest biomass extraction for bioenergy attracted the attention of mechanical engineers, who designed and occasionally manufactured and tested residue collection prototypes under the premise that such mechanizations would produce greater volumetric returns at acceptable cost (Christopherson 1983; Sicard-Lussier 1984). However, aside from the bundler, which has been modified from the agricultural sector, none of these prototypes have been commercialized, with most forestry professionals noting that experience and learning through repeated exposure appear to have caused the greatest improvement in the techno-economics of residue recovery. For instance, Junginger et al. (2005) documented a steady decrease in production costs in Sweden through the 1990s and attributed this to the phenomenon of the “experience curve”, whereby supply chains and processes become optimized through repeated exposure (learning) of managers and labourers to new practices. Part of this process has included slight modification of existing technologies, including modified felling heads and grapples capable of handling and processing smaller-diameter material (Gingras 1995) and chippers with optimized components (Horng 1986; Gu and Shen 2002; Jensen et al. 2004; Abdallah et al. 2011; Hellstrom et al. 2011; Kovac et al. 2011).
The specific approach to recovering harvest residue varies depending on the pre-existing management regime and forest supply chain. Silvicultural systems and machinery capable of accommodating full-tree harvesting provide the lowest cost means of producing harvest residue because the entire tree is extracted to roadside where residue becomes concentrated as a by-product of product separation. If the harvest residue is instead separated from the roundwood before being extracted from the cutover (termed “cut-to-length” or “tree-length” harvesting), additional labour and/or capital must be employed in recovering the residue to roadside. For instance, conventional delimming and topping parameters can be modified to increase utilization of the unmerchantable distal portions of felled trees (Cormier and Tremblay 2010; Desrochers 2011; Meek 2011; Plamondon 2011), machinery used for roundwood recovery can be employed for residue recovery when free time is available (Volpe and Desrochers 2011), and/or machinery can be used to recover residue after the initial operation (Ryans and Desrochers 2006; Karha et al. 2011; Spinelli et al. 2012). Additional volumes of energy wood can also be procured opportunistically in the form of stumps and root systems (Eriksson and Gustavsson 2008) and incidental trees not normally recovered during commercial operations, depending on the situation. For example, in mechanized partial harvest operations, the increased damage to residual trees (Pinto and Smith 2007) offers the opportunity to improve operational productivity by recovering damaged and low-quality incidentals not included in silvicultural prescriptions (Meek and Lussier 2008) while providing potential silvicultural benefits in terms of reduced downed woody debris, light transmittance, and growing stock improvements for some species assemblages (Cormier and Tremblay 2010).

Comminution machinery (chippers or grinders) is used in most cases before transportation – either at roadside or, occasionally, in the cutover – to break up the residue into smaller, more homogenous pieces, thereby increasing bulk density, maximizing the amount of material transported per trip, and subsequently maximizing the cost-effective transport distance to ≈100 km. Containerized trucks referred to as “chip vans” and/or containerized forwarders capable of holding and transporting comminuted material are used in these situations. Both comminution and container technologies have been used by the pulp and paper industry since the 1960s (Powell 1982). If transport distances are kept to a minimum (no greater than ≈30 km), loose residue can be transported with logging trucks and comminuted with higher-
efficiency stationary comminution equipment at mill or terminal yards (Asikainen 1998; Spinelli et al 2007; Rauch and Gronalt 2010). This approach benefits from reduced capital requirements, allowing contractors to bring material to market cost-effectively when terminal chippers (e.g. at a mill) and related supply chain infrastructure are available locally.

The cost reductions that have been achieved since the 1990s have served to improve the profitability of residue recovery operations and the total amount of biomass that has been made available for bioenergy production. In Sweden, for instance, the proportion of biomass in the national district heating fuel mix increased from ≈33% in 2003 (Ericsson et al. 2004) to ≈66% in 2010 (Borjesson and Ahlgren 2010). Forest residue (i.e. harvest and thinning residue) likely represents an increasing fraction of this total. In Finland, the use of forest residue in heating and electrical applications quadrupled between 2000 and 2006, from 1.8 TWh to 7.0 TWh (Karha 2011). Although forest residue utilization has remained negligible in most other regions, including more successful bioenergy producing nations like Austria (Kanzian et al. 2009), establishment of new bioenergy capacity in the OECD will require continued mobilization of forest residue as cheap mill and urban wood residue supplies are depleted. The cost-reduction process (experience curve) and subsequent increases in forest residue supply can be expected to continue as bioenergy markets develop, with supply reaching a maximum once all sustainably and techno-economically available residue supplies are recovered to market annually.

2.4.5 Reconciling limitations of harvest residue with large-scale bioenergy

As reviewed above, once mill residue and urban wood waste surpluses have been fully utilized (which is already the case in most regions), the lack of energy crops and constraints of market and value-added principles on the use of roundwood for bioenergy will limit near term forest bioenergy growth in most regions to harvest residue (and thinning residue). Although considerable improvements in the techno-economics of harvest residue recovery have been made since the 1970s, and can be expected to continue, the negligible contribution that harvest residue has made to bioenergy growth over the last 40 years is indicative of an underlying biophysical scarcity. To illustrate this, assume a per hectare residue recovery of 10 dry tonnes, which is optimistic given the various techno-economic and environmental constraints that are likely to be encountered at operational scales. Forest Management Units
in the Great Lakes – St. Lawrence forest region of Ontario, which have an average operating area of 1,500 hectares, would produce about 15,000 dry tonnes annually under this recovery assumption. This amount of material would be unable to support a bio-electricity plant greater than 3 MWe (Table 2.3).

Table 2.3: Relationship between plant type and scale, annual biomass demand, and the land area required to support annual biomass demand with harvest residue (@ 10 dry tonnes per ha). Note that average harvest area for typical Forest Management Unit in Ontario is 1,500 hectares.

<table>
<thead>
<tr>
<th>Plant type</th>
<th>Plant scale</th>
<th>Annual biomass demand (dry tonnes)</th>
<th>Citation</th>
<th>Hectares required to meet annual harvest residue demand (@ 10 dry tonnes per hectare)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Institutional heat 100 kWth</td>
<td>60</td>
<td>IEA 2007</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Institutional heat 800 kWth</td>
<td>975</td>
<td>Desrochers 2011</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>District heat 1 MWth</td>
<td>1,200</td>
<td>IEA 2007</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Small cogeneration 500 kW/ 1 MWth</td>
<td>3,500</td>
<td>IEA 2007</td>
<td>350</td>
<td></td>
</tr>
<tr>
<td>Small cogeneration 2 MWe</td>
<td>10,000</td>
<td>IEA 2007 + Wiltsee 2000</td>
<td>1,000</td>
<td></td>
</tr>
<tr>
<td>Medium cogeneration 5 MWe</td>
<td>30,000</td>
<td>IEA 2007</td>
<td>3,000</td>
<td></td>
</tr>
<tr>
<td>Bio-electricity (co-firing) 200 MW @ 5% co-firing rate</td>
<td>90,000</td>
<td>MacDonald 2011a</td>
<td>9,000</td>
<td></td>
</tr>
<tr>
<td>Bio-electricity 10 MWe</td>
<td>125,000</td>
<td>Wiltsee 2000</td>
<td>12,500</td>
<td></td>
</tr>
<tr>
<td>Bio-electricity 20 MWe</td>
<td>140,000</td>
<td>Liddell 2011</td>
<td>14,000</td>
<td></td>
</tr>
<tr>
<td>Bio-electricity 25 MWe</td>
<td>308,000</td>
<td>Wiltsee 2000</td>
<td>30,800</td>
<td></td>
</tr>
<tr>
<td>Bio-electricity 30 MWe</td>
<td>251,000</td>
<td>Wiltsee 2000</td>
<td>25,100</td>
<td></td>
</tr>
<tr>
<td>Bio-electricity 40 MWe</td>
<td>376,000</td>
<td>Wiltsee 2000</td>
<td>37,600</td>
<td></td>
</tr>
<tr>
<td>Bio-electricity 45 MWe</td>
<td>561,000</td>
<td>Wiltsee 2000</td>
<td>56,100</td>
<td></td>
</tr>
<tr>
<td>Bio-electricity 49.9 MWe</td>
<td>846,000</td>
<td>Wiltsee 2000</td>
<td>84,600</td>
<td></td>
</tr>
<tr>
<td>Bio-electricity 60 MWe</td>
<td>768,000</td>
<td>Wiltsee 2000</td>
<td>76,800</td>
<td></td>
</tr>
<tr>
<td>Liquid bio-fuel -</td>
<td>1,100,000</td>
<td>MacDonald 2011a</td>
<td>110,000</td>
<td></td>
</tr>
</tbody>
</table>
The current policy emphasis on large-scale bioenergy production clearly does not match with the biophysical and techno-economic constraints of harvest residue. Instead, the high biomass demand of bio-electricity and liquid bio-fuel facilities requires that supplies are sourced in multiple forms from multiple locations, complicating logistics (Allen et al. 1998; Kumar et al. 2003; Van Belle et al. 2003; Rentizelas et al. 2009; Richard 2010). Harvest residue constitutes a minor supply source for such facilities, the majority of the supply being sourced from wastes, unused and/or unharvested roundwood, natural disturbances, and energy crops. The low conversion efficiency and non-asymptotic production economics of bio-electricity and liquid bio-fuel plants also increase the biomass procurement radius within which annual biomass demand must be satisfied, exceeding the benchmark of \( \approx 100 \) km beyond which transportation of loose and comminuted residue is cost-effective. This, in turn, requires artificial market stimulation (e.g. subsidization, carbon taxation) and installation of energy densification terminals within the biomass procurement radius, where loose and/or comminuted biomass can be consolidated and have its energy density improved via pelletization or liquification before conveyance to market (Richard 2010). Although pellet and chip transport are both weight-limited, pelletization tends to reduce transportation costs relative to wood chips because moisture content is lower and dry mass and energy content are subsequently higher. However, overall costs inevitably increase when densification or liquification occur. For instance, when harvest residue and/or roundwood is used, the final delivered cost of wood pellets increases to $150-$250 because of the relatively high cost of pelletization processes (KPMG 2008; Thek and Obernbeger 2009). For transport distances less than \( \approx 100 \) km, this is 2 to 4 times the delivered cost of wood chips produced from harvest residue and roundwood, which averages between $50 and $80 per dry tonne (Reynolds et al. 2008; Ralevic et al. 2010; Cormier 2011; Desrochers 2011).

The increased supply chain complexity and costs entailed in the pursuit of medium-scale and large-scale pathways ultimately reduce certainty that biomass demand will be met throughout the lifetime of the facility, increasing investment risk. There are a host of logistical concerns and capital costs that can serve to eliminate the economic attractiveness of medium-scale and large-scale bioenergy projects. Densification equipment must be purchased, terminal yards and storage facilities constructed, and large truck fleets scheduled and managed. As an example, consider that a bio-fuel plant on the lower end of the projected range of profitable
bio-fuel plant scales (200 to 1,000 megaliters) would require the biomass equivalent to a 300 MW power plant, requiring 150–160 tonnes of biomass per day (Richard 2010; Stasko et al. 2011). Supplying this amount of biomass to the plant would require approximately 50 truckloads each day (Richard 2010). The large geographic area required to support the increased biomass supply also requires a significant increase in the number of suppliers. Co-firing projects in the USA require supply chain managers to expand procurement from 2 to 3 coal suppliers supplying 16 million tonnes of coal to include 120 biomass suppliers supplying only 90,000 tonnes of biomass (Johnson 2012). The high risk associated with such a complicated supply chain is often reason for plant owners to avoid co-firing, instead incurring the cost of installing emissions control systems (Johnson 2012).

Even in ideal conditions, where bio-electricity facilities have had access to low cost by-products of seemingly sufficient volume, there are a number of records of bio-electricity production failing as a result of supply chain disruptions. These disruptions have occurred as a result of such factors as reduced forest industry activity and reduced policy support, requiring constant ad hoc changes in fuel procurement and energy output (Wiltsee 2000; Bain et al. 2003; Boralex 2003). Boralex, a Quebec-based owner and operator of electricity generation facilities in northeastern NA and Europe, developed urban wood residue supply chains for some of its bio-electricity facilities in eastern NA in response to mill residue supply shortages (Boralex 2003). A bio-electricity plant in Washington was forced to use waste oil, asphalt shingles, petroleum coke, and other miscellaneous wastes due to forest biomass scarcities (Wiltsee 2000). In California, where the bio-electricity industry experienced rapid development in the 1980s under unprecedented policy incentives, demand for biomass quickly exceeded the available supply, leading to a “biomass fuels crisis” where biomass costs increased beyond acceptable levels (Bain et al. 2003). A further disruption of the Californian bio-electricity sector occurred when incentives for bio-electricity were removed in the early 1990s, leading to a decline in bio-electricity capacity (Bain et al. 2003; Nicholls et al. 2008). Between 1980 and 2000, 51 bio-electricity plants were established and 29 of those plants shut-down, a capacity loss of ≈250 MW (Nicholls et al. 2008). When considering the limitations of waste-based biomass sources and harvest residue, and the market uncertainty of roundwood, the economic sustainability of medium-scale and large-scale applications is highly uncertain without re-allocation of roundwood, the establishment
of large expanses of energy crops, and significant increases in policy support (e.g. subsidization, carbon taxation).
Chapter 3 – Recovering Small-Diameter Roundwood for Bioenergy Production Using a Modified Tree-Length Method in Semi-Mechanized Partial Harvest Operations

3.1 Introduction

3.1.1 Harvest residue recovery in the OECD

Harvest residue – including unmerchantable stem sections and branches discarded during conventional forest operations – has been recognized as a potential source of energy wood since interest in large-scale bioenergy production first emerged in the 1970s. This material can be recovered at relatively low cost when integrated with conventional forest operations because many of the overhead costs (e.g. road building, planning, and inventory) are already borne by the merchantable roundwood products. When harvest residue is recovered concurrently with roundwood, the additional recovery can also serve to increase machine utilization, leading to overall reductions in annual operating costs (Puttock 1995; Volpe and Desrochers 2011; Saunders et al. 2012). In combination with the additional revenues obtained by selling the residue on energy markets, integration can improve the economics of forest operations, enabling contractors to profitably harvest marginal stands and deliver roundwood to distant markets by re-distributing costs over a larger volume (Puttock 1995). Other potential benefits of using harvest residue for bioenergy include silvicultural benefits (Smith et al. 1985; Hudson 1995; Gullberg and Johansson 2006; Munsell and Germain 2007; Abbas et al. 2011) and avoidance of competition for roundwood, a concern in regions with existing pulp, paper, panel, and/or composite production capacity (Lundmark 2006; Galik et al. 2009; Plieninger et al. 2009; Spelter and Toth 2009; Thek and Oberberger 2009; Abt et al. 2010; Conrad et al. 2010; Schwarzbauer and Stern 2010; Tromborg and Solberg 2010; Moiseyev et al. 2011; UNECE/FAO 2011).

