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A PROCEDURE TO ASSESS WOODY BIOMASS SUPPLIES FOR A POTENTIAL ENERGY FACILITY

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ABSTRACT

Woody biomass from natural forests has substantial potential to be used as a feedstock for renewable energy production in the United States. Nonetheless, the availability for use in energy facilities is limited by various factors that can be classified as biophysical, social, and economic constraints. This study developed an analytical framework to estimate supply of woody biomass for a potential energy facility location that considers multiple constraining factors using publicly available data and models. The framework is intended to estimate potential supplies based on conducting regeneration harvests. For simplicity, harvests were assumed to be clearcuts done by and integrated harvesting operation that produce sawlogs, pulpwood and woody biomass. Forest Inventory and Analysis (FIA) data are used to represent the forest resource base. Biophysical, social, and economic constraints are assessed to estimate their impact on potential supplies of woody biomass available to the hypothetical energy facility. A case study of siting a hypothetical woody biomass energy facility in Williamsport, Pennsylvania is used to apply the developed framework.

The procedure to estimate potential supplies begins with an assessment of forest conditions within the energy facility's procurement region. A series of analyses are then conducted to provide information about the potential quantity of woody biomass that could be sustainably recovered by harvesting biophysically and socially accessible forestland. Potential costs, both roadside and delivered, for wood harvested from FIA plots are calculated to develop supply curves under different sets of constraint thresholds and scenarios on pulpwood-sized biomass utilization (PU). Results indicate that within a 100-mile radius of the hypothetical energy facility, standing inventory should continue to

increase and over-harvesting is not occurring. The supply curves developed for the base-case constraint thresholds and base-case PU scenario indicate that the maximum woody biomass quantity recovered from harvest would be 149.96 million dry tons under both biophysical and social constraints. Up to 69.00 million dry tons can be produced at roadside for a cost of $50 per dry ton. The estimated quantity of woody biomass delivered to the hypothetical energy facility was reduced substantially to 4.60 million dry tons at delivered cost of $50 per dry ton. This translates into about 97,000 dry tons of woody biomass that could be supplied each year at this cost level. As expected, most low-cost supplies came from within a 50-mile radius around the energy facility, indicating that delivered cost, which is largely a function of the transportation cost, limits the procurement range of affordable woody biomass for use by the energy facility.

Sensitivity analyses using different combinations of constraint thresholds to simulate high and low supply suggest that social constraints had a greater effect on potential supplies than biophysical constraints in both cases. In the PU scenarios, when all pulpwood-sized biomass was assumed to be used by traditional pulpwood users, at small quantities the supply of low-cost wood chips available for energy use is greater than when some pulpwood-sized biomass is assumed to be unused. This is because more woody biomass that can be used for energy is produced from the tops and limbs of pulpwood-sized biomass, which is a much cheaper material. When all pulpwood-sized biomass is assumed to be utilized for energy production, less low-cost supply would be available. Thus, when pulpwood demand is high and energy wood demand is low, the two uses are complementary. However, when larger quantities are demanded for energy the use of woody biomass for energy is competitive with conventional users of pulpwood.

The procedure proposed and demonstrated in this research can be utilized by organizations interested in assessing and evaluating potential supplies of woody biomass for a proposed energy facility location. Results from this study could be beneficial to policy makers or public agencies to develop better strategies to support the future development of woody biomass energy systems.

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Chapter 1

Introduction

1.1 Use of Woody Biomass for Renewable Energy

Concern about climate change, growing energy demand, increasing crude oil price volatility, and the need to secure and strengthen national energy independence have renewed interest in renewable energy sources in the United States. Renewable energy sources, including biomass, hydropower, wind, geothermal, and solar, provided roughly 9% of total energy consumption in 2011, up from 6.4% in 2005 (U.S. Energy Information Administration, 2012). Among various renewable energy sources, woody biomass is the second largest in the U.S. after hydropower, making up about 29% of total renewable energy supply in 2012 (U.S. Energy Information Administration, 2013).

Woody biomass can be utilized in a wide variety of applications in the energy sector. It can be burned directly (e.g., logs, woodchips) or turned into different types of combustors (e.g., bricks and pellets) or gas through gasification technology to generate electricity (Wilkerson & Perlack, 2009). Biomass, can be co-fired with coal and natural gas to generate heat and/or electricity in combined heat and power (CHP) facilities (White, 2010). At smaller-scales, woody biomass is also burned directly in heating systems for individual homes or institutions such as schools and hospitals (McDill, 2011). In addition to heat and power uses, woody biomass can be converted to cellulosic ethanol through hydrolysis and fermentation technologies for transportation fuel (Wilkerson & Perlack, 2009).

Woody biomass can be derived from a diverse resource base: 1) forestland, 2) agriculture, and 3) secondary residues and waste (U.S. Department of Energy, 2011). Woody biomass from forestland includes chips and roundwood procured from various forest management and silvicultural activities. These include commercial harvests for conventional forest products, thinning (e.g., precommercial thinning), regeneration harvests, and fuel reduction treatments. Woody biomass from agricultural resources includes chips from crops such as hybrid willow and poplar. The final category is residues and waste from pulping liquors, mill residues (i.e., sawmills and secondary wood processors), and urban waste (e.g., construction and demolition wastes). This research focuses on woody biomass from natural forests as a sustainable source of renewable energy.