To ensure that the overall profit of the forest operation is maintained, residue recovery should not reduce the rate of roundwood production (Baker et al. 2010). Yet harvest residue is widely dispersed and has a low market value compared to roundwood, so the profitability of
Residue supply chains depend critically on maximizing recovery and integrating with conventional supply chain machinery and processes. Maximizing recovery is particularly important when supplying large-scale facilities with high demand, including combined heat and power (CHP) facilities at pulp and paper mills, stand-alone bio-electricity or CHP facilities, and liquid bio-fuel plants. Therefore, in North America where policy has tended to favor large-scale applications, and where intensive mechanized forestry predominates, residue recovery has been researched most extensively in clearcut operations (Cormier and Ryans 2006; Volpe and Desrochers 2011), intensive partial harvest operations (Chisholm and van Raalte 1980; Christopherson 1983; Briedis et al. 2011), and partial harvest operations in marginal stands containing a large amount of unused roundwood (Cameron 1981). At roadside, the recovered material, which includes fine branches and small-diameter stems, is typically comminuted into smaller particles after the product separation phase to increase bulk density for transportation (Desrochers et al. 1994).

### 3.1.2 Harvest residue recovery in mechanized partial harvest operations

Less intensive partial harvest silvicultural systems (i.e. single-tree selection and shelterwood) typical of the managed tolerant hardwood forests of northeastern North America have received less research attention than mechanized clear-cuts and have made negligible contributions to bioenergy production beyond the residential firewood sector. The main challenges to recovering residue during these operations include low recovery per unit area harvested, small operating areas, and low mechanization. Single-tree selection and shelterwood operations typically remove only 20-34% and 40-60%, respectively, of standing live trees at harvest, with the goal of optimizing the natural regeneration and growth of shade-tolerant and mid-tolerant tree species that are used in the production of high-value wood products (OMNR 1998). Commercial forest operations in these systems predominantly use the tree-length harvesting method, whereby felled trees are delimbed and topped by a chainsaw operator such that only the merchantable portion of the tree is recovered. The diameter at which tree branches and stems are delimbed and topped (“top diameter”) depends on tree size and form but is typically 18 cm for tolerant hardwoods (OMNR 2007), reflecting both the decurrent branching pattern of hardwood species and the average merchantability standards of forest mills and firewood merchants. The delimbed and topped trees (referred to...
as “tree-lengths”) are extracted with cable or grapple skidders to roadside and subsequently processed into merchantable roundwood according to prevailing markets and management culture (Hamilton 2012). Unmerchantable stem sections and branches that do not meet diameter limits or quality standards are discarded in the cutover.

The few studies that have investigated residue recovery from partial harvest operations in tolerant hardwood stands have focused on approaches that aim to recover the entire unmerchantable distal portions of trees (branches and stem tops), including second pass operations (Cameron 1981; Christopherson 1983) and mechanized full-tree harvesting with roadside comminution (Cormier and Tremblay 2010). Although recovering the discarded unmerchantable distal portions of trees after merchantable roundwood operations is carried out by some contractors for residential firewood markets (OMNR 2008), this is an expensive means of procuring biomass over a large area because additional labour and fuel (and in some cases, machinery) must be employed in bringing the material to roadside, counteracting any improvements in machine utilization. Integrating the full-tree method in a single pass is more cost-effective but the increased width of extracted trees is likely to lead to unacceptable levels of residual damage in some stands. It is generally agreed that successful integration of full-tree harvesting within less intensive partial harvest systems requires a modified skid trail layout that concentrates harvesting along corridors, or an increase in the fraction of total basal area removed (Christopherson 1983; Cormier 2011).

An alternative, low cost approach to recovering residue in a single pass is to modify the delimming and topping phase of tree-length operations in a manner that increases the volume of each delimbed and topped tree without leading to increased residual stem damage during extraction. Chainsaw operators can modify their delimming and topping decisions such that additional unmerchantable branches and distal sections of branches and stems, including sweeping and fine branches, are retained on the extracted tree-length without increasing damage during extraction. Preliminary trials in mechanized shelterwood operations (which employ feller-bunchers and grapple skidders) have demonstrated that restricting delimming to lateral branches that can cause damage during extraction and avoiding topping results in a level of residue recovery per hectare that is similar to clear-cut operations when small-diameter incidental trees are also recovered (Cormier and Tremblay 2010). The additional
material, which includes difficult-to-handle small sweeping branches, fine branches, and small diameter stems, must be comminuted at roadside for cost-effective transportation, unless transport distances are short (within ≈20 km).

3.1.3 Harvest residue recovery in semi-mechanized partial harvest operations

Semi-mechanized single-tree selection operations (which typically employ chainsaws and cable skidders) make important contributions to wood supply in southeastern Canada and parts of the northeastern USA (Leak et al. 1969; McKechnie et al. 2011). Compared to mechanized shelterwood operations, integration of a modified tree-length harvesting method is associated with additional technical and economic barriers. Operations occur within smaller harvest blocks, between 60% and 80% of standing basal area is retained, product separation and sorting phases must carefully manage roundwood within small processing areas (landings), and extraction phase machinery (cable skidders) is not designed to cost-effectively handle small pieces (<10 cm) (Silversides and Sundberg 1988). Furthermore, the amount of residue recovered to each landing is likely to be insufficient for cost-effective roadside comminution, unless combined with unused roundwood normally sold as pulp or firewood (Cormier 2011). These technical and economic constraints have led researchers to conclude that residue recovery from semi-mechanized single-tree selection operations is not feasible, and therefore unlikely to contribute to future forest biomass supply in Canada (Gingras and Favreau 1996; Zhang et al. 2010; McKechnie et al. 2011). For example, in a recent estimate of harvest residue supply from public lands in Ontario, McKechnie et al. (2011) assumed residue-to-roundwood recovery ratios of 40%, 20%, and 0% for clear-cut, shelterwood, and single-tree selection, respectively.

Recent trends in bioenergy markets, including interest in the development of both small- and large-scale bioenergy, and a growing pellet trade (Heinimo and Junginger 2009; Spelter and Toth 2009), warrant a more thorough assessment of residue recovery from semi-mechanized partial harvest operations. Residue could be recovered within the silvicultural and mechanical constraints of semi-mechanized partial harvest operations by implementing a modified tree-length method slightly different from what has been tested in mechanized shelterwood operations. Specifically, the diameter at which tree branches and stems are cut could be reduced such that additional recovery is limited to unmerchantable branches and stem tops of
a form and length that can be processed into small-diameter roundwood, avoiding the need for roadside comminution (Desrochers 2012). The additional material could be processed into small-diameter roundwood at landings with merchantable roundwood and transported with conventional logging trucks. The small-diameter roundwood could be consolidated at sawmills, terminal yards, or pellet plants and comminuted or densified with high-efficiency stationary equipment in larger areas with more space to maneuver (Asikainen 1998; Rauch and Gronalt 2010), potentially as part of a larger supply of unused low-quality roundwood in regions that have experienced recent pulp mill closures (Levin et al. 2011). Roundwood (including small-diameter roundwood) has a number of storage benefits compared to chips, including reduced dry matter loss (Pulkki 1991), reduced moisture uptake, improved handling, reduced infrastructure requirements (i.e. roundwood can be stored outdoors under tarps), and reduced contamination during subsequent material movement (Desrochers 2012).

Despite the promise of this approach, the potential supply of energy wood will be limited by both technical and economic constraints. The branching frequency of hardwood species increases with distance from the stem base, and therefore reducing top diameters beyond the conventional 18 cm standard will lead to an increase in the number of cuts made per tree. The additional time spent delimbing and topping will increase the energetic expenditure of the chainsaw operators, who are already subject to high biomechanical stresses during conventional forest operations (Hagen 1990; Hagen et al. 1998). Furthermore, at the stand level, the high variance in stand structure and terrain conditions typical of tolerant hardwood forests could complicate implementation at operational scales (Meek and Lussier 2008). For instance, when the density of marked trees is high or when extraction distances are short, reductions in the rate of felling and delimbing and topping could reduce the productivity of the extraction phase, thereby decreasing merchantable roundwood production and total profit of the operation (Baker et al. 2010). Successfully implementing a modified tree-length harvesting method without reducing merchantable roundwood production and profit will largely depend on local stand structure and terrain. For those operational situations where harvest residue recovery can be integrated without reducing merchantable roundwood production, there is a need to quantify the actual volume and costs of producing harvest residue.
In this chapter, I quantified recovery and costs of this modified tree-length harvesting method in semi-mechanized partial harvest operations with both motor-manual and mechanized felling. Recovery was estimated at both the tree- and stand-level, using a combination of inventory data and tree-level measurements taken during harvest trials conducted in tolerant hardwood stands in central Ontario, Canada. I also conducted a time-motion study of the chainsaw operators to quantify the extra delimbing and topping time required to implement a modified tree-length approach. Finally, I estimated the final cost of the processed energy wood at the point of energy production, after harvesting, processing into small-diameter roundwood, transport, and stationary comminution. Based on the results and observations during the trials, I discuss the operating and policy conditions in which energy wood procured using the modified tree-length harvesting method could be a viable means of increasing bioenergy capacity in the tolerant hardwood region.

3.2 Methods

3.2.1 Study area and operational context

The harvest trials were conducted at the Haliburton Forest and Wildlife Reserve (HFWR), a 25,000 ha privately-owned property located in central Ontario, Canada. The property is situated within the Great Lakes-St. Lawrence (GLSL) forest region (Rowe 1972), where the majority of the managed forest land base is publicly-owned. The predominant forest type within the GLSL forest region is the tolerant hardwood forest which is primarily composed of sugar maple (Acer saccharum), American beech (Fagus americana), yellow birch (Betula allegheniensis), and eastern hemlock (Tsuga canadensis). These shade-tolerant and mid-tolerant species are managed using partial harvest silvicultural systems, including single-tree selection, shelterwood, and group selection. At HFWR, the relative share of single-tree selection, shelterwood, and group selection over the total managed area of 25,000 ha is 70%, 20%, and 10%, respectively (Schleifenbaum pers. comm.). On public lands in the GLSL, single-tree selection and shelterwood both have a relative share of 35% over the total managed area, the remaining 30% being clear-cut in non-tolerant hardwood forest (Cormier 2012).
Forest operations are concentrated during the winter months when freezing temperatures reduce the potential for damage to substrate and residual trees. Trees are marked with paint prior to harvest to ensure forest contractors only remove trees selected in accordance with silvicultural prescriptions. Chainsaws are typically used to fell, delimb, and top trees, and the resulting tree-lengths are usually extracted using cable skidders. Motor-manual felling (with chainsaws) is replaced by mechanical felling (with feller-bunchers) in some stand conditions. In this case, delimming and topping of felled and piled trees still occurs by chainsaw in the stand, and tree-lengths are extracted either with cable skidders or grapple skidders. Tolerant hardwood tree species are delimbed and topped at diameters of 18 cm, which is also standard practice on public lands (OMNR 2007). Product separation occurs on landings, either motor-manually or with processing machinery. Processed logs are transported to destination with self-loading logging trucks. High-quality roundwood is delivered to the Haliburton Forest sawmill, veneer logs are sent off-site when markets are available, and the majority of low quality roundwood is supplied to local firewood producers, as no pulp market for roundwood exists in the area. Mill residue is sold on a variety of markets including pulp and paper, livestock bedding, and landscaping mulch. Small unmerchantable wood that remains following product separation at landings (“processing residue”) is collected for use locally as firewood.

3.2.2 Pre-harvest plot inventory

The harvest trials were conducted in two separate harvest blocks, one for motor-manual felling (2010) and one for mechanized felling (2011). The harvest blocks used in both trials were marked following a standard prescription for single-tree selection (OMNR 2004). Prior to the motor-manual felling trial (2010), the harvest block was inventoried to quantify stand structure and composition and to enable estimation of recovery at the stand level (per hectare). Ten one-hectare plots were established in previously-marked stands and randomly assigned to one of two treatments: conventional tree-length harvesting (five one-hectare plots), in which chainsaw operators delimbed and topped trees as they normally do, and modified tree-length harvesting (five one-hectare plots), in which chainsaw operators modified delimming and topping decisions to increase recovery (see below). At the center point of each of the ten one-hectare plots, a circular 0.25 ha plot was established and species
and diameter at breast height (DBH) were recorded for all marked and unmarked standing trees >10 cm. The mechanized felling trial (2011) used the same treatments but without inventoried plots. Both trials used the same tree-level measurement methods (see below).

3.2.3 Harvest trials

The motor-manual felling trial was conducted between February and March in 2010, and the mechanized felling trial was conducted between January and March in 2011. In both trials, the conventional treatment was implemented by asking forest contractors to delimb and top trees as they normally do. Minimum top diameters were set at the standard hardwood limit of 18 cm (OMNR 2007) and only material that could be processed into merchantable roundwood was recovered. In the modified treatment, chainsaw operators altered conventional delimming and topping practices to retain additional branch and top wood that they judged could be extracted without exceeding residual damage standards and that could be processed into log-lengths (small-diameter roundwood) transportable with conventional logging trucks. An 8 cm to 10 cm top diameter guideline was set. Lateral branches and the top portions of branches and coniferous stems that were judged to present a residual damage risk and/or to be of unsuitable form for processing into log lengths (roundwood) were cut and discarded before extraction.

3.2.4 Volume recovery estimation and statistical analysis

Operational monitoring trials are typically designed to estimate total volume and/or mass recovered for large contiguous harvesting areas (entire harvest blocks) by weighing loaded trucks and chip vans after product separation is complete (e.g. Reynolds et al. 2008; Cormier and Tremblay 2010; Desrochers 2011; Volpe 2012). The advantage of this approach is that it is highly efficient, and it can be very accurate as well, particularly in uniform harvest blocks. However, the disadvantage is that it requires large harvest blocks, designated landings, and access to truck scales. Furthermore, treatment effects may be confounded by inter-stand variation in structure (i.e. diameter distribution), especially in uneven-aged tolerant hardwood forests. I therefore took a tree-level approach to estimation of total volume and/or mass recovered by measuring the dimensions of recovered tree-lengths and applying a volume equation. This data was used to develop regression equations relating DBH to tree-
length volume. I used these equations in combination with diameter distributions from our ten one-hectare plots inventoried before the motor-manual felling trial of 2010 to estimate stand-level (per hectare) recovery.

The volume of each recovered tree-length (n = 895) was estimated by taking length and end diameter measurements of the main stem and any attached branches (from the base to the top end of the measured stem or branch) and applying a volume equation. I could not partition length and end diameter measurements into smaller segments because the extraction and processing phases of monitored operations were concurrent. A “conic-paraboloid” equation (Fraver et al. 2007), which describes a geometric form between a parabolic and conic frustum, was used to estimate volume from the tree-length measurements. This equation was selected because it is reported to have the best performance for long and/or irregular pieces compared to other volume formulae with two end-diameter inputs (Fraver et al. 2007). The volume of each tree-length was calculated by summing the volume estimates for its respective measured segments. All volume estimates were converted to dry mass (0% moisture content) using a generic m³ to dry mass (kg) conversion factor of 600 kg per m³, which is intermediate the basic density of sugar maple and beech reported by Jessome (1977) and Alemdag (1985).

Tree-length data was aggregated for both trials and treatments and used to develop regression models. Analyses of covariance were then performed with R (2008) to test the effect of tree-length harvesting method (modified treatment vs. conventional treatment) and felling method (motor-manual vs. mechanized) on tree-length volume recovery. To determine if the additional tree-length volume recovery in the modified treatment was statistically significant, analysis of covariance was performed with tree-length volume as the response variable, base diameter as a predictor variable controlling for tree size, and treatment as a dummy variable. A separate analysis of covariance was performed with felling method as a dummy variable to determine whether tree-length volume recovery significantly differed between the mechanized felling and motor-manual felling trials. This supplementary test was undertaken because it is conceivable that the piling of felled trees typical of mechanized felling with feller-bunchers may affect motor-manual deliming and subsequent tree-length volume recovery relative to motor-manual felling, where trees are not deliberately concentrated in
piles. Analysis of covariance was also performed on log-transformed data to gauge the degree to which heteroscedasticity affected results and conclusions derived from analysis of untransformed data.

I estimated recovery at the stand level by combining the diameter distributions of our inventoried ten one-hectare plots with our tree-length data collected over the two trials (n = 895). Base diameters of all tree-lengths were converted to DBH with base diameter-DBH equations developed from a subset of tree-lengths measured during the 2011 trials. Two tree-length volume regression equations (one for the modified treatment and one for the conventional treatment) predicting the recovered volume of each tree-length from tree size (DBH) were then developed based on our aggregated data. The two tree-length volume regression equations were applied to the diameter distribution of each one-hectare plot to arrive at two estimates of volume recovery for each of the 10 plots (per hectare): a conventional volume estimate and a modified volume estimate. For each plot, I calculated the expected increase in per hectare recovery by subtracting the conventional volume estimate from the modified volume estimate.

Since the additional volumes recovered from the modified tree-length harvesting method were expected to be comprised of branch material, I calculated a branch recovery fraction which expressed the number of branches as a fraction (or percentage) of the number of tree-lengths for each treatment and size class. During the 2010 trial, I also quantified product recovery for two modified treatment plots and four conventional treatment plots to determine the product category into which the additional branch material was processed. Three product categories were used: 1) high-quality roundwood (veneer/sawlogs), 2) low-quality roundwood (pulpwood/firewood/harvest residue), and 3) processing residue (small pieces of wood leftover following product separation). The conic-paraboloid equation (Fraver et al. 2007) was applied to these measurements to arrive at product volume estimates and to calculate the fraction of total product volume that each product category represented. I did not quantify the form of additional roundwood pieces recovered from the modified treatment.
3.2.5 Time-motion study of felling operations

I conducted time-motion studies of the motor-manual felling, delimbing, and topping phase during the 2010 trials to quantify felling productivity losses and additional delimbing and topping time resulting from modified tree-length harvesting. Time-motion data was collected in both treatments using FPInnovations’ TS1000 software installed on handheld computers. A total of 13.7 productive machine hours were monitored over three hectares in the modified treatment and 3.6 productive machine hours were monitored over 1 hectare in the conventional treatment. Time-motion data was collected for each of the productive functions that the chainsaw operator performed during working hours, including felling, walking and brushing, and delimbing and topping, as well as delays (operational and non-operational). The additional time per working hour that the chainsaw operator spent delimbing and topping was calculated by comparing the delimbing and topping time of both treatments. I was unable to control for operator effect (different crews worked in the modified and conventional treatments).

3.2.6 Supply chain productivity and delivered costs

To determine the delivered cost of residue in comminuted form ($/dry tonne), I first estimated machine productivity for each phase of the operation from felling to truck transport. Machine productivity is a standardized measure of the rate at which wood is processed by a machine performing productive functions, expressed as m$^3$ processed per productive machine hour (PMH). Calculation of machine productivity allows for estimation of the cost of processed wood at each operational phase when combined with an estimate of the cost per productive machine hour ($/PMH). The total delivered cost per m$^3$ can then be calculated by adding the cost per m$^3$ of each of the phases from felling through to truck transport. I used machine productivity figures and costing parameters available from FPInnovations’ machine productivity database (ProVue) and from personal communications with experienced forest engineers (Appendix 3.1 and 3.2). In estimating the cost per PMH ($/PMH) for each machine, I used the standard machine costing procedure for forest operations (Rickards and Savage 1983). For the terminal chipper, data on productivity and cost per PMH were provided by Desrochers (pers. comm.). For the logging truck costing model, the number of trips made per year was inferred from the total volume of merchantable
roundwood produced at Haliburton in 2010 (Schleifenbaum pers. comm.). The payloads of merchantable roundwood and small-diameter roundwood in logging trucks were assumed as 25 dt and 15 dt per truck, respectively (Desrochers 2011; Volpe 2012). The payload of wood chips in chip vans was assumed as 21.75 dt per van (Cormier pers. comm.).

Residue handling was concurrent with roundwood handling in the early phases of both monitored trials and therefore I needed to partition the costs of residue handling from roundwood handling. Residue handling was only considered to affect productivity and thus incur a cost during the deliming and topping phase and the slashing phase, and did not vary between the motor-manual and mechanized trials. No productivity losses or additional costs were expected for the felling and extraction phases because residue was not handled directly during these phases. To estimate the cost of the additional deliming and topping time spent by the chainsaw operator in the deliming and topping phase, I first multiplied the chainsaw operator cost per PMH ($44.51) by a fraction corresponding to the percent increase in deliming and topping time estimated from the time-motion study (10.8%). The resulting value ($4.81/PMH) was then divided by the productivity of residue production for the felling-delimbing-skidding phase (1.03 m$^3$/PMH), which was estimated by multiplying the productivity of roundwood production for this phase (10 m$^3$/PMH) by a fraction corresponding to the percent increase in tree-length volume calculated for the modified treatment (10.3%). The resulting cost per m$^3$ of residue ($4.67) was an estimate of the cost of bringing the residue to roadside before product separation and can be interpreted as the additional wage paid to the chainsaw operator for his additional working time. The productivity and cost per m$^3$ of handling, processing, and sorting residue during the product separation phase was made equivalent to the productivity and cost per m$^3$ of handling, processing, and sorting roundwood, estimated from previous FPInnovations studies (ProVue). Since residue was transported and comminuted independently of roundwood, all costs for these activities were allocated to the residue. Total residue costs were calculated for an array of transport distances for both logging truck transport and chip van transport to illustrate the effect of supply chain configuration and transportation distance on final delivered cost (Figure 1a and 1b, Appendix 3.3 and 3.4). Costs per m$^3$ ($/m^3$) were converted to costs per dry tonne ($/dry tonne) by dividing by the basic density of 0.6 dry tonnes/m$^3$ for hardwood (Jessone 1977; Alemdag 1985).
3.3 Results

3.3.1 Stand composition and tree marking

The inventoried harvest block was composed of 46% sugar maple (*Acer saccharum*), 32% American beech (*Fagus americana*), 7% yellow birch (*Betula allegheniensis*), 6% hemlock (*Tsuga canadensis*), and 2% ironwood (*Ostrya virginiana*), with the remaining 9% representing 16 other species, none of which exceeded 1% of total composition. Total basal area per hectare ranged from 20.9 m$^2$ to 35.1 m$^2$, with a mean marked basal area of 6.5 m$^2$ (SD ± 2.3 m$^2$). The percentage of total basal area that was marked in each of the 10 plots ranged from 13% to 36% of total standing basal area, with a mean of 23%. Stand basal area by size class before and after harvest is typical of single-tree selection systems (Figure 3.1).

![Figure 3.1: Mean basal area per hectare by size class, before and after harvest.](image)

3.3.2 Tree-level and stand-level harvest residue recovery

Over both trials, a total of 895 trees were felled, delimbed, and extracted, with sugar maple and American beech accounting for 87% of this total. The analysis of covariance procedure
found that tree-lengths delimbed and topped using the modified method had a significantly greater volume ($p = 7.4 \times 10^{-8}$) and a significantly smaller top diameter ($p = 2 \times 10^{-16}$) than trees delimbed and topped using the conventional method (Table 3.1, Figure 3.2). Felling method did not have a significant effect on tree-length volume recovery ($p = 0.09$). On average for both trials, the modified method increased recovery by 10.3%, or 0.06 m$^3$ (36 kg) per tree-length, and decreased top diameter by 5.4 cm. Percent recovery increased with tree size, from 0% for the smallest size class to 13% for the largest (Table 3.1, Figure 3.2, Appendix 3.5). Analysis of covariance of the log-transformed data confirmed that statistical significance and reported $R^2$ values for the untransformed data were not confounded by heteroscedasticity (Appendix 3.6).

Table 3.1: Comparison of recovery metrics for modified tree-length and conventional tree-length harvesting by size class (standard error is reported in brackets)

<table>
<thead>
<tr>
<th>Size class (DBH, cm)</th>
<th>Modified treatment</th>
<th>Conventional treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Mean tree-length volume incl. branches (m$^3$)</td>
</tr>
<tr>
<td>10-25.9</td>
<td>116</td>
<td>0.32 (±0.01)</td>
</tr>
<tr>
<td>26-37.9</td>
<td>209</td>
<td>0.61 (±0.01)</td>
</tr>
<tr>
<td>38-49.9</td>
<td>106</td>
<td>0.91 (±0.02)</td>
</tr>
<tr>
<td>50+</td>
<td>23</td>
<td>1.19 (±0.08)</td>
</tr>
<tr>
<td>Total</td>
<td>454</td>
<td>0.64 (±0.01)</td>
</tr>
</tbody>
</table>
Figure 3.2: Linear relationship between DBH and recovered tree-length volume for the modified treatment \(y = 0.0279x - 0.2861, n = 453, r^2 = 0.7117\) and the conventional treatment \(y = 0.0239x - 0.2084, n = 441, r^2 = 0.7051\).

For the inventoried stands, the additional material recoverable from modified tree-length harvesting in semi-mechanized partial harvest operations was estimated to average 3.2 m\(^3\) per hectare (1.9 dry tonnes), and to range from 2.1 m\(^3\) (1.3 dry tonnes) to 4.5 m\(^3\) (2.7 dry tonnes). The majority of this additional volume was in the form of branches normally discarded during conventional operations (see below). Mean total volume (roundwood and residue) recovered per hectare was 35.7 m\(^3\) (21.4 dry tonnes) (SD ±9.3) in the 2010 harvest block, and ranged from 23.7 m\(^3\) (14.2 dry tonnes) to 51.8 m\(^3\) (31.1 dry tonnes) per hectare.

### 3.3.3 Branch and product recovery

Trees recovered using the modified tree-length method had more branches than trees recovered using the conventional tree-length method (Table 3.2). The number of branches per tree-length also increased with increasing tree size (Table 3.2). Of the total 288.7 m\(^3\) (173.2 dry tonnes) recovered from the modified treatment, 8.0% (23.2 m\(^3\) (13.9 dry tonnes))
was comprised of branches (185 branches), compared to 2.9% (7.3 m$^3$ (4.4 dry tonnes)) of the total 255.8 m$^3$ (153.5 dry tonnes) recovered from the conventional treatment (50 branches). Branches were recovered intact, attached to parent tree: independently skidded large branches and small diameter stem sections in the modified treatment comprised less than 1% of extracted pieces.

Table 3.2: Branch recovery fractions (number of branches to number of tree-lengths) by size class and treatment.

<table>
<thead>
<tr>
<th>Size class (DBH)</th>
<th>Modified</th>
<th>Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-25.9 cm</td>
<td>0.14</td>
<td>0.02</td>
</tr>
<tr>
<td>26-37.9 cm</td>
<td>0.42</td>
<td>0.12</td>
</tr>
<tr>
<td>38-49.9 cm</td>
<td>0.63</td>
<td>0.19</td>
</tr>
<tr>
<td>50+ cm</td>
<td>0.61</td>
<td>0.20</td>
</tr>
<tr>
<td>Total</td>
<td>0.41</td>
<td>0.11</td>
</tr>
</tbody>
</table>

During the 2010 trial, roundwood (including small-diameter roundwood) and processing residue (small pieces of wood leftover following product separation) produced from the six one hectare plots monitored during the 2010 trials (two modified, four conventional) were measured. The percentage of low quality roundwood was higher in the modified treatment (55.9% vs. 39.8%) and the percentage of processing residue was lower in the modified treatment (3.0% vs. 5.6%), providing support for the observation that the majority of the additional branch material recovered using the modified tree-length method was processed into small-diameter roundwood.

3.3.4 Operational productivity

Delimbing and topping time in the modified treatment increased by 6.5 minutes per working hour on average relative to the conventional treatment. Expressed as a percentage of total productive time worked, 32.1% of the chainsaw operators’ total working time was spent delimbing and topping in the modified treatment, versus 21.3% in the conventional treatment (Figure 3.3). This increase in delimbing and topping time proportionally reduced additional time (including rest time) and was associated with a felling productivity decrease of -3.2 trees felled per productive machine hour (PMH). It was generally agreed by all research participants that efficiency and mobility of the cable skidders were not compromised by the average additional 0.06 m$^3$ (36 kg) per tree-length in the modified treatment. The tree-lengths
produced from modified delimming and topping were extracted to landing where the additional branch wood was processed into small-diameter roundwood and transported to a holding yard with conventional logging trucks. When implementing the modified treatment to produce small-diameter roundwood, chainsaw operators were observed to make cuts below branch nodes or below segments of branches that could not produce a 1.3 m roundwood piece length, as is standard practice in conventional roundwood operations that include roundwood transport (OMNR 2007; Van Deusen and Roesch 2011).

Figure 3.3: Proportion of total working time that the chainsaw operator spent conducting various activities associated with felling and delimming and topping by treatment. *"Additional time” includes rest time and delays.

3.3.5 Costs

The roadside cost of the residue after product separation was estimated as $7.97 per m$^3$ when allocating 10.8% of the total cost per PMH for chainsaw operation ($44.51) to the residue and allocating the full slashing cost per m$^3$ to the residue. The total cost of the residue after delivery to the yard 65 km away and comminution was estimated as $31.62 per m$^3$ ($52.70
per dry tonne). This represents the cost of the residue before energy conversion if the residue is converted to energy at the place of terminal comminution, e.g. a sawmill. If the terminally comminuted residue is instead transported to a conversion facility a further 65 km away with a chip van, the final delivered cost of residue increases to $45.57 per m$^3$ ($75.95$ per dry tonne) (Table 3.3). Transport costs represented the most significant cost center for both scenarios (Appendix 3.7). When residue is converted to energy at the place of terminal comminution after 65 km transport with logging trucks, transport costs represent 40% of the total procurement cost. When residue is transported an additional 65 km with chip vans after terminal comminution, the relative contribution of transport costs to total procurement cost increases to 58%.

Table 3.3: Costs of merchantable roundwood and residue for semi-mechanized single-tree selection operations employing the modified tree-length method with motor-manual felling (one chainsaw operator and one cable skidder operator).