1.2 Woody Biomass Supplies from Natural Forests: Opportunities and Issues

Various factors motivate interest in using woody biomass from natural forests for energy in the U.S. A key factor is resource abundance across the landscape. Forestland covers roughly one third (751 million acres) of the total land area of the U.S., and between 1953 and 2007 standing inventory more than doubled from 103 billion cubic feet to 248 billion cubic (Smith et al., 2009). The estimated net annual rate of growth of the growing stock inventory averaged about 2.8% annually between 1996 and 2007 (Smith et al., 2009).

Vast forest areas, and increases in growing stock suggest the potential for removing woody biomass for renewable energy production, while providing various ecological, social, and economic benefits. For example, many of the forests in the western U.S. are susceptible to catastrophic wildfires due to forest biomass overstocking. When wildfires occur under these conditions, they are much more severe and difficult to control, resulting in unwanted ecological and environmental degradations. Markets for woody biomass derived from fuel reduction treatments could offset the costs of these treatments and help reduce the unnaturally high wildfire hazards. In addition, markets for woody biomass could provide incentives for forestland owners to conduct beneficial silvicultural treatments such as thinnings and salvage harvests.

In the northeast and north-central forests of the US, there is substantial volume of wood in small, poorly formed, or commercially undesirable trees, referred to as “low-use wood.” The increasing quantity of these trees has been attributed to unsustainable harvesting practices such as diameter limit cutting that remove all merchantable trees larger than a specified diameter and high grading practices that remove more commercial species (Nyland, 1992; Kenefic & Nyland, 2005; Munsell et al., 2007). Traditional markets for such materials, such as pulp and paper mills, have declined in the past two decades, especially in Pennsylvania (Pennsylvania Hardwoods Development Council, 2008; Wiedenbeck et al., 2010). Therefore, developing a woody biomass markets could potentially offer financial compensation for landowners wishing to conduct sustainable forestry practices that utilize low-use wood. Furthermore, careful and planned biomass harvesting can complement other forest management and silvicultural objectives, including opening the forest canopy to stimulate desired species regeneration, improving forest health, and creating early successional wildlife habitat (e.g., wild turkey, woodcock and forest bird species). Apart from that, woody biomass markets present a new economic opportunity, especially for rural economic development and job growth, particularly in the logging industry (Perez-Verdin et al., 2008; Bailey et al., 2011).

In addition to opportunities and potential benefits, concerns exist about the potential negative environmental impacts of woody biomass harvesting for energy production. Negative environmental impacts associated with woody biomass production revolve primarily around the removal of deadwood and associated habitat, which could affect forest wildlife habitat and biodiversity, and deteriorate soil productivity due to nutrient loss. Other concerns include soil compaction from harvesting machineries and negative effects on water quality due to soil erosion and sedimentation in stream water (Burger, 2002; Lattimore et al., 2009; Evans & Kelty, 2010; Janowiak & Webster, 2010).

Beyond the potential negative environmental impacts, there is uncertainty about the potential of woody biomass to reduce carbon emissions through replacement of fossil fuels. In particular, the assumption that combustion of woody biomass is carbon neutral and that trees that are harvested for energy use produce no net carbon emissions because the emitted carbon will be reabsorbed by the new growing trees has been challenged (Searchinger et al., 2009). Empirical studies based on carbon accounting claim that increasing woody biomass removals from forests will both reduce the carbon stocks and carbon sink capacity, and because burning woody biomass temporarily emits more carbon into the atmosphere than fossil fuels per unit of energy produced, such burning will create initial excess carbon emissions in the atmosphere, also referred as biomass “carbon debt” (Manomet Center for Conservation Sciences, 2010; McKechnie et al., 2010). Over time, this carbon debt will be paid off by the regrowth of the harvested forest, but the time until the debt is repaid varies depending on several factors, including form of energy generated (i.e., electric, thermal or combined or heat and power), sources of woody biomass feedstock, type of fossil fuel displaced, and management intensity (Manomet Center for Conservation Sciences, 2010; McKechnie et al., 2010). On the other hand, Malmsheimer et al. (2011) argue that there is no net release of carbon into the atmosphere, particularly in the U.S., since the forests are being managed sustainably and forest inventories have been stable or increasing throughout the years.