<table>
<thead>
<tr>
<th>Cost Item</th>
<th>Cost of Roundwood ($CAD/m^3$)</th>
<th>Cost of Residue ($CAD/m^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cost to roadside (felling-delimming/topping-skidding phases)</td>
<td>$15.10</td>
<td>$4.67</td>
</tr>
<tr>
<td>Slashing cost</td>
<td>$3.30</td>
<td>$3.30</td>
</tr>
<tr>
<td>Total cost to roadside after product separation (slashing)</td>
<td>$18.40</td>
<td>$7.97</td>
</tr>
<tr>
<td>Logging truck cost (@ 65 km transport distance)</td>
<td>$11.83</td>
<td>$12.51</td>
</tr>
<tr>
<td>Total delivered cost to terminal yard 65 km from landing</td>
<td>$30.23</td>
<td>$20.48</td>
</tr>
<tr>
<td>Terminal comminution cost</td>
<td>-</td>
<td>$11.14</td>
</tr>
<tr>
<td>Total cost of comminuted residue at terminal yard</td>
<td>-</td>
<td>$31.62 ($52.70 per dry tonne)</td>
</tr>
<tr>
<td>Chip van cost – comminuted chips (@ 65 km transport distance)</td>
<td>-</td>
<td>$13.95</td>
</tr>
<tr>
<td>Total cost of comminuted residue with post-comminution transport to conversion facility 65 km from terminal yard</td>
<td>-</td>
<td>$45.57 ($75.95 per dry tonne)</td>
</tr>
</tbody>
</table>
3.4 Discussion

3.4.1 Volume recovery

Of the wide range of silvicultural systems and operating conditions in North America, semi-mechanized single-tree selection operations have the lowest per hectare recovery of roundwood and the highest technical constraints to residue recovery. The finding that 1.3 to 2.7 dry tonnes (+10%) of residue can be recovered per hectare at a cost between $50 and $80 (CAD) – which is competitive with other more intensive silvicultural systems and operating conditions (Reynolds et al. 2008; Ralevic et al. 2010; Cormier 2011; Desrochers 2011) – adds to existing harvest residue recovery research demonstrating that additional volumes can be procured from virtually any forest operation with slight modifications to conventional methods and technologies. Although residue recovery per hectare is 75-95% lower than residue recovery estimates reported for mechanized clearcut and shelterwood operations (Reynolds et al. 2008; Cormier and Tremblay 2010; Peltola et al. 2011), the additional volumes could still support bioenergy growth at acceptable cost with proper supply chain organization and management.

The recovery estimate is expected to represent the maximum potential recovery when roadside comminution is not integrated with operations and when the terminal yard is not located within ≈20 km of the landing (which would allow for recovery and transport of fine branches not recovered in the trial). Because of the decurrent branching pattern of hardwoods, reducing top diameters beyond those observed in the trial is likely lead to the recovery of material that is not sectionable into small-diameter roundwood that can be efficiently handled, leading to decreases in productivity during the processing, sorting, and truck transport phases. Concerns of forest contractors over exceeding logging damage standards are also expected to contribute to the central tendency of delimbing and topping decisions and subsequent recovery in single-tree selection operations. Mechanized cut-to-length operations, which currently form a minor component of harvesting in the tolerant hardwood region, might increase recovery relative to tree-length approaches because skidding damage and worker safety are not as much of a concern. Under this system, felled and delimbed trees would be sectioned into roundwood and small-diameter roundwood with harvesting machinery (processors) and forwarded to roadside in the bunks of wheeled
machines (forwarders). Future research on residue recovery in single-tree selection systems should consider this mechanized alternative, which is expected to become more common in the tolerant hardwood region as skilled logging professionals become increasingly scarce (Meek 2006; Girard and Roy 2009).

3.4.2 Supply chain logistics

Although roundwood form was not quantified in this study, hardwood log sweep has been shown to increase with a decrease in end-diameter (Hamner et al. 2007), and visual observations during the study confirmed this. The asymmetry of small-diameter roundwood will reduce bulk density and could lead to payload losses of between 25% and 40% relative to conventional roundwood transport (Volpe 2012) and wood chip transport (Desrochers 2011). However, the payload loss and handling difficulties can be offset by storage benefits of small-diameter roundwood relative to wood chips, including reduced dry matter loss (Pullki 1991), reduced moisture uptake, improved handling, reduced infrastructure requirements (i.e. roundwood can be stored outdoors under tarps), and reduced contamination during subsequent material movement (Desrochers 2011; 2012). If roundwood is too irregular in form to reach acceptable bulk density, volume capacity of conventional logging trucks could be increased at low cost with the use of wooden or steel mesh panels (Stampfer and Kanzian 2006). Over short distances, using conventional logging trucks modified to hold smaller diameter material can be the economically optimal choice as long as the amount of fine material transported is minimized (Spinelli et al. 2007). A potential logistical problem is the small landing sizes typical of partial harvest operations, but as long as landings consolidate at least 10 hectares of material recovered from modified tree-length operations, there would be enough small-diameter roundwood for a full truckload. Consolidation of material from multiple landings would occur at terminal yards or mill yards, depending on the conversion facility being supplied.

Considerable uncertainty surrounds the feasibility of implementing modified tree-length harvesting at operational scales. Forest operations occur over hundreds of hectares and over long periods of up to three months, often in sub-zero temperatures, and therefore the additional delimming and topping effort required of the chainsaw operators might be unsustainable. Motor-manual chainsaw felling and delimming and topping is associated with
a high rate of injury and chronic pain (Hagen 1990; Hagen et al. 1998). The additional \( \approx 6.5 \) minutes spent delimbing and topping per working hour would take away from valuable rest time and thus might increase the risk of injury and/or the willingness of chainsaw operators to implement the modified method over time, even with a wage increase commensurate with residue production ($4.81 per m\(^3\) residue). For motor-manual felling and delimbing and topping, an additional concern is whether the felling rate loss of \( \approx 3 \) trees per PMH will lead to productivity losses in the skidding phase if the chainsaw operator is not able to remain ahead of the skidder operator. A more realistic expectation – particularly for motor-manual felling configurations – is that modified tree-length delimbing and topping will occur in certain operational conditions when topography, weather, extraction distance, and, possibly, wages allow (Meek and Lussier 2008; Volpe and Desrochers 2011).

3.4.3 Potential bioenergy pathways

Wood pellet production and distribution has been growing considerably in Canada in recent years, supplied by sawmill residue and driven mainly by European demand (Spelter and Toth 2009). It is conceivable that wood pellet prices could rise to a level sufficient to cover the cost of using harvest residue and roundwood as raw material (about $150-200 per dry tonne of pellets; KPMG 2008) over the next decade if renewable energy subsidies, carbon markets, and co-firing policies continue to strengthen (Spelter and Toth 2009; Thek and Obernberger 2009), providing a possible market for residue procured from single-tree selection systems. In the near term, however, the most economically viable option in a single-tree selection context is to chip the material at terminal yards for supply to bioenergy facilities, including small-scale (500 – 2,000 kW) bio-electricity and cogeneration plants, and community heating plants. Although development of such facilities is still pending, procurement costs would be significantly reduced compared to pellet-based systems (see Section 4.3.2.).

Based on the recovery estimates, I am able to make inferences regarding the potential for bioenergy production at HFWR and in the larger GLSL forest region. The annual single-tree selection harvest area at HFWR is \( \approx 1,000 \) hectares, and most Forest Management Units (FMUs) on public lands in Ontario’s tolerant hardwood forest region have annual single-tree selection harvest areas ranging between 1,000 and 3,500 hectares. Assuming a 1.9 dry tonne per hectare recovery and a modified tree-length implementation rate of 67% (assuming forest
contractors will be able to implement the modified TL method on 2/3 of the total harvested area), the volume of recovered residue from an FMU with an annual harvest area of 1,500 hectares (1900 dry tonnes) is not sufficient to meet the demands of bio-electricity and cogeneration plants between 1 MWe and 5 MWe, which have biomass demands of between 6,000 and 30,000 dry tonnes per year (IEA 2007). The demands of such facilities could only be met if the harvest residue supply was combined with mill residue and unused roundwood. Based on the costing analysis and linear transport equation for logging trucks (Appendix 3.3), using harvest residue in this way could be profitable for transport distances up to 110 km at a market price of $60 per dry tonne after comminution at the location of energy production. A 1 MWe facility with a capacity factor of 75% could meet the annual electricity demands of approximately 600 households, or ≈4% of the households in Haliburton county (Appendix 3.8A). However, this scenario is unlikely because bio-electricity production for sale to the provincial grid is not economically viable at current rates (Monieson Centre 2011) and long-term diversion of mill residue and/or unused roundwood (over the lifetime of an electricity facility) could have high opportunity costs.

The available volumes of residue from a typical FMU with an annual harvest area of 1,500 hectares could instead support a 1 MWth community heating facility (i.e. district or institutional heating), or a cogeneration facility with an electrical capacity no greater than 250 kWe/500 kWth (Cleary pers. comm.). This could be achieved at lower public cost and without the need for a diversion of roundwood or mill residue. A 1 MWth community heating plant could provide enough heat for approximately 400 households (Appendix 3.8B), whereas a 1 MWth institutional heating plant could meet the heating demands of a small hospital (Desrochers 2011). Alternatively, a 250 kWe/500 kWth cogeneration plant could meet the electricity demands of 150 households and the heating demands of 200 households or, if installed at a small sawmill, the electricity and heating demands of the mill plus the electricity demands of 85 households if excess electricity was fed into the grid (Appendix 3.8C).

The transportation analysis shows that these supply options – which would involve terminal yards and chip vans – could be profitable for a $60 per dry tonne price when the total transport distance (logging trucks and chip vans) remains below ≈70km, but there is
considerable potential that the market price could increase naturally if capital subsidies for community heating infrastructure were available. On an equivalent energy basis, forest biomass is cheaper than heating oil, electricity, and natural gas as a heating fuel in many areas for delivered costs up to $120 per dry tonne (Samson et al. 2005; Ghafghazi et al. 2010; FPInnovations 2012). These fuel cost savings can result in an overall reduction in the unit cost of energy over the lifetime of the facility (Dasappa et al. 2003; Desrochers 2011). Once the infrastructure is established (e.g. district heating facilities, institutional heating facilities, terminal chipping yards within 100 km of managed forests) and as fossil fuel prices continue to rise, harvest residue supply for heating and small cogeneration facilities could be sustained without continued subsidization (Samson et al. 2005; Wilson et al. 2012), a major barrier to the proliferation of bio-electricity.

The low biomass demand of community heating and small cogeneration facilities provides the opportunity to utilize locally-sourced forest biomass, reducing transportation costs and simplifying supply chain logistics relative to regional or international biomass supply chains (Eriksson 2008). Community heating facilities also require boiler technicians, maintenance technicians, and fuel procurement personnel, and therefore support for this pathway would result in net employment benefits relative to conventional forms of heating, as has been observed in Austria (Madlener and Koller 2007). Using the linear transport equations for logging trucks and chip vans (Appendix 3.3 and 3.4), the economical transport distance could increase to over 150 km for a market price of $120 per dry tonne. Given the success of district heating and institutional heating in European countries under direct policy incentives, including capital grants and subsidies (Ericsson et al. 2004; Madlener 2007; Madlener and Koller 2007; Nicholls et al. 2009; Gan and Smith 2011a), tax exemptions (Scarlat et al. 2011), and carbon/energy taxes (Ericsson et al. 2004), further detailed economic analyses are needed to gauge the degree to which policy instruments supporting community heating infrastructure may facilitate the expansion of sustainable forest bioenergy in the tolerant hardwood region. If society is interested in increasing electricity generation or liquid fuel production with forest biomass sourced from partial harvest systems, serious consideration should be given to the use of low-quality roundwood in marginal stands (unused roundwood) and/or modification of existing silvicultural prescriptions for additional removals (Christopherson 1983; Cormier 2011).
4.1 Bioenergy policy and research in Ontario

The federal and provincial governments of Canada have implemented a number of policy measures supportive of bioenergy production in recent years, including bio-fuel production standards (national), bio-electricity subsidization (ON, BC, QC, NS), pulp and paper facility energy efficiency upgrades (MacDonald 2011b), and carbon taxation (BC). Ontario’s recent policy targets and incentives have been particularly pronounced, and have included: 1) termination of coal power by the end of 2014; 2) an increase in renewable power capacity from 5% to 12% by 2020 (OME 2010); 3) co-firing of one of the province’s coal generating stations with wood pellets; 4) the introduction of a feed-in tariff (FIT) program that pays an elevated price for decentralized renewable electricity, including household-level renewable electricity projects less than 10 kW; 5) ethanol production subsidies (Maure 2009); and 6) support for bioenergy research through pre-existing multidisciplinary research programs (e.g. MITACS; OGS), newly-developed research programs specific to bioenergy (e.g. the Centre for Research and Innovation in the Bio-economy (CRIBE)), and the organization of operational research trials in the GLSL.

In Ontario, specific emphasis of forest bioenergy policy has been on the generation of electricity as a means of partially replacing the coal generation deficit, and this bio-electricity bias is reflected in the existing body of research that has evaluated the costs and benefits of forest bioenergy production in the province. Many of the details of the centralized and decentralized bio-electricity options have been examined by the provincial and regional forest research community, including the Ontario Ministry of Natural Resources (OMNR), Ontario Power Generation (OPG), forest companies, research institutions, and academia. Here, I review the current state of knowledge regarding forest biomass supply, benefits, and costs in the province of Ontario before making an argument for a policy approach that prioritizes decentralization, efficiency, and integration by providing direct incentives for smaller-scale heating and cogeneration pathways.
4.2 Forest biomass supply and energy potential in Ontario

4.2.1 Provincial forest biomass supply and energy potential

Research that has been undertaken in the province to date has determined that the total amount of forest biomass that could be made available from existing forest supply chains, waste streams, and the unused annual allowable cut (AAC) for energy production is approximately 10 million dry tonnes (Appendix 4.1). Two-thirds of this total would be derived from the boreal forest region, with the remaining one-third derived from the GLSL forest region. The total 10 million dry tonnes of forest biomass could support approximately 4% (700 MW) of the province’s current electricity generation capacity (19,049 MW), or 5% of total electricity supply in the province (Zhang et al. 2010; Mabee et al. 2011b; OPG 2012).

These estimates of biomass and bio-electricity potential in Ontario rely heavily on unused low-quality roundwood from existing operations and hypothetical operations in the unused AAC (Speers 2009; Zhang et al. 2010; Levin et al. 2011; Mabee et al. 2011b; McKechnie et al. 2011), comprising approximately 8 million dry tonnes, or 80% of the total provincial estimate. The problem with these sources is that they are relatively expensive and can carry opportunity costs in areas where a value-added manufacturing industry exists or has a chance of existing in the near future. Harvest residue from existing operations has significant cost benefits but is relatively scarce, constituting the remaining 2 million dry tonnes (Speers 2009), or 20% of the total provincial forest biomass supply estimate. FPInnovations’ BiOS model, which estimates the delivered cost of biomass based on inventory and techno-economic factors, may eventually be coupled with local road maps and potential centers of demand mapped with GIS to produce regionalized estimates of forest biomass supply at specified costs (cost-supply curves) to aid in reliably determining actual biomass supply potential for the province.