1.3 Problem Statement

While the topic of carbon neutrality surrounding the harvesting of woody biomass for energy is being debated among policy makers, industries, researchers, foresters, and the public, current use of energy derived from woody biomass is relatively small, accounting for only 2% of total U.S energy use (U.S. Energy Information Administration, 2012). Even though various policy instruments have been established at both the federal and state levels to spur the use of woody biomass feedstock for energy (Aguilar & Saunders, 2010), development has been sluggish in some places due to barriers and challenges that vary locally and regionally (Sundstrom et al., 2012). For example, in the northeastern U.S., among the greatest challenges are uncertainties over whether non-industrial private forest landowners will engage in timber harvesting at all, let alone for woody biomass production (Benjamin et al., 2009). Other critical challenges discussed include the lack of a market, the high cost of harvesting and transporting woody biomass, overlapping demand for some of the forest products that would likely increase competition and price of the competing materials, immature woody biomass conversion technologies for the commercial production of biofuels, and social acceptance of woody biomass as clean energy, among others (Guo et al., 2007; Aguilar & Garrett, 2009; Benjamin et al., 2009; Becker et al., 2011; Sundstrom et al., 2012). Within this context, central to the development of an energy project that would utilize woody biomass from natural forests is the question of whether adequate and sustainable supplies of the material can be procured at a competitive cost. Often, business developers and wood procurement managers struggle in quantifying whether there are adequate woody biomass supplies within their proposed woodshed area. Therefore, an accurate and dependable method to assess woody biomass supplies from natural forests is necessary for the successful development of woody biomass energy.

To this end, numerous studies have attempted to estimate woody biomass supplies using various methodologies in order to help resource or procurement managers, business developers, public agencies, and policy makers make informed decisions. Typically, at least one of three types of constraining factors – biophysical, social, and economic – that affect woody biomass availability are considered. Biophysical constraints are factors that can limit harvesting potential due to physical landscape features, or due to site productivity. Social constraints include attitudinal and policy factors that influence harvesting options such as biomass harvesting guidelines, forests removed from timber production by legislative statues, forest landowner attitudes toward harvesting, and decreasing ownership sizes due to parcelization. Economic constraints are those that elevate harvesting and transportation costs above the level woody biomass purchasers are willing or able to pay.

With the various constraints that limit potential supplies, previous studies have focused on estimating the amount of woody biomass available subject to biophysical constraints (c.f.,Milbrandt, 2005; Perlack et al., 2005). This type of estimate is sometimes known as physical availability. A growing number of studies have attempted to include economic constraints such as roadside or delivered costs of woody biomass (c.f.,Langholtz et al., 2006; Wu et al., 2011; U.S. Department of Energy, 2011), and include data on competing woody biomass users (c.f.,Stasko et al., 2011) to estimate the amount of wood available at different price points. This type of estimate is typically known as economic availability. A few have looked at availability of wood harvested for sawlogs, pulpwood, biomass or other products considering both biophysical and social constraints (c.f.,Butler et al., 2010; Metcalf, 2010).

Because assumptions, methods and weight given to each of the constraining factors – biophysical, social, and economic – differ from one study to another, woody biomass estimates from one study may be difficult to compare with those from another. Nonetheless, each constraining factor has a different magnitude of impact on woody biomass availability. For example, studies that focus on biophysical and social constraints conclude that social constraints have a greater impact on availability of wood than biophysical limits, particularly in the northern U.S. (Butler et al., 2010). On the other hand, studies that give greater emphasis to economic constraints often demonstrated that the costs of delivering the materials from the forest to an energy facility determine the feasibility of the energy project (Langholtz et al., 2006). So far, little is known about the cumulative impact of biophysical, social, and economic constraints on woody biomass supplies for energy uses.

Previous studies have generally focused on larger geographical regions even though the constraining factors that affect woody biomass are frequently more local. For example, guidelines for harvesting biomass can differ between states and forest certification organizations (Evans et al., 2010) and may be specific to different forest types and conditions (The Forest Guild Biomass Working Group, 2010). Some factors, especially economic constraints, can be very site specific (e.g., harvest costs) and location-specific (e.g., transportation costs) (McDill, 2011), which eventually would affect the roadside and delivered costs of woody biomass. Furthermore, estimated costs could vary greatly depending on the location and operating environment where the material is harvested and transported. Therefore, aggregated supply functions based on larger, non-spatial geographical regions may not be appropriate for practical use, especially in the investment decision-making processes such as siting and sizing an energy facility in a particular location.

To date, little attention has been given to estimating woody biomass supply delivered to a specified energy facility location in a way that considers the full suite of constraints – biophysical, social, and economic – that affect availability. Yet, failure to include these constraints in woody biomass supply assessment, particularly in the Northern region where the majority of the forestland belongs to private forestland owners who have little intention of managing for timber production (Butler, 2008), could provide misleading information on potential supplies. An approach that utilizes publicly available data without using an overly complex model to assess woody biomass from natural forests can serve as a useful tool to the public, particularly woody biomass-based business developers, wood procurement managers, and forest planners.

1.4 Study Goal

The goal of this study is to develop an analytical framework for estimating sustainable supplies of woody biomass from natural forests for a hypothetical energy facility location, taking into account biophysical, social, and economic constraints that affect availability and using publicly available data and published literature. This framework is applied in a case study for siting a hypothetical woody biomass-based energy facility in Williamsport, Pennsylvania. Results from the case study are used to present and analyze the characteristics of potential supplies around the hypothetical energy facility as a result of combining biophysical, social and economic constraints into a common modeling framework. The resulting procedure can be used by organization interested in analyzing potential supplies of woody biomass within a proposed energy facility wood procurement area.

1.5 Dissertation Outline

This dissertation consists of five chapters. Chapter 1 presents background information and describes the research problem, research goal, and justification of the study. Chapter 2 provides a review of pertinent literature to define woody biomass for energy, it discusses elements for sustainable supplies, and it identifies factors that constraint availability as well as the methods employed by previous works to assess woody biomass supplies. Chapter 3 presents the analytical framework that describes how woody biomass supplies can be estimated and analyzed in the context of the three constraining factors – biophysical, social, and economic − that affect woody biomass availability for energy production. Chapter 4 describes in detail the procedure and methods used to implement the developed framework to assess woody biomass supplies for a case study of siting a woody biomass based energy facility in Pennsylvania. Chapter 5 presents and discusses the results from applying the analytical framework to the case study area. Chapter 6 provides concluding remarks, recommendations for future studies and discusses the contribution of the work.

Chapter 2

Literature Review

2.1 Introduction

This section surveys the existing literature and identifies research gaps relevant to assessing the supply of woody biomass. The chapter begins with a discussion of the various definitions of woody biomass used in previous studies and defines the term for the purposes of this study. Since sustainability is an important factor for woody biomass supply analysis, issues related to the impact of woody biomass harvests on the environment and the associated guidelines for sustainable forest harvesting will be outlined. In addition, sustainability elements identified in other studies to ensure a sustainable woody biomass supply for energy production will be discussed. The chapter also covers data sources used to estimate woody biomass supplies and the biophysical, social, and economic constrains addressed in previous studies in order to identify research gaps and guide the selection of variables and methods for this study. Finally, the overall conclusions of the review are presented.

2.2 Definition of Woody Biomass for Energy Use

There is no agreed upon definition of woody biomass. Often, the terms "biomass," "woody biomass," and "forest biomass" are used interchangeably in scientific papers and public agency reports (c.f.,Barry et al., 2007; Evans et al., 2010; Skog & Stanturf, 2011). Brown (1997) provides a general definition of forest biomass as "the total amount of aboveground living organic matter in trees expressed as oven-dry tons per unit area" (p.4). If the end use of the resources (i.e., energy) is incorporated, the definition is often limited to the parts of trees used for energy and derived from forestland (Skog & Stanturf, 2011). It must be noted, however, that the definition differs from one study to another.

The term forest biomass can be broad depending on the types of biomass sources included. For example, Perlack et al. (2005) in the Billion-Ton Study and Skog and Stanturf (2011) used a broader interpretation of forest biomass that included tree crowns and other tree components that are left in the forest as *logging residues* after commercial logging operations, low-quality or smaller diameter stems usually removed during thinning operations, unused mill residues from primary (e.g., sawmills residues) and secondary (e.g., pulping liquor) wood processing mills, and other sources such as urban wood waste, including urban wood residues, construction and demolition waste and tree trimmings. Likewise, White (2010) used the set of biomass sources found in Perlack et al. (2005) and Skog and Stanturf (2011), in addition to short-rotation woody crops (SRWC) sources. In an update report of the Billion-Ton Study, forest biomass is a primary resource consisting of logging residue generated from harvests of conventional forest products, including tops and branches of merchantable trees, cull trees, cull tree components, and also small diameter trees from thinning operations on timberlands (i.e., forestland capable of producing at least 20 cubic feet of wood per acre per year) or on other forestland (other than timberland) to reduce risks of wildfires and improve forest health, and unused wood from conversion of forestland to non-forest uses (U.S. Department of Energy, 2011). Also listed under primary resources is a new category known as “conventionally sourced wood,” and is defined by U.S. Department of Energy (2011) as “additional operations to provide pulpwood-sized roundwood for bioenergy applications” (p.17). Two additional operations considered were from “additional harvest” of pulpwood-sized trees from thinning operations and from a diversion of traditional pulpwood used to make pulp and panel products into energy use (U.S. Department of Energy, 2011). Unused wood residues from wood processing mills and urban wood waste were listed under wood waste resources while woody crops like hybrid poplar and willow grown for short rotations were grouped under cropland resources (U.S. Department of Energy, 2011).

Others have preferred to use a narrow definition and emphasized that woody biomass is the byproduct of forest operations and typically has low value. For example, Barry et al. (2007) defined woody biomass as “the byproduct of management, restoration, and hazardous fuel reduction treatments, including trees and woody plants (i.e., limbs, tops, needle, leaves, and other woody parts, grown in the forest, woodland, or rangeland environment)” (p.1). Evans et al. (2010), based on a review of existing biomass harvesting guidelines in the northeastern U.S., parts of Canada and northern Europe countries, used the terms “biomass” and “woody biomass” terms interchangeably, and defined biomass as “vegetation removed from the forest, usually logging slash, small-diameter trees, tops, limbs, or trees not considered merchantable in traditional markets” (p. 1). According to Evans et al. (2010), woody biomass has been historically referred to as materials that have low value and typically cannot be sold for higher value products such as timber or pulpwood; however, regional variation and market conditions could affect what is considered woody biomass material for energy use, but still it is likely to be from a low quality product.