4.2.2 GLSL forest biomass supply and energy potential

In the GLSL forest region, 90% (2.7 million dry tonnes) of the total estimated forest biomass supply (3 million dry tonnes) consists of unused roundwood from existing operations and from potential operations in the unused AAC (Zhang et al. 2010; Levin et al. 2011). The remaining 10% (380,000 dry tonnes) of the estimated supply is composed of harvest residue
(McKechnie et al. 2011) (Appendix 4.2). The relatively low contribution of harvest residue to the total biomass supply estimate for the GLSL reflects the precautionary assumption by most forest researchers that harvest residue availability in the region would be constrained by the prevalence of partial harvesting (Gingras and Favreau 1996; Zhang et al. 2010; McKechnie et al. 2011). Such systems are generally assumed to be incapable of accommodating FT harvesting because of residual damage concerns, which would limit recovery of harvest residue to unmerchantable distal portions of trees that do not constitute a residual damage hazard during extraction. For instance, the residue estimate of 380,000 dry tonnes published by McKechnie et al. (2011) was based on the assumption that FT would be integrated with clearcut operations, resulting in a residue recovery ratio of 40%, and that a modified TL method that retains as much of the distal portions of the tree as possible while maintaining damage standards would be applied in shelterwood operations, resulting in a residue recovery ratio of 20%. Residue recovery from single-tree selection was regarded as not being techno-economically possible.

Recent partial harvesting research in the GLSL forest region has overturned previous assumptions regarding the infeasibility of residue recovery for bioenergy production in partial harvest systems. In addition to the 10% increase in recovery from single-tree selection trials that I have reported in Chapter 3, recent research by FPInnovations and OMNR in the GLSL forest region in Ontario and Quebec has demonstrated that residue recovery in shelterwood systems can be made comparable to that of clear-cutting when FT harvesting or modified TL harvesting is implemented (Cormier and Tremblay 2010; McPherson and Jones 2012). This would augment the residue recovery rate for shelterwood systems from the previously-assumed 20% to 30-40% of roundwood production in most stand conditions if the existing research is representative (Appendix 4.3). This increase in residue recovery has been deduced from the results of modified TL trials in shelterwood operations (Cormier and Tremblay 2010), which estimated a residue recovery ratio of 28.3% for modified TL harvesting, from residue recovery ratios for intolerant hardwood species recovered during FT operations in boreal environments, which range from 10% to 20% (Ericsson and Nilsson 2006; Reynolds et al. 2008), and from the fact that tolerant and mid-tolerant tree species managed in shelterwood systems have a much larger amount of aboveground biomass than
boreal species. Therefore, the harvest residue supply potential of the GLSL forest region is likely to be larger than the 380,000 dry tonne estimate presented by McKechnie et al. (2011).

McKechnie et al. (2011) estimated residue availability in the GLSL by applying their clearcut and shelterwood residue recovery ratios (40% and 20%) to Sustainable Forest Management Model (SFMM) projections of annual roundwood production for each silvicultural system in the region. Without access to the SFMM, I am unable to quantify the increase in the annual harvest residue availability estimate relative to the 380,000 dry tonnes presented by McKechnie et al. (2011). However, using a coarse area-based method, I have estimated the annual harvest residue availability for the GLSL forest region as approximately 650,000 dry tonnes, based on the total annual harvesting area presented in the most recent Forest Management Plans for the GLSL (Appendix 4.4; Cormier pers. comm.). This mass of harvest residue could support a 50-60 MW bio-electricity facility (Wiltsee et al. 2000), contributing to 6-8% of the maximum installed bio-electricity capacity potential in Ontario (720 MW). Note that this higher estimate of residue availability does not change the total bio-electricity potential of the province by more than a fraction of a percentage, compared to the 380,000 dry tonne estimate by McKechnie et al. (2011). Harvest residue would constitute approximately 20% of the total available forest biomass supply for the GLSL forest region, instead of the initial assumption of 10%. Note that my estimate does not consider environmental constraints that are likely to reduce actual availability on some sites.

4.3 Assessing the limitations, costs, and benefits of bio-electricity production in Ontario

4.3.1 Technical and economic barriers to decentralized electricity generation

The harvest residue recovery trial reported in Chapter 3 was initiated in response to interest in developing a gasification facility at the Haliburton Forest and Wildlife Reserve (HFWR). Electricity was to be supplied to the provincial grid for revenue under the provincial FIT program, and heat was to be used for mill heating requirements (e.g. lumber drying, space heating). However, since the project began, a number of barriers to successfully establishing and operating decentralized bio-electricity facilities under the FIT program have become apparent. The most important of these barriers is the insufficient FIT rate for bio-electricity.
Queen’s University researchers have estimated that the current rate would require a three-to-four-fold increase to shorten payback periods to lengths considered acceptable by potential investors (Monieson Centre 2011). Moreover, technical issues associated with inadequate transmission line capacity have effectively barred decentralized bio-electricity production from occurring in many regions, including Haliburton. Public support for the costs of installing additional transmission line capacity and of augmenting and sustaining FIT rates for bio-electricity is unlikely in light of the Auditor General of Ontario’s recent warning that continued subsidization would raise electricity prices in the province (Auditor General of Ontario 2011).

In the case that the barriers to decentralized bio-electricity production are surmounted through a combination of additional transmission line capacity and augmentation of FIT rates for bio-electricity, or use of electricity locally without grid transmission, the presented research has served to demonstrate the techno-economic limits of harvest residue recovery in a single-tree selection context. Not only is the recoverable mass of harvest residue per hectare low (1.9 dry tonnes/ha on average), but the additional time required to implement the modified TL approach will inevitably reduce roundwood production rates in many commonly-encountered operational situations (e.g. short extraction distance, high density of marked trees, chainsaw operator health and safety), and therefore cannot be implemented in those situations.

For purposes of discussion, I assume that the modified TL approach can only be implemented on 2/3 of the total annual harvest area at the HFWR because of these various operational limitations and the assumption that extraction distances within 200 m cannot accommodate the modified TL method without reducing roundwood production rates (Meek pers. comm.). Using the annual harvest area for 2010-11 (934 hectares) the annual volume of residue is estimated as 1183 dry tonnes, an amount sufficient to support a 250 kWe/500 kWth cogeneration facility (Wood and Rowley 2011) or an 800 kWth institutional heating facility (Desrochers 2011). At the HFWR sawmill, the available biomass would likely be used for internal electricity and/or heating demands such as mill power, mill space heating, and/or lumber drying. However, exporting excess electricity to the grid at profit with a facility of such low electrical output is highly unlikely: the study that determined that bio-electricity
rates would have to increase three-to-four-fold considered a 50 MW facility (Monieson Centre 2011), which would have much lower costs per kWh of electricity produced compared to a smaller facility.

Generating an amount of electricity sufficient to cover the capital costs of a grid-feeding system under the FIT program would require a facility with a much larger electrical output. I assume here that a 1 MWe plant with a 30% conversion efficiency is the minimum cost-effective scale, although the optimum scale is as large as possible (50-60 MWe). This hypothetical 1 MWe facility installed at the HFWR sawmill, would require at least 3000 dry tonnes of woody biomass annually, an amount that would have to be supplied with a mixture of harvest residue (1183 dry tonnes), mill residue, and low-quality roundwood. The mill residue and low-quality roundwood supply – originating from existing operations at HFWR – would be diverted from conventional markets (e.g. pulp, firewood, landscaping). Increasing energy wood supply beyond the availability of these sources would require implementation of a modified TL approach without topping (would require carefully placed terminal yards within 20-30 km of landings), harvesting in marginal stands, and/or silvicultural prescription modification.

If decentralized bio-electricity production is pursued in the GLSL forest region with the goal of maximizing bio-electricity output with the available forest biomass (without concern for efficiency and use of heat in cogeneration applications), the least cost approach would be to carefully site a small number of large capacity bio-electricity facilities (50-60 MW), so long as procurement costs do not exceed threshold levels. This is because the production economics of bio-electricity facilities improve as plant scale increases. Specifically, as scale increases, the cost per unit of electrical output decreases, a function of higher electrical conversion efficiency and economies of scale effects (Kumar et al. 2003; Dornburg and Faaij 2001; Gan and Smith 2011b). Mabee et al. (2011b) coarsely estimated that 12 60 MW facilities (assumed to be cogeneration) could be supported in the province with the available 10 million dry tonnes if co-firing is not pursued. Approximately 4 of these 12 60 MW facilities could be supported in the GLSL forest region with the available 3 million dry tonnes. In reality, the procurement cost benefits of smaller-scale facilities with smaller procurement radii would lead to the establishment of bio-electricity facilities less than 60
MW in many areas, such that a decentralized approach includes a range of bio-electricity facility scales depending on local and regional biomass availability.

4.3.2 Costs and benefits of decentralized and centralized bio-electricity production

Variability in the energetic, economic, and environmental benefits of bio-electricity production among centralized and decentralized approaches is insignificant when compared to variability in cost. For instance, the energetic benefits of centralized bio-electricity production appear substantial given that co-firing tends to have an electrical conversion efficiency of ≈35% compared to ≈20% for smaller decentralized facilities. However, the difference among the two pathways in their potential contribution to provincial electricity supply would not vary by more than a percentage point (e.g. Zhang et al. 2010; Mabee et al. 2011b). Marginal differences in energetic and GHG benefits have also been demonstrated for centralized vs. decentralized liquid bio-fuel production systems (Eranki and Dale 2011). There is also no reason to suspect that centralized bio-electricity will produce more jobs per unit of energy produced or that the marginal GHG benefits of displacing fossil fuels in higher-efficiency centralized electricity generation applications will have any significant positive GHG or human health impact relative to a decentralized approach if emission standards are met.

Variability in costs of bio-electricity production among the two approaches can be expected to be far greater than variability in benefits. Cost therefore becomes the main bottleneck of policy decisions and the sustainability of those decisions. When considering capital costs, a decentralized approach is obviously much more expensive because the facilities have yet to be established. The need for investment amounts to hundreds of millions of dollars if implemented province-wide to the full potential of the resource. However, there are important cost savings that could be realized by decentralized facilities, thereby offsetting a portion of the increased cost of electricity production. For instance, cost savings would be realized relative to co-firing if the plant’s forest biomass procurement radius remained local, within limits that would contain the costs of transportation. Significant cost savings would also be realized relative to co-firing if the plants used wood chips instead of wood pellets: when comparing a wood chip-based decentralized bio-electricity strategy with that of a
centralized pellet co-firing strategy, procurement costs for wood chips are lower than those of pellets for road transport distances up to 5,000 km, equivalent to the distance between Halifax and Calgary (Appendix 4.5). Searcy et al. (2007) found that rail transport of wood chips becomes economical over truck transport for a 500 km transport distance. Given that costs of pelletization are three-to-four times higher than costs of chipping, shipping pellets by rail from pellet plants might reduce the break-even point from the estimated 5,000 km for truck transport to between 1,500 and 2,000 km. The final cost per kWh of electricity generated under the two approaches – a function of capital infrastructure and maintenance costs, operating costs, storage costs, transaction costs, and discounting assumptions – requires further study and is not addressed here.

4.3.3 The high costs and marginal benefits of large-scale bioenergy

Unbiased quantification and comparison of the total energetic, economic, and environmental benefits of various bioenergy pathways and the costs of realizing those benefits is critical to developing sustainable, optimized policy. However, there has been and continues to be distinct bias in favor of bio-electricity and bio-fuel pathways in North American bioenergy policy (Wilson et al. 2012), including in Ontario. There are a number of political and structural reasons for this. Perhaps most important is the existing regulatory and structural state of the energy sector, which is almost exclusively concerned with the generation and transmission of electricity. In Ontario, for example, the energy sector is regulated by the Ontario Energy Board which oversees the electricity and natural gas sectors. No single regulatory entity holds mandate over the heating sector. This structural state can be viewed as a direct consequence of the centralized nature of electricity, natural gas, and other commodity markets, and the decentralized nature of heating, which – while often achieved with commodity fuels (particularly natural gas) – can only be distributed locally. This pre-existing condition is made rigid by corporate and business interests in the returns associated with investment in large-scale energy projects and the perception by citizens that renewable energy and associated costs (e.g. taxation, subsidization, research funding) will provide a direct benefit to themselves if electricity and liquid fuel are supported. Small-scale bio-heating only directly benefits the local rural community in which it is being produced and mostly translates into cost savings rather than profit. Finally, the perceived climate benefits
of large-scale renewable energy, including bioenergy, also tend to elicit strong sentiment among members of the general public and certain political parties, such that maximization of GHG mitigation is prioritized over minimization of public cost and a more precautionary approach.

Energetic and climate benefits of large-scale bioenergy pathways (electricity, transport fuel) are marginal and uncertain and therefore do not make for strong arguments in favor of supporting such pathways. In Ontario, allocating all available biomass to bio-electricity in large 60 MW facilities or at coal generating stations would generate \( \approx 5\% \) of provincial electricity demand on an annual basis (Zhang et al. 2010; Mabee et al. 2011b), representing a total installed capacity of approximately \( \approx 700 \) MW or \( \approx 4\% \) of the current total electricity generation capacity of 19,049 MW in the province (OPG 2012). Allocating all available forest biomass to liquid bio-fuel pathways would displace approximately 500 million litres of gasoline, equivalent to \( \approx 3\% \) of annual gasoline consumption in Ontario (McKechnie 2012). Presumed climate benefits of coal replacement and low-efficiency transport bio-fuel pathways are confounded by the marginal GHG offset potential of bioenergy (which is proportional to energy output), and uncertainty, including uncertainty of climate dynamics (IPCC 1990), uncertainty of continued international cooperation and coordination on mitigation efforts, and uncertainty of carbon neutrality (Ter-Mikaelian et al. 1995; Ter-Mikaelian et al. 2011; Schulze et al. 2012). Enhancing biomass supply to an extent that will increase jurisdictional bio-electricity or bio-fuel supply beyond 10\% and that will make a significant dent in the jurisdiction’s GHG profile will require large expanses of energy crops, a costly supply source that remains unproven at the large scales required.

4.4 The case for a forest bioenergy strategy that prioritizes decentralization, efficiency, and integration

Contrary to what many proponents of bioenergy claim (e.g. Ragauskas et al. 2006; Gronowska et al. 2009; Zhang et al. 2010), biomass supply analyses like those recently undertaken in Ontario clearly demonstrate that the available forest biomass supply is scarce relative to total energy demands, not abundant. And the forest biomass supply becomes even more scarce when the economic costs that form the basis of responsible cost-benefit analysis and policy development are considered. These are basic facts about the forest biomass
resource that should serve as the basis for forest bioenergy policy in the province. Specifically, 1) forest biomass is scarce and cannot contribute to more than 10% of jurisdictional bio-heat, bio-electricity, or bio-fuel supply, and 2) forest biomass is loosely distributed in space, leading procurement costs to represent the largest cost center of a given bioenergy pathway. Establishment of large expanses of energy crops is the only means by which this 10% limit can be surpassed, but there are major environmental and economic obstacles to such an undertaking. Following from this, arguments in favor of a more gradual, decentralized forest bioenergy strategy that provides targets and incentives for high-efficiency small-to-medium scale heating and cogeneration applications emerge. The reasons in favor of this approach are not restricted to lower public costs, but also extend to the broader issues of forest sector competitiveness and sustainability, energy sector sustainability, and environmental sustainability. I conclude this final chapter with a review of these four arguments for a gradual, more decentralized approach to forest bioenergy policy.