Benjamin et al. (2010) suggested that forest biomass should be known as “energy wood” to describe any woody material derived from the forest for energy use. The reasons for this are twofold. First, it avoids the perception that forest biomass is a “waste” material that mostly comes from sources such as conventional logging operations residues (i.e., logging residues) and the non-merchantable stems. Second, “energy wood” has its own market (i.e., energy) and can be derived from any forest derived woody materials, even though current market conditions do not permit the use of material reserved for higher values products (e.g., pulpwood, sawtimber, and veneer log) (Benjamin et al., 2010). According to McDill (2011), the use of the term “residues” for woody biomass is misleading and could lead to erroneous analysis. This is partly because distinction between “residues” and “products” is determined by the market price. For example, when woody biomass prices are high enough to justify “residue” utilization, then so called “residue” becomes a product.

Based on the review of previous studies, for the purpose of this study, woody biomass is defined as any woody material from natural forest that has the potential to be used as an energy feedstock.

2.3 Sustainability Considerations for Extracting Woody Biomass from Natural Forests

Forests provide numerous goods and services as well as biological diversity that must be maintained and protected so that the future generations can derive the same benefits from the forests that we enjoy today. Therefore, extracting woody biomass from natural forests needs to be done sustainably while we “meet the needs of the present without compromising the ability of future generations to meet their own needs,” (World Commission on Environment and Development, 1987). The term” sustainability,” also frequently referred to as sustainable development, has various interpretations, but it typically incorporates three common elements: environmental, economic, and social concerns. While these three elements are important, in this section the environmental impacts of woody biomass harvests are the main focus.

Similar to harvesting of conventional forest products, harvesting woody biomass for energy raises concerns over potential adverse environmental impacts. One issue of particular concern with woody biomass harvesting is soil productivity. According to Burger (2002), nutrient deficiencies are much more common after woody biomass harvests (i.e., whole tree harvests) than after conventional harvests that remove only the tree boles. This is partly because a large proportion of the nutrients in trees are located in their twigs, bark and leaves (Burger, 2002). Intensive woody biomass harvesting could also remove significant dead wood from the site, which in the long term could affect forest soil organic matter (SOM), a vital component for soil productivity that promotes plant growth, through wood decomposition (Burger, 2002). In addition, use of heavy machinery and frequent re-entry to the logging site to collect woody biomass can cause physical site disturbance including soil compaction and soil erosion (Janowiak & Webster, 2010). Typically, soil compaction reduces soil porosity and increases bulk density, which decreases water-holding capacity and can impede root growth (Lattimore et al., 2009). Soil erosion, on the other hand, affects soil productivity by removing organic matter commonly found on top of the soil surface by water flows and runoff, especially on sloping terrain (Burger, 2002).

Another concern related to woody biomass harvesting is its impact on biodiversity and wildlife. Extraction of woody biomass, especially dead wood, can degrade or convert habitat for various flora and fauna uniquely present within an area (Janowiak & Webster, 2010). Dead wood, in the form of standing and down wood, is an essential component of forest biodiversity because it provides habitat for plants and animals including providing shelter and space for many wildlife species, and it offers an important food source for litter decomposers such as fungi, mosses and liverworts (Evans & Kelty, 2010). Thus, increased removal of dead wood during biomass harvests will likely impact species composition, diversity and abundance due to modification and removal of this habitat element.

Woody biomass harvesting without proper management practices can increase soil erosion and sedimentation into stream channels or other water bodies and can negatively affect water quality. High sediment yield in stream water can impact clean water supplies for human consumption or for recreational purposes, and it can also increase turbidity, which can harm aquatic organisms and habitats (Lattimore et al., 2009). In addition to soil erosion and sedimentation caused by harvesting activities, another common concern is the increase of nitrate-nitrogen concentrations, especially when herbicides are used to suppress vegetation regrowth during site preparation activities (Neary, 2002). Leaching of nitrate (N) into streams or groundwater can pose a health threat to organisms, especially to human beings, and increased levels of N can cause eutrophication and stimulate excessive growth of algae (Lattimore et al., 2009).

Given the potential adverse impact of woody biomass harvesting on the environment, efforts to establish woody biomass supplies from the forests have considered environmental sustainability criteria as a means to reduce negative impacts of biomass harvest on the environment. These criteria are typically applied by means of using voluntary Best Management Practices (BMPs) and biomass harvesting guidelines (U.S. Department of Energy, 2011). Typically, BMPs focus on prescribing practices for harvesting conventional products. Biomass harvesting guidelines impose additional restrictions on the amount of woody biomass to be retained and on the number of re-entries to the harvesting site in order to protect sensitive areas (e.g., shallow soils) including low nutrient sites and to minimize disturbance for future forest productivity (Skog & Stanturf, 2011). Several states in the U.S. have developed biomass harvesting and retention guidelines; however, due to differences in ecosystems, these guidelines differ greatly, but they share some common elements including dead wood and slash retention, wildlife and biodiversity (e.g., sensitive area and habitat inventory), water quality and riparian zones, soil productivity, and silvicultural system concerns (Evans et al., 2010). Among the most prominent elements discussed is dead wood, with differences in the amounts needed on the harvesting site. For example, Pennsylvania’s guidelines suggest retaining 15 to 30% of the “harvestable biomass” while Missouri suggests 33% retention (Pennsylvania Department of Conservation and Natural Resources, 2007; Missouri Department of Conservation, 2008). Wisconsin, on the other hand, calls for retaining 5 or more oven dry tons per acre of fine woody debris on site (Herrick et al., 2009). To supplement and enhance the existing biomass harvesting guidelines, the Forest Guild Biomass Working Group (2010) has developed forest biomass retention and harvesting guidelines for the forests and conditions in the northeastern U.S. The guidelines focus on retention targets for dead woody material (DWM) or snag trees and water quality and riparian zones. In general, the guidelines suggest retaining 1/4 to 1/3 of tops and limbs if more than one third of the basal area on a site is being removed, and they recommend 100 ft. riparian buffers around vernal pools to maintain a shaded forest floor and to avoid sources of sedimentation (e.g., ruts, bare soil).

While harvest retention criteria help to safeguard environmental sustainability, for an energy facility to remain economically feasible, knowledge about the sustainable and continuous supply of woody biomass is important. For this reason, a concept similar to sustained yield can be applied (Sherman, 2007; Kelty et al., 2008). Typically, this concept assumes that the sustainable biomass harvest should not exceed inventory growth.

2.4 Data Used in Woody Biomass Supply Assessment

In the United States, the most common data sources used to estimate woody biomass supplies from natural forests is from the Forest Inventory Analysis (FIA) program publicly accessible through the U.S. Department of Agriculture (USDA) Forest Service website (USDA Forest Service, 2012a). Various data options and reporting tools are available for the public to access. The two types of data most often used to estimate woody biomass quantities are the Timber Product Output (TPO) and FIA forest inventory databases (FIADB).

The TPO database provides county-level estimates of logging residues and other removals data. Logging residues refer to portions of growing stock trees left in the forest following conventional forest harvesting operations to produce wood products such as veneer logs, sawtimber, and pulpwood. Other removals, on the other hand, result from other forest operation such as precommercial thinning and forest clearing for development, agriculture or other non-forest purposes. The USDA Forest Service compiles logging residue and other removal information every five years; the most recent year was the RPA (Resource Planning Act) survey year 2012. The data are derived by linking information from primary timber product users' surveys, both industrial and non-industrial, harvest utilization studies and FIA measurement plot data. Many studies have utilized TPO data to assess woody biomass supplies (e.g., Milbrandt, 2005; Perlack et al., 2005; U.S. Department of Energy, 2011). Nonetheless, according to Manomet Center for Conservation Sciences (2010), the data have several drawbacks including outdated parameters and survey sampling errors, and inclusion of volume due to breakage or residual stand damage which could result in overestimation of logging residues.

The FIADB contains detailed measured, assigned and computed data on forest inventory from across the U.S. and its territories (Woudenberg et al., 2011). Measured data include attributes collected in the field such as tree diameters and heights, and plot slopes. In contrast, assigned and computed data include attributes populated in the office. An example of an assigned attribute includes county and ownership groups, whereas computed attributes include tree volumes and area expansion factors. The FIADB contains periodic inventory data from as early as 1968 and annual inventory data, initiated after 1999 (Woudenberg et al., 2011). The annual inventory data are derived using a standardized plot design and common data measurements across FIA work units. It also entails the use of a three-phase sampling scheme. Phase 1 uses remotely sensed data in the form of aerial photographs and satellite imagery for initial plot measurement and stratification. Phase 2 consists of field sampling to collect traditional inventory data (e.g., tree height, diameter at breast height (dbh) at an intensity of one plot, covering about a 1-acre sample area, within each 6,000-acre hexagonal sampling frame). Phase 3 is a subset of Phase 2 sample plots on which additional forest health indicator attributes are measured (e.g., tree crown condition, understory vegetation, soil attributes). Detailed information on the FIA sampling scheme, stratification methodology and plot design can be found in Bechtold and Patterson (2005).

The use of the FIADB in previous woody biomass supply studies is diverse. Some studies used the data to estimate woody biomass supply based on simulated thinning to reduce wildfire risk and to improve forest health (Fried et al., 2005; Skog & Barbour, 2006). Others used the data to assess the potential amount of woody biomass available for annual harvest (Sherman, 2007; Manomet Center for Conservation Sciences, 2010; Buchholz et al., 2011).

2.5 Constraining Factors Affecting Supplies of Wood from Natural Forests

Forest inventory data can be used to estimate the potential maximum supply of woody biomass from natural forests. Nevertheless, the estimated inventory occurs across a land base with varying biophysical, social, and economic constraints that limit potential supplies of woody biomass. This section reviews the various biophysical, social, and economic factors that can constrain the wood supply, whether it is harvested for sawtimber, pulpwood, energy, or other forest products.

2.5.1 Biophysical Constraints

Previous studies that assessed woody biomass supply have taken into account biophysical constraints (e.g., Fried et al., 2005; Sherman, 2007; Buchholz et al., 2011). Other studies have documented the effects of biological or physical constraints toward access to private forestland for wood harvesting, or on the amount of wood or timber available for harvest (Butler et al., 2010; Metcalf, 2010; Metcalf & Finley, 2011). The various biophysical constraining factors considered, can be grouped into logistics, forest productivity level, and tree size.