COST

Throughout the marginal and erratic 40 year development of the bioenergy sector, owners and operators of the existing installed large-scale bioenergy capacity – particularly bio-electricity plants – have been able to manage the procurement cost problems of forest biomass by locating facilities adjacent to pre-existing production and waste management systems, where low-quality biomass residue becomes concentrated at low cost (e.g. forest mills, forest management zones, urban wood waste reserves). Increasing bioenergy capacity beyond the availability of these low cost sources requires that bioenergy proponents move into the heterogeneous forest landscape to procure biomass. In procuring material from forest landscapes, costs of biomass after being prepared for combustion increase considerably. For example, when by-products and wastes are used, procurement costs range from a minimum of $0 per dry tonne of sawmill residue to a maximum of $60 per dry tonne of wood pellets produced from sawmill residue. Procuring energy wood directly from forest operations increases this cost range from a minimum of $40 per dry tonne of wood chips produced from roundwood or harvest residue to up to $200 per dry tonne of wood pellets produced from roundwood or harvest residue (KPMG 2008; Thek and Obernberger 2009; Appendix 4.6). After the costs of transporting the prepared biomass to market are included, total
procurement costs will increase beyond these ranges in most situations, especially for large-scale pathways which have larger procurement radii. In the EU, where fossil fuel taxation has historically been relatively high (Davoust 2008), industry and the general public are more accustomed to the cost. North Americans may be less willing to support these costs (e.g. Auditor General of Ontario 2011), especially in light of the marginal energetic benefits such subsidization will provide and the recent development of lower cost natural gas in the region.

As discussed in chapter 3, using chipped harvest residue as a fuel for heating applications can result in procurement cost reductions relative to heating oil, electricity, and natural gas for distances up to 150 km. This in itself, however, does not provide a strong argument in favor of heating applications via lower public cost. Proper assessment of the relative cost benefits of biomass heating systems compared to conventional heating systems requires a life cycle costing approach that incorporates all system costs into the analysis, including differential capital and operating costs. The final cost of energy production (e.g. $ per kWh) of two alternative pathways can then be compared for reliable determination of the least cost approach.

Like bio-electricity and bio-fuel pathways, bio-heating applications have higher initial capital costs and operation and maintenance costs than conventional fossil fuel-based pathways of similar scale. This relates to fundamental differences in basic chemical and physical properties of the two fuels: biomass has a lower energy density, poorer combustion characteristics, and does not exist naturally in liquid or gaseous form. For chip-based systems, additional costs of employing a technician responsible for maintaining the fuel delivery system must also be incurred. Dasappa et al. (2003) estimated that initial capital cost and operation and maintenance costs for a gasifier-based furnace were increased by $108.75 and $22.69, respectively, compared to a diesel furnace. This can deter decision-makers and investors from supporting such pathways.

However, the relatively high capital and operation and maintenance costs of biomass heating systems can be offset over the lifetime of the facility by consistent fuel cost reductions. Dasappa et al. (2003) calculated a decrease in total life cycle fuel cost by -$893.82, assuming that biomass fuel cost was 25% of fossil fuel cost. Such fuel cost savings over the lifetime of
a bioenergy project ultimately reduced the final unit cost of heat energy from 3.42 cents per kWh\textsubscript{th} for a diesel-based system to 0.97 cents per kWh\textsubscript{th} for a biomass gasification-based system. A federally-funded institutional heating project in Quebec has also demonstrated that the payback period can be shortened to 7 years when local harvest residue is used (Government of Canada 2010; Desrochers 2011). Further evidence of the good economic performance of bio-heating projects comes from the growth of such pathways in Finland, Sweden, and Austria (Lind 1979; Pingoud et al. 1999; Hillring et al. 2002; Ericsson et al. 2004; Madlener 2007; Madlener and Koller 2007; Thornley and Cooper 2008; Richter et al. 2009; Karha 2011).

The energy cost benefits of heating pathways have direct implications for other cost metrics that serve as important policy references in the climate era, such as mitigation or abatement cost. Wilson et al. (2012) showed that abatement costs for replacing fuel oil in heating applications (including residential pellet and commercial boilers) are negative (-$50 to -$92 per Mg of CO\textsubscript{2} equivalent displaced), whereas abatement costs of replacing a fraction of coal in electricity generation are positive (+$149 per Mg of CO\textsubscript{2} equivalent displaced). When considering the greater ease of planning and logistics management for smaller-scale facilities utilizing locally-sourced forest biomass, the potential cost-benefits of heating applications provide the strongest reason in favor of heating incentives, deserving of further consideration and study in North America.

**FOREST SECTOR COMPETITIVENESS AND SUSTAINABILITY**

In recent years, bioenergy has been heralded by many as a means of saving the ailing Ontario forest sector. Allocating all available forest biomass – including the unused AAC – to centralized and decentralized electricity generation would provide direct, immediate benefits to the forest sector, including revenue, job creation, and silvicultural improvement of the resource. However, the costs of such an approach have received less attention than the more easily-deduced absolute potential. Successful implementation of a large-scale approach would require significant subsidization of bio-electricity or bio-fuel production costs, and/or the implementation of a provincial carbon tax or cap-and-trade scheme. The high costs of production ultimately arise from the high procurement costs incurred in using roundwood
and harvest residue sourced from forest operations as fuel, a procurement option that has largely been avoided by the existing global bio-electricity and bio-fuel industries because subsidization, carbon taxation, and cap-and-trade schemes have not been of sufficient strength. Reasons for the lack of strength of these policy instruments relate to fundamental concerns that subsidization, carbon taxation, and cap-and-trade schemes could lead to competition for forest biomass with existing incumbents as well as result in more economy-wide negative externalities, including increases in energy prices, increases in public debt, and increases in the price of fossil fuel-derived goods and services.

Since the 1970s, forest industry incumbents, policy-makers, and researchers have emphasized the need for an integrated approach to bioenergy production that maintains a solid industrial base for value-added manufacturing and treats bioenergy as a complementary pathway capable of utilizing lower quality forest biomass (e.g. Nautiyal 1979). The prevalence of residue and waste use in the OECD forest bioenergy sector confirms that this is exactly how forest bioenergy has developed over the last 40 years, including in Ontario. Although an integrated approach was much more easily advocated and pursued in the 1970s and 1980s when conventional solid wood and fiber product markets were healthy and climate policy was non-existent, there are deeper strategic points in favor of this approach that relate to revenue, employment, and sustainability: revenues under future liquid bio-fuel, bio-material, bio-chemical, or engineered wood product markets would likely be higher, employment for manufacturing pathways is higher than employment for combustion pathways, and continued operation is not as dependent on subsidization. Just as with the alternative energy-maximization approach to bioenergy, there are many caveats to this argument, including the possibility for carbon taxation to reduce the public burden, but it nevertheless forms a logical argument that has been and continues to be used in favor of a precautionary, integrated approach to forest bioenergy.

If a precautionary approach that aimed to support smaller-scale heating and cogeneration pathways was pursued in the province, the economic and silvicultural benefits of a bioenergy market would still accrue to the forest sector, only more gradually. Bioenergy would serve as an important alternative revenue stream as the value-added manufacturing industry is transformed through research, market development, and capital investment. For instance, the
development of heating markets for locally-sourced harvest residue in and around the forest management units of the province would provide an alternative revenue stream for contractors and a potential means of increasing economical roundwood supply for value-added pathways by increasing the total fraction of the AAC that can be harvested profitably (Puttock 1995). Such harvesting would be implemented with silvicultural strategies appropriate to the ecological conditions of the stand, improving the economic and ecological quality of future rotations. The establishment of “biorefineries” as alternative value-added manufacturing facilities for future value-added products like liquid bio-fuels, bio-chemicals, and bio-materials (e.g. Mabee et al. 2006) is compatible with this approach when roundwood and energy crops are used. A wood pellet market could develop as well at reasonable cost if supplied with low cost sawmill residue (Spelter and Toth 2009).

ENERGY SECTOR SUSTAINABILITY

The issue of future energy system stability, i.e. the ability of energy systems to meet future energy demands, is a central concern common to all nation-states and constituent economies. Earthen fossil fuel and uranium reserves are expected to last approximately 100 years if current global energy demand, as driven by economic activity, is maintained or increased (Shafiee and Topal 2009). If current levels of energy supply are not maintained with the use of thorium and a novel technological breakthrough (e.g. liquid fuel thorium reactors, nuclear fusion), human civilization must reduce energy demand. In light of this pressure of necessity and the more intrinsic, responsible reasons for conservatively utilizing scarce natural resources, all OECD nations recognize that improving energy efficiency is the most cost-effective means of achieving energy conservation goals in the long-term.

A key to realizing any energy sector goal (including energy efficiency) is to focus on heating pathways, which represent the majority of secondary energy supply in most OECD nations. In Canada in 2009, for instance, heat energy constituted 80% of total energy consumed in the residential sector and 58% of total energy consumed in the commercial/institutional sector (NRCAN 2012). Bioenergy, solar, and geothermal have a fundamental efficiency advantage relative to wind and hydroelectric technologies in that heat can be supplied to consumers at high conversion efficiencies of between 75% and 90%, without the need for prior conversion
to electricity. Converting to electricity and transmitting the electricity to distant consumers reduces the efficiency of electric heating systems to less than 30%. Renewable pathways like bioenergy can distribute heat to single or multiple buildings using stoves or furnaces or district heating networks that circulate water, air, or another heat-conducting medium, avoiding the energy losses associated with electrical conversion and transmission in electricity-based heating. The low biomass demand of heating facilities also enables owners and operators of such facilities to comfortably source supplies from the local area without concern over the logistics of mobilizing and sustaining regional biomass supply chains (Richard 2010), ensuring that the established energy system capacity will be sustained without heavy reliance on government subsidization or other policy measures. Cogeneration could eventually be coupled to these systems for local transmission when supplies are sufficient, although the economics of such systems have yet to be resolved (Fuss et al. 2012; Siler-Evans et al. 2012).

ENVIRONMENTAL SUSTAINABILITY

Policy dictating the sustainable extent and intensity of forest harvesting cannot be expected to change under any approach to bioenergy production if policy continues to prioritize sustainability in terms of both habitat provisioning and site productivity. Given the complexity of forest ecosystems, knowledge regarding these topics is incomplete (Berch et al. 2011; Thiffault et al. 2011) and therefore a precautionary, adaptive approach to forest policy and management is and will continue to be advocated in Ontario (Puddister et al. 2011) and other responsibly-managed jurisdictions. Within this context, there has been a recent trend towards decreases in the annual allowable cut of many provinces and increases in the prevalence of partial harvesting, also referred to broadly as “ecological forestry” and more specifically as “structural retention silviculture” or “multi-cohort forest management” (e.g. Franklin et al. 2002; Bebber et al. 2005; Thorpe et al. 2008; Aubry et al. 2009; Kuttner 2011). If these trends continue under growing societal valuation of natural ecological conservation and the more practical economic benefits of reducing annual allowable cut quotas in some regions (Mathey et al. 2009), the future supply of forest biomass for bioenergy production will contract, making cost-effective, logistically-feasible large-scale bioenergy production increasingly difficult. Further contraction in supply will occur if
continued long-term soil productivity research (e.g. Powers et al. 2005) discovers that forest ecosystems are more sensitive to biomass removals than previously thought. Heating and smaller-scale cogeneration pathways are advantaged under such developments because of their reduced biomass demand. A further benefit of low-demand heating and small-scale cogeneration pathways is the ability to accommodate more precautionary, environmentally-friendly harvesting methods at reasonable cost. For example, tree-length and cut-to-length harvesting methods with differential topping and delimming, as reported in Chapter 3 and reported by Plamondon (2011), Cormier and Tremblay (2010), Meek (2011), and Desrochers (2012), retain nutrient-rich foliage and fine branches on site.

4.5 Concluding remarks

Although boom-and-bust cycles have been common to the Canadian forest sector since the 1970s (Mabee et al. 2006), the current economic situation within the Canadian forest sector is unique in the ≈80 year history of production forestry. The conventional industry has been destabilized as a result of a combination of exogenous events including the recent global economic downturn, the increase in the value of the Canadian dollar, the US housing market collapse, and competition with more cost-effective and productive South American and Asian value-added manufacturers. A historic lack of investment in new infrastructure and value-added products is also to blame (Lazar 2010). Efficient use of public funds, together with investment from remaining and new industry incumbents, is needed to revitalize the forest economy. In moving forward, policy strategies that seek to increase the capacity of bioenergy must take larger issues pertinent to the forest and renewable energy sectors into consideration, seeking to strategically integrate bioenergy production within the existing framework of knowledge, markets, and infrastructure, as has been achieved in the bioenergy sector to date (Lundmark 2006). Bioenergy production should continue to be integrated with existing and new infrastructure supporting the manufacturing of value-added products, including future value-added products like cross-laminated timber (CLT), bio-materials, bio-chemicals, and potentially liquid bio-fuels (FPAC 2010; Lazar 2010).

There is no imminent danger that justifies rushing the deployment of large-scale bio-electricity and bio-fuel applications, especially given the recent production spike in natural gas and plans in many jurisdictions to continue expanding properly-regulated nuclear power.
In fact, this recent growth in natural gas offers the opportunity for a revision of bioenergy policy away from low-efficiency, large-scale bioenergy and towards a truly sustainable and decentralized model that prioritizes efficiency, directly supports heating applications, and promotes cogeneration and liquid bio-fuel production when volumes are sufficient. This shift in renewable policy, from the current emphasis on deployment of renewables at least cost (e.g. at the largest possible scale of electricity generation) towards a renewable policy that balances energy output and GHG mitigation with energy efficiency has also been advocated for the USA (Brown et al. 2007).

The present research indicates that forest contractors can recover harvest residue from all silvicultural systems and harvesting configurations with minor changes to existing operations. With proper supply chain management, the residue can be delivered to market in an acceptable form at costs between $50-80 per dry tonne of wood chips when bioenergy production is local (within ≈150 km). This delivered cost is competitive with heating oil, electricity, and natural gas when used locally in heating applications, which can lead to an overall reduction in the cost per unit of heat produced. In concert with the sustainable transformation of centralized electricity systems (e.g. Equinox Summit 2012), continued growth of residential firewood and wood pellet markets, and the imposition of more rigorous energy efficiency standards and regulations, small-scale decentralized bioenergy in commercial and institutional facilities could cost-effectively contribute to energy systems in perpetuity.