Logistical factors have been applied to account for areas that have operability challenges, including areas with excessive slopes, areas too close or too far from roads, and areas inundated by water. The presence of logistical factors has been determined either using spatial data (Metcalf, 2010; Metcalf & Finley, 2011) or directly from the FIADB (Fried et al., 2005; Butler et al., 2010; Buchholz et al., 2011). The thresholds used to remove wood supplies from harvest due to logistic factors vary from one study to another. Slope thresholds range between 40 to 50 percent and higher, usually based on the maximum operability of a ground-based harvesting system. Although skyline-harvesting could be used, such systems are much more expensive and therefore economically infeasible for a low-value product like biomass (Fried et al., 2005). For areas close to roads, Metcalf (2010) removed forestland areas within a 24-foot buffer on local and state roads. Other studies included FIA plots that were more than 2000 feet (Fried et al., 2005) or one mile and above (Butler et al., 2010; Buchholz et al., 2011) from the nearest road. Areas that are too wet represent another logistical constraint since harvesting areas with standing water are uncommon, especially in the northern region, although not impossible (Butler et al., 2010). These wet areas are generally identified based on the physiographic class code value “hydric” in the FIADB.

Forest productivity and tree size have also been assumed to affect the amount of wood available for harvest (Butler et al., 2010). Forestland with an annual productivity of below 20 cubic feet per acre is unlikely to be sustainably harvest, and is thus constrained (Butler et al., 2010). For tree size, forestland stocked primarily by trees less than 5.0 inch dbh (i.e., seedling/sapling) has been considered constrained (Fried et al., 2005; Butler et al., 2010).

2.5.2 Social Constraints

Previous work has found that social constraints are far more significant in limiting access to forestland or availability of wood for harvest than biophysical constraints, especially for states in the northern region (Butler et al., 2010; Metcalf, 2010; Metcalf & Finley, 2011).Various factors has been considered but variables and methods differ appreciably among studies and have focused primarily on family forestland or non-industrial private forest landowners (NIPFLs). Generally, social constraints to wood availability can be grouped into landowner management objectives and attitudes and behaviors toward harvesting, and the institutional framework including policy, legislation, and regulation.

2.5.2.1 Forest Landowners' Management Objectives and Their Attitudes and Behavior toward Harvesting

Forestland ownership patterns differ across the U.S., with the Rocky Mountain and Pacific Coast dominated by the public ownership including the U.S. Department of Agriculture Forest Service, the Department of Interior Bureau of Land Management, and other federal, state, county and municipal agencies. In contrast, much of the forestland in the Northern and Southern regions are controlled by private owners (Butler, 2008). It is important to note that forest landowner management objectives and their attitudes and behaviors toward harvesting vary greatly.

Public forests account for 44% (328 million acres) of all forestland (751 million acres) in the U.S. (Smith et al., 2009) and are managed by different government agencies for a range of objectives and governed by policies that are unique to each agency, and in some cases to each forest. Public forests can be managed intensively for timber production, ecological restoration, forest health maintenance (e.g., areas prone to wildfire or invasion by insects and disease), and other forest uses such as recreation. Also, some public forests receive little if any active management, including areas removed by public land use regulation (e.g., wilderness and roadless areas and streamside management zones). Empirical studies suggest that public forestland is less likely to be harvested than is private forestland (Wear & Flamm, 1993).

Private forestlands are owned by diverse owners ranging from the forest industry to non-industrial private forest landowners (NIPFLs). Industrial forest owners, also known as corporate owners, control one-third of the private forestland (138 million acres or 18% of all forestland in the U.S). This includes companies that manage forestland primarily for timber production, timber investment management organizations (TIMOs), and other companies that may or may not have forest management as their primary objectives (Butler, 2008). The NIPFLs hold the other two-thirds of the private forestland (285 million acres or 38% of all forestland). These owners include, individuals, couples, estates, trusts, nongovernmental organizations, clubs, associations, and other unincorporated groups (Butler, 2008). Family forests are a subset of NIPFLs, consisting of individuals, couples, estates, trusts, or other unincorporated groups. Collectively they hold 92% of the NIPFL's and 62% of the private forestland (264 million acres) (Butler, 2008). With such diverse NIPFLs, studies have documented that these landowners hold their land for various purposes (Finley & Kittredge, 2006; Butler, 2008). Research has also shown that reasons for owning forestland differ regionally (Butler & Leatherberry, 2004). For example, enjoyment of beauty and scenery is the most common reason for owning forestland in the western and the Northern regions, while timber production is a much more important reason in the South (Butler & Leatherberry, 2004).