Continued demonstration of the feasibility and cost benefits of residential, commercial, and institutional heating pathways, as is occurring in Quebec (Government of Canada 2010; Cross 2011; Desrochers 2011), is a critical next step in fostering the development of sustainable bioenergy in Ontario and, more broadly, North America. Once evidence of the net benefits of heating pathways in the specific conditions of the province is sufficiently accumulated and disseminated, policy incentives for residential, commercial, and institutional heating sectors can be implemented justifiably. The success of market deployment policies in Europe (Gan and Smith 2011a), particularly capital grants, tax rebates, and subsidies that allow owners and operators of residential and commercial buildings and institutions to absorb the initial costs of converting heating systems to biomass
(Madlener and Koller 2007), suggest that this policy option should be considered. This may allow local markets for harvest residue and other low-quality biomass to develop at lower cost to society and in concert with the recovery of the roundwood-based value-added manufacturing industry and continued growth of the renewable energy sector. Considerable efforts and market controls may be required to ensure that the scarce biomass resource is not pelletized or liquefied and sold on international commodity markets to supply the insatiable demands of low-efficiency, large-scale bioenergy producers under climate era policy.
Literature Cited


Cleary, J. pers. comm. Post-doctoral research fellow, Faculty of Forestry, University of Toronto.


Cockwell, M. pers. comm. PhD candidate, Faculty of Forestry, University of Toronto.


Cormier, D. pers. comm. Research Leader, FPInnovations – Forest Operations. Pointe-Claire, QC.


Desrochers, L. pers. comm. Researcher, FPInnovations – Forest Operations. Pointe-Claire, QC.


Krigstin, S. pers. comm. Assistant Professor, Faculty of Forestry, University of Toronto. Toronto, ON.


Meek, P. pers. comm. Researcher, FPInnovations – Forest Operations. Pointe-Claire, QC.

Michaelsen, J. pers. comm. Program Leader Energy, FPInnovations – Forest Operations, Pointe-Claire, QC.


Robinson, J.M. and Honer, T.G. 1974. Without fear or favour: an account of wood measurement in Canada. CFS. Forest Management Institute, Ottawa, ON.


Ryans, M. pers. comm. Program Leader, FPInnovations – Forest Operations. Pointe-Claire, QC.


Schleifenbaum, P. pers. comm. Haliburton Forest and Wildlife Reserve owner and operator. Haliburton, ON.


SEREX. 2012. Available at http://www.serex.qc.ca/


## Appendices

Appendix 1.1: Three-scale classification of bioenergy technologies.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Output</th>
<th>Capacity</th>
<th>Scale</th>
<th>Cost (installed)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firewood stove</td>
<td>Heat</td>
<td>1-25 kWth</td>
<td>Small</td>
<td>$1,000-$5,000</td>
<td>-</td>
</tr>
<tr>
<td>Pellet stove</td>
<td>Heat</td>
<td>1-25 kWth</td>
<td>Small</td>
<td>$1,000-$5,000</td>
<td>-</td>
</tr>
<tr>
<td>Boiler</td>
<td>Heat (hot water)</td>
<td>200 kWth</td>
<td>Small</td>
<td>-</td>
<td>SEREX 2012</td>
</tr>
<tr>
<td>Boiler (moving grate)</td>
<td>Heat (institutional space heating and hot water)</td>
<td>800 kWth</td>
<td>Small</td>
<td>1.3 million CAD</td>
<td>Desrochers 2011</td>
</tr>
<tr>
<td>Organic Rankine Cycle</td>
<td>Heat and Electricity</td>
<td>200 kWe, 980 kWth</td>
<td>Small</td>
<td>1.25 million EURO</td>
<td>Wood and Rowley 2011</td>
</tr>
<tr>
<td>Gas turbine</td>
<td>Heat and Electricity</td>
<td>100 kWe, 200 kWth</td>
<td>Small</td>
<td>635,000 EURO</td>
<td>Wood and Rowley 2011</td>
</tr>
<tr>
<td>Gasifier + Stirling engine</td>
<td>Heat and Electricity</td>
<td>35 kWe, 145 kWth</td>
<td>Small</td>
<td>250,000 EURO</td>
<td>Wood and Rowley 2011</td>
</tr>
<tr>
<td>Gasifier + Internal combustion</td>
<td>Heat and Electricity</td>
<td>250 kWe, 500 kWth</td>
<td>Small</td>
<td>1.35 million EURO</td>
<td>Wood and Rowley 2011</td>
</tr>
<tr>
<td>District heating (grate boiler)</td>
<td>Heat</td>
<td>500 kWth – 1 MWth</td>
<td>Small</td>
<td>3.1 million CAD</td>
<td>Schweig 1997</td>
</tr>
<tr>
<td>Organic Rankine Cycle</td>
<td>Heat and Electricity</td>
<td>1.2 MWe</td>
<td>Small-to-Medium</td>
<td>6 million CAD</td>
<td>Yablecki et al. 2011</td>
</tr>
<tr>
<td>Organic Rankine Cycle</td>
<td>Heat and Electricity</td>
<td>2.6 MWe</td>
<td>Small-to-Medium</td>
<td>13 million CAD</td>
<td>Yablecki et al. 2011</td>
</tr>
<tr>
<td>Small steam CHP</td>
<td>Heat and Electricity</td>
<td>2.2 MWe</td>
<td>Small-to-Medium</td>
<td>7.7 million CAD</td>
<td>Yablecki et al. 2011</td>
</tr>
<tr>
<td>Small steam CHP</td>
<td>Heat and Electricity</td>
<td>4.6 MWe</td>
<td>Small-to-Medium</td>
<td>16.1 million CAD</td>
<td>Yablecki et al. 2011</td>
</tr>
<tr>
<td>Entropic cycle</td>
<td>Heat and Electricity</td>
<td>1 MWe</td>
<td>Small-to-Medium</td>
<td>5.5 million CAD</td>
<td>Yablecki et al. 2011</td>
</tr>
<tr>
<td>Entropic cycle</td>
<td>Heat and Electricity</td>
<td>2.2 MWe</td>
<td>Small-to-Medium</td>
<td>12.1 million CAD</td>
<td>Yablecki et al. 2011</td>
</tr>
<tr>
<td>District heating</td>
<td>Heat</td>
<td>5 MWth</td>
<td>Small-to-Medium</td>
<td>300 million</td>
<td>Cross 2011</td>
</tr>
<tr>
<td>District heating (grate)</td>
<td>Heat</td>
<td>1-30 MWth</td>
<td>Small-to-Medium</td>
<td>-</td>
<td>Al-Mansour and Zuwala</td>
</tr>
<tr>
<td>Plant Type</td>
<td>Energy Source</td>
<td>Power Output (MWe)</td>
<td>Scale</td>
<td>Notes</td>
<td></td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>---------------------</td>
<td>--------------------</td>
<td>--------</td>
<td>--------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Pulp and paper cogeneration (boiler)</td>
<td>Heat and Electricity</td>
<td>10-30</td>
<td>Medium</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Stand-alone bio-electricity plant (boiler)</td>
<td>Electricity</td>
<td>10-60</td>
<td>Medium</td>
<td>Wiltsee 2000; Bain et al. 2003</td>
<td></td>
</tr>
<tr>
<td>Co-firing</td>
<td>Electricity</td>
<td>50-700</td>
<td>Large</td>
<td>Al-Mansour and Zuwala 2010</td>
<td></td>
</tr>
<tr>
<td>Fast pyrolysis</td>
<td>Pyrolysis oil (fuel, transport fuel, or chemicals)</td>
<td>100-400 dry tonnes per day</td>
<td>Large</td>
<td>CRIBE 2012</td>
<td></td>
</tr>
<tr>
<td>Liquid bio-fuel plant</td>
<td>Liquid bio-fuel</td>
<td>150-160 dry tonnes per day</td>
<td>Large</td>
<td>Richard 2010; Stasko et al. 2011</td>
<td></td>
</tr>
</tbody>
</table>
Appendix 2.1: List of potential forest products available with existing and future technologies (Krigstin pers. comm.).

<table>
<thead>
<tr>
<th>FOREST PRODUCT TYPE</th>
<th>FOREST PRODUCT TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solid wood products and engineered wood products</strong></td>
<td>-Cross laminated timber (single-storey and multi-storey residential, commercial, and institutional building construction)</td>
</tr>
<tr>
<td></td>
<td>-Laminated veneer lumber (furniture, construction)</td>
</tr>
<tr>
<td></td>
<td>-Lumber (construction, furniture)</td>
</tr>
<tr>
<td></td>
<td>-Medium-density fibreboard (furniture, construction)</td>
</tr>
<tr>
<td></td>
<td>-Oriented strand board (furniture, construction)</td>
</tr>
<tr>
<td></td>
<td>-Oriented strand lumber (construction)</td>
</tr>
<tr>
<td></td>
<td>-Particleboard (furniture, side walls)</td>
</tr>
<tr>
<td></td>
<td>-Ultra-low density fibreboard (furniture)</td>
</tr>
<tr>
<td><strong>Pulp, paper, bio-chemical, and bio-material products</strong></td>
<td>-Bleached chemi-thermo-mechanical pulp (paper, paperboard, furnishings)</td>
</tr>
<tr>
<td></td>
<td>-Cellulose acetate (photographic film base, adhesive component, eyeglass frame material)</td>
</tr>
<tr>
<td></td>
<td>-Dissolving pulp (textiles, cellophane, cellulose acetate)</td>
</tr>
<tr>
<td></td>
<td>-Furfural (chemical solvent, chemical intermediate)</td>
</tr>
<tr>
<td></td>
<td>-Kraft pulp (paper, paperboard)</td>
</tr>
<tr>
<td></td>
<td>-Lightweight coated paper (magazine paper)</td>
</tr>
<tr>
<td></td>
<td>-Lignin (dispersants in cement applications, chemical additives for oil and agricultural sectors, vanillin, ethanol, xylitol, dust suppression agent)</td>
</tr>
<tr>
<td></td>
<td>-Mechanical pulp (newsprint)</td>
</tr>
<tr>
<td></td>
<td>-Methanol (formaldehyde, plastics, paints, explosives, gasoline, fuel, solvents, methanol fuel cells)</td>
</tr>
<tr>
<td></td>
<td>-Nanocellulose (paper, composites, plastics, food additive, water absorbent, medical, cosmetic, and pharmaceutical manufacturing, computer components)</td>
</tr>
<tr>
<td></td>
<td>-Pyrolysis oil (chemicals, fuels)</td>
</tr>
<tr>
<td><strong>Fuel, energy, and other products</strong></td>
<td>-Bark (heat, electricity, landscaping mulch, animal bedding)</td>
</tr>
<tr>
<td></td>
<td>-Biochar (fertilizer, steel manufacturing, air and water filtration)</td>
</tr>
<tr>
<td></td>
<td>-Electricity (appliances, manufacturing, telecommunications, service sector)</td>
</tr>
<tr>
<td></td>
<td>-Ethanol (transport fuel)</td>
</tr>
<tr>
<td></td>
<td>-Fischer-Tropsch diesel (transport fuel)</td>
</tr>
<tr>
<td></td>
<td>-Fischer-Tropsch gasoline (transport fuel)</td>
</tr>
<tr>
<td></td>
<td>-Heat (process heating, space heating, hot water heating)</td>
</tr>
<tr>
<td></td>
<td>-Low pressure steam (process energy)</td>
</tr>
<tr>
<td></td>
<td>-Pellets (heat, electricity, animal bedding)</td>
</tr>
<tr>
<td></td>
<td>-Sawdust and shavings (engineered wood products, heat, electricity, landscaping mulch, animal bedding)</td>
</tr>
<tr>
<td></td>
<td>-Torrefied pellets (heat, electricity, animal bedding)</td>
</tr>
<tr>
<td></td>
<td>-Wood chips (pulp manufacturing, engineered wood products, heat, electricity, landscaping mulch, animal bedding, metal and glass manufacturing)</td>
</tr>
</tbody>
</table>
Appendix 3.1. Costing parameters for mechanized felling, motor-manual felling-delimbing/topping, cable skidding, and slashing (Meek pers. comm.; Hamilton pers. comm.).

<table>
<thead>
<tr>
<th></th>
<th>Feller-buncher</th>
<th>Chainsaw</th>
<th>Cable skidder</th>
<th>Slasher(^\text{10})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model and specifications</td>
<td>John Deere 753G</td>
<td>150 cc</td>
<td>John Deere 540G-III</td>
<td>Serko</td>
</tr>
<tr>
<td>Machine life</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Purchase price</td>
<td>$550,000</td>
<td>$1,500</td>
<td>$250,000</td>
<td>$350,000</td>
</tr>
<tr>
<td>Salvage value</td>
<td>$55,000</td>
<td>$0</td>
<td>$25,000</td>
<td>$35,000</td>
</tr>
<tr>
<td>Interest rate</td>
<td>8%</td>
<td>8%</td>
<td>8%</td>
<td>8%</td>
</tr>
<tr>
<td>Insurance</td>
<td>$22,000</td>
<td>$0</td>
<td>$5,500</td>
<td>$7,700</td>
</tr>
<tr>
<td>Lifetime maintenance cost</td>
<td>$495,000</td>
<td>$500</td>
<td>$225,000</td>
<td>$315,000</td>
</tr>
<tr>
<td>Operating hours per year</td>
<td>2,000</td>
<td>2,000</td>
<td>2,000</td>
<td>2,000</td>
</tr>
<tr>
<td>Fuel cost</td>
<td>$1.50</td>
<td>$1.50</td>
<td>$1.50</td>
<td>$1.50</td>
</tr>
<tr>
<td>Fuel consumption (L per PMH)</td>
<td>35</td>
<td>2.0</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Oil cost</td>
<td>$3.00</td>
<td>$0.50</td>
<td>$2.00</td>
<td>$2.00</td>
</tr>
<tr>
<td>Wage per SMH (includes overhead for salaries)</td>
<td>$29.70</td>
<td>$29.70</td>
<td>$29.70</td>
<td>$29.70</td>
</tr>
<tr>
<td>Cost per SMH</td>
<td>$146.16</td>
<td>$33.39</td>
<td>$79.84</td>
<td>$103.80</td>
</tr>
<tr>
<td>Utilization rate</td>
<td>75%</td>
<td>75%</td>
<td>75%</td>
<td>75%</td>
</tr>
<tr>
<td>Cost per PMH</td>
<td>$194.88</td>
<td>$44.51</td>
<td>$106.45</td>
<td>$138.40</td>
</tr>
<tr>
<td>Productivity (m(^3) per PMH)</td>
<td>46.6 (Girard and Roy 2009)</td>
<td>10.0 (ProVue)</td>
<td>42.0 (ProVue)</td>
<td></td>
</tr>
<tr>
<td>Cost per m(^3)</td>
<td>$4.18</td>
<td>$15.10</td>
<td>$3.30</td>
<td></td>
</tr>
<tr>
<td>Cost per dry tonne</td>
<td>$6.97</td>
<td>$25.17</td>
<td>$5.50</td>
<td></td>
</tr>
</tbody>
</table>

\(^{10}\) Slasher productivity for residue (small-diameter roundwood) was assumed to be the same as typical slasher productivity for roundwood.
Appendix 3.2. Costing parameters for self-loading logging trucks and chip vans (Desrochers pers. comm.; Michaelsen pers. comm.).

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Self-loading logging truck</th>
<th>Chip van</th>
</tr>
</thead>
<tbody>
<tr>
<td>- specifications</td>
<td>-</td>
<td>125 m³ maximum volume</td>
</tr>
<tr>
<td>Tractor and trailer life</td>
<td>10 and 11</td>
<td>5 and 10</td>
</tr>
<tr>
<td>Tractor + Trailer purchase price</td>
<td>$270,000</td>
<td>$285,000</td>
</tr>
<tr>
<td>Tractor + Trailer salvage value</td>
<td>$40,500</td>
<td>$42,000</td>
</tr>
<tr>
<td>Interest rate</td>
<td>8%</td>
<td>8%</td>
</tr>
<tr>
<td>Insurance</td>
<td>$12,000</td>
<td>$3,000</td>
</tr>
<tr>
<td>Lifetime maintenance cost</td>
<td>$315,000</td>
<td>$102,436</td>
</tr>
<tr>
<td>Operating days per year per truck (@ 3 trips per day and 3 trucks)</td>
<td>93 (roundwood only); 103 (roundwood and residue)</td>
<td>200</td>
</tr>
<tr>
<td>Fuel cost</td>
<td>$1.50</td>
<td>$1.50</td>
</tr>
<tr>
<td>Loading/Unloading/Personal time (minutes per trip)</td>
<td>90 (roundwood); 110 (residue)</td>
<td>90</td>
</tr>
<tr>
<td>Wage per SMH (includes overhead for salaries)</td>
<td>$29.70</td>
<td>$29.70</td>
</tr>
<tr>
<td>Travel distance per trip</td>
<td>65 km</td>
<td>65 km</td>
</tr>
<tr>
<td>Dry tonnes per trip</td>
<td>25 (roundwood); 15 (residue)</td>
<td>21.75 (chips)</td>
</tr>
<tr>
<td>Cost per trip</td>
<td>$479.81 (roundwood only); $448.63 (roundwood and residue)</td>
<td>$366.12</td>
</tr>
<tr>
<td>Cost per SMH</td>
<td>$204.51 (roundwood only); $198.42 (roundwood and residue)</td>
<td>$89.03</td>
</tr>
<tr>
<td>Utilization rate</td>
<td>90%</td>
<td>80%</td>
</tr>
<tr>
<td>Cost per PMH</td>
<td>$227.23 (roundwood only); $220.47 (roundwood and residue)</td>
<td>$117.16</td>
</tr>
<tr>
<td>Cost per m³</td>
<td>$12.41 (roundwood only); $12.51 (roundwood and residue)</td>
<td>$13.95 (chips)</td>
</tr>
<tr>
<td>Cost per dry tonne</td>
<td>$20.68 (roundwood only); $20.85 (roundwood and residue)</td>
<td>$23.25 (chips)</td>
</tr>
</tbody>
</table>
Appendix 3.3: Linear relationship between final delivered residue cost ($/dry tonnes) and distance travelled (km) for logging truck transport \( (y = 1.3223x + 46.198) \). Final delivered cost includes all costs incurred before transportation (delimbing/topping and slashing, as well as terminal comminution cost).
Appendix 3.4: Linear relationship between final delivered residue cost ($/dry tonnes) and distance travelled (km) for chip van transport \((y = 1.6924x + 57.721)\). Final delivered cost includes all costs incurred before transportation (delimbing/topping, slashing, logging truck transport for 65 km, and terminal comminution).
Appendix 3.5: Box plots of volume per recovered tree in each treatment for four size classes.
Appendix 3.6: R output for analysis of covariance of volume per recovered tree and DBH using log-transformed data.

Call:
`lm(formula = LogCPV ~ LogDBH + T)`

Residuals:
- Min    1Q  Median    3Q   Max
-0.56972 -0.05709  0.01289  0.07354  0.43043

Coefficients:

|                  | Estimate | Std. Error | t value | Pr(>|t|) |
|------------------|----------|------------|---------|----------|
| (Intercept)      | -0.481392| 0.048516   | -9.922  | < 2e-16  *** |
| LogDBH           | 1.504097 | 0.031314   | 48.033  | < 2e-16  *** |
| T                | -0.029821| 0.007802   | -3.822  | 0.000142 * * * |

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.1167 on 892 degrees of freedom
Multiple R-squared: 0.7222, Adjusted R-squared: 0.7215
F-statistic: 1159 on 2 and 892 DF, p-value: < 2.2e-16
Appendix 3.7: Relative contribution of each operational phase to total procurement cost.
Appendix 3.8: Assumptions and calculations used to determine number of households in Haliburton county that could have electrical and heating needs supported with bioenergy facilities at various scales.

Average annual household energy consumption = 27,000 kWh (CBEEDAC 2011)

Average annual household heat consumption = 16,200 kWh (assuming 60% of energy is heat for space and water heating; DOE 2011)

Average annual household electricity consumption = 10,800 kWh (assuming 40% of energy is electricity for lighting, air conditioning, and other appliances; DOE 2011)

Average annual electricity consumption of Haliburton Forest sawmill = 720,000 kWh

A) 1 MWe bio-electricity facility:
Capacity factor = 75%
Total annual generation = 1 MJ/sec * 60 sec * 60 min * 24 hrs * 365 days * 0.75 c.f. = 23,652,000 MJ/yr or 6,570,000 kWh/yr
Total number of households supported annually = 6,570,000 kWh/yr / 10,800 kWh/household = 608

B) 1 MWth community heating facility:
Capacity factor = 75%
Total annual heat production = 1 MJ/sec * 60 sec * 60 min * 24 hrs * 365 days * 0.75 c.f. = 23,652,000 MJ/yr or 6,570,000 kWh/yr
Total number of households supported annually = 6,570,000 kWh/yr / 16,200 kWh/household = 405

C) 250 kWe/500 kWth cogeneration facility:
Capacity factor = 75%
Total annual electrical generation = 250 kJ/sec * 60 sec * 60 min * 24 hrs * 365 days * 0.75 c.f. = 5,913,000 MJ/yr or 1,642,500 kWh
Total number of households supported annually = 1,642,500 kWh/yr / 10,800 kWh/household = 152
Total annual heat production = 500 kJ/sec * 60 sec * 60 min * 24 hrs * 365 days * 0.75 c.f. = 11,826,200 MJ or 3,285,000 kWh
Total number of households supported annually = 3,285,000 kWh/yr / 16,200 kWh/household = 202
Electricity used at Haliburton Forest sawmill = 720,000 kWh
Excess electricity fed into local or regional grid from Haliburton Forest sawmill = 922,500 kWh
Total number of households supported annually from excess electricity = 922,500 kWh / 10,800 kWh = 85
Appendix 4.1: Forest biomass availability estimates for Ontario (includes Boreal and GLSL forest regions).

<table>
<thead>
<tr>
<th>Type</th>
<th>Estimate</th>
<th>Citation</th>
<th>Potential electricity capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unused harvested roundwood and unused unharvested roundwood</td>
<td>4.7-5.8 million tonnes (green)</td>
<td>Speers 2009</td>
<td></td>
</tr>
<tr>
<td>Unused unharvested roundwood (unused AAC)</td>
<td>4.5 million tonnes (dry)</td>
<td>Mabee et al. 2011a (based on Zhang et al. 2010)</td>
<td></td>
</tr>
<tr>
<td>Forest residue</td>
<td>2.9-3.7 million tonnes (green)</td>
<td>Speers 2009</td>
<td></td>
</tr>
<tr>
<td>Forest residue</td>
<td>5.3 million tonnes (dry)</td>
<td>Sidders et al. 2008 (BIMAT)</td>
<td></td>
</tr>
<tr>
<td>Mill residue</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SRWCs</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TOTAL</td>
<td>≈10 million dry tonnes (80% roundwood, 20% residue)</td>
<td>-</td>
<td>600-720 MW (Mabee et al. 2011a)</td>
</tr>
</tbody>
</table>
Appendix 4.2: Forest biomass availability estimates for the GLSL forest region in Ontario before operational research trials (see Section 4.2).

<table>
<thead>
<tr>
<th>Type</th>
<th>Estimate</th>
<th>Citation</th>
<th>Potential electricity capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unused harvested roundwood</td>
<td>1 million tonnes (dry)</td>
<td>Levin et al. 2011 + extrapolation</td>
<td>80 MW</td>
</tr>
<tr>
<td>Unused unharvested roundwood (unused AAC)</td>
<td>1.8 million tonnes (dry) (McKechnie et al. 2011)</td>
<td>Zhang et al. 2010 (OMNR estimates pers. comm. by Spaans, R.)</td>
<td>150-200 MW</td>
</tr>
<tr>
<td>Forest residue</td>
<td>0.38 million tonnes (dry)</td>
<td>McKechnie et al. 2011</td>
<td>30-40 MW</td>
</tr>
<tr>
<td>Forest residue</td>
<td>0.66 million tonnes (dry)</td>
<td>Present study</td>
<td>50-60 MW</td>
</tr>
<tr>
<td>Mill residue</td>
<td>0</td>
<td>Levin et al. 2011</td>
<td>-</td>
</tr>
<tr>
<td>SRWCs</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TOTAL</td>
<td>≈3 million dry tonnes (90% roundwood, 10% residue)</td>
<td>-</td>
<td>200-300 MW (based on Mabee et al. 2011a);</td>
</tr>
</tbody>
</table>
Appendix 4.3: Harvest residue recovery ratios and per hectare estimates for various silvicultural systems and harvesting methods.

<table>
<thead>
<tr>
<th>Silvicultural system</th>
<th>Harvesting method</th>
<th>Previous harvest residue recovery ratio (McKechnie et al. 2011)</th>
<th>Present harvest residue recovery ratio (residue production as a percentage of roundwood production) (deduced from Cormier and Tremblay 2010; Reynolds et al. 2008; and larger tree size typical of shelterwood systems)</th>
<th>Potential per hectare harvest residue recovery (based on present harvest residue recovery ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clearcut</td>
<td>FT</td>
<td>40%</td>
<td>40%</td>
<td>15 – 20 dt</td>
</tr>
<tr>
<td>Shelterwood</td>
<td>FT</td>
<td>-</td>
<td>40%</td>
<td>15 – 20 dt</td>
</tr>
<tr>
<td>Shelterwood</td>
<td>Modified TL</td>
<td>20%</td>
<td>30%</td>
<td>10 – 15 dt</td>
</tr>
<tr>
<td>Single-tree selection</td>
<td>Modified TL with topping</td>
<td>-</td>
<td>10%</td>
<td>1 – 3 dt</td>
</tr>
</tbody>
</table>
Appendix 4.4. Total annual area harvested commercially under the three silvicultural systems for all GLSL FMUs and estimates of annual potential residue recovery for all commercial harvesting activities in the GLSL forest region (from latest forest management plans; Cormier pers. comm.).

<table>
<thead>
<tr>
<th>Forest Management Unit</th>
<th>Single-Tree Selection</th>
<th>Shelterwood</th>
<th>Clearcut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sudbury</td>
<td>136 ha/yr</td>
<td>1772 ha/yr</td>
<td>5121 ha/yr</td>
</tr>
<tr>
<td>Ottawa</td>
<td>607 ha/yr</td>
<td>1497 ha/yr</td>
<td>1146 ha/yr</td>
</tr>
<tr>
<td>Nipissing</td>
<td>1771 ha/yr</td>
<td>3081 ha/yr</td>
<td>3851 ha/yr</td>
</tr>
<tr>
<td>Northshore</td>
<td>2076 ha/yr</td>
<td>2138 ha/yr</td>
<td>4428 ha/yr</td>
</tr>
<tr>
<td>Algoma</td>
<td>3522 ha/yr</td>
<td>2862 ha/yr</td>
<td>3422 ha/yr</td>
</tr>
<tr>
<td>Algonquin</td>
<td>7322 ha/yr</td>
<td>5402 ha/yr</td>
<td>723 ha/yr</td>
</tr>
<tr>
<td>Bancroft-Minden</td>
<td>1992 ha/yr</td>
<td>921 ha/yr</td>
<td>654 ha/yr</td>
</tr>
<tr>
<td>Spanish</td>
<td>151 ha/yr</td>
<td>201 ha/yr</td>
<td>10605 ha/yr</td>
</tr>
<tr>
<td>Mazinaw-Lanark</td>
<td>1084 ha/yr</td>
<td>975 ha/yr</td>
<td>325 ha/yr</td>
</tr>
<tr>
<td>Temagami</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total area harvested</td>
<td>18661 ha/yr</td>
<td>18849 ha/yr</td>
<td>30275 ha/yr</td>
</tr>
<tr>
<td>Residue recovery per hectare (dt/ha)</td>
<td>2 dt/ha @ 50% implementation rate</td>
<td>10 dt/ha/yr</td>
<td>15 dt/ha</td>
</tr>
<tr>
<td>Total dt available</td>
<td>18661 dt/yr</td>
<td>188490 dt/yr</td>
<td>454125 dt/yr</td>
</tr>
<tr>
<td>Total, all silvicultural systems</td>
<td></td>
<td>661276 dt/yr</td>
<td></td>
</tr>
</tbody>
</table>
Appendix 4.5: Comparison of the delivered cost per dry tonne of wood chips and wood pellets produced from harvest residue for a range of post-preparation truck transport distances. Based on average post-preparation wood chip cost of $50 per dry tonne and an average payload of 21.75 dry tonnes and post-preparation wood pellet cost of $200 per dry tonne and an average payload of 32.63 dry tonnes (KPMG 2008; Cormier pers. comm.).

<table>
<thead>
<tr>
<th>Distance</th>
<th>Wood chip transport</th>
<th>Wood pellet transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 km</td>
<td>$100</td>
<td>$350</td>
</tr>
<tr>
<td>100 km</td>
<td>$125</td>
<td>$375</td>
</tr>
<tr>
<td>200 km</td>
<td>$150</td>
<td>$400</td>
</tr>
<tr>
<td>1,000 km</td>
<td>$400</td>
<td>$600</td>
</tr>
<tr>
<td>2,500 km</td>
<td>$850</td>
<td>$1000</td>
</tr>
<tr>
<td>5,000 km</td>
<td>$1,625</td>
<td>$1,675</td>
</tr>
<tr>
<td>10,000 km</td>
<td>$3,150</td>
<td>$3,000</td>
</tr>
</tbody>
</table>

Appendix 4.6: Cost of various sources of forest biomass after preparation.

<table>
<thead>
<tr>
<th>Source of biomass</th>
<th>Form of prepared biomass</th>
<th>Cost per dry tonne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mill residue</td>
<td>Wood chips, bark</td>
<td>$0-30</td>
</tr>
<tr>
<td>Mill residue</td>
<td>Wood pellets</td>
<td>$40-80</td>
</tr>
<tr>
<td>Roundwood or harvest residue</td>
<td>Wood chips</td>
<td>$40-80</td>
</tr>
<tr>
<td>Roundwood or harvest residue</td>
<td>Wood pellets</td>
<td>$150-200</td>
</tr>
</tbody>
</table>