Attitudes and behaviors of NIPFLs towards forest harvesting have been discussed at great length. Young and Reichenbach (1987) showed that landowner attitudes toward timber harvesting (i.e., intention to harvest) are related to their beliefs from past experience. Kuuluvainen et al. (1996) found that forest ownership objectives correlate with owners' harvesting behavior. Factors that have been found to affect landowners' decisions to harvest include forest characteristics (e.g., growing stock volumes, tree species), timber prices, and landowner characteristics (e.g., age, income, job) (Dennis, 1989; Kuuluvainen et al., 1996). Another factor that can affect harvesting is the number of acres owned (McDonald et al., 2006). A major concern related to family forests is the rate at which they are being subdivided into smaller parcels (Butler, 2008); which will become an obstacle in securing future wood supplies as smaller tracts infer higher management and harvesting costs (Cubbage et al., 1989; Greene et al., 1997). Typically, harvesting costs increase rapidly on tracts below 20 acres and often become economically prohibitive below10 acres except for tracts that have high quality timber (Cubbage, 1983; Cubbage et al., 1989; Kittredge et al., 1996).

In recent years, studies have also considered landowners' attitudes toward harvesting biomass. Joshi and Mehmood (2011) looked at the willingness of NIPFLs to supply woody biomass for bioenergy in the southern states including Arkansas, Florida and Virginia. They found that landowners are more likely to supply woody biomass when they have wildlife management objectives. In addition, they found that younger landowners owning large forest tract are more willing to supply biomass (Joshi & Mehmood, 2011). Another study conducted in Lee County, Alabama found that willingness to supply woody biomass is positively correlated with the number of acres owned, having a steady biomass market, and opportunities to contribute to local economic development (Paula et al., 2011). Not surprisingly, a factor like "the right price" or a price that is at least equivalent to the existing pulpwood price would strongly affect the southern NIPFLs willingness to supply woody biomass (Joshi & Mehmood, 2011; Paula et al., 2011). In contrast, Markowski-Lindsay et al. (2012) conducted a study to understand the willingness of family forest owners in Massachusetts to harvest woody biomass, and they found that the likelihood of harvesting is quite low and the supply is inelastic with respect to price.

Studies that have assessed the supply of wood with respect to social constraints have identified attitude and behavior of NIPFLs as constraining factors (Butler et al., 2010; Metcalf, 2010; Metcalf & Finley, 2011). Butler et al. (2010) measured owner attitudes toward harvesting based on ownership objectives, harvesting experience and harvesting intentions variables taken from National Woodland Owner Survey (NWOS) responses (Butler et al., 2005). Metcalf (2010) used owner harvest opposition and reports of previous commercial harvest as measures of harvest attitudes and behavior taken from a survey of Pennsylvania NIPFLs to investigate access to private forest land in two counties in Pennsylvania, Berks and Huntingdon. He concluded that private forest landowners in Berks County, which was categorized as a developed or developing county, are more opposed to harvesting and less likely to harvest timber compared to landowners in Huntingdon County, a less developed county. In addition, he found that landowners with relatively small acreages are more opposed to harvesting and less likely to conduct a commercial harvest.

2.5.2.2 Institutional Issues Related to Woody Biomass

Institutional policies and regulation can support or limit woody biomass availability (Skog & Stanturf, 2011). These actions are usually in the form of legislation at the federal, state, or local levels that establish public policy interventions or forest practices guidelines.

Various U.S. policies have been established to promote the use of woody biomass for energy production. Policy instruments established to promote woody biomass specifically for power production and consumption include: renewable energy mandates, tax credits and grants for renewable electricity, rural energy grants, tax credits for residential biomass energy, green power purchase goal, government bonds, and state-level energy programs (Aguilar et al., 2011). Legislation established to promote the production of biofuels from woody biomass, includes the Energy Independence and Security Act of 2007 (EISA 2007). This act mandated increased use of biofuels through the renewable fuel standards, and the Biomass Crop Assistance Program (BCAP), which was created as part of the Food, Conservation and Energy Act of 2008 to assist owners and operators of agriculture and NIPFs who wish to be involved in biomass energy program (Aguilar et al., 2011).

While policy is an important instrument to promote the expansion of woody biomass energy, policies can also limit woody biomass (Skog & Stanturf, 2011). An analysis by Skog and Stanturf (2011) based on USDA Forest Service (2009) studies, for example, indicates that the EISA 2007, which promotes and sets renewable energy target mandates, excludes use of woods derived from federal lands for energy use. Interestingly, they also point out that the 2008 Farm Bill placed different restrictions, allowing woody biomass derived from fuel reduction treatments or forest health improvement activities from federal lands for energy production. This discrepancy in defining the sources of woody biomass materials that can be used for energy production in many legislation documents is apparent and is currently under discussion (Skog & Stanturf, 2011).

Society, through state government, has directly influenced forest harvest practices guidelines that affect the amount of woody biomass available for energy production. Forest biomass harvesting guidelines place more restrictions on what can be harvested, how much can be removed, where harvesting is limited, and to some extent are similar to Best Management Practices, developed particularly for harvesting conventional products. These guidelines were specifically developed to promote sustainable harvesting and to protect forest ecosystems and the environment. Usually, woody biomass guidelines are developed to address common issues, including dead wood and slash retention and riparian buffer zones. Previous work that assesses social constraints toward wood availability has counted riparian buffer requirements as a constraint (Butler et al., 2010).

2.5.3 Economic Constraints

Economic constraints can limit the potential supply of woody biomass from natural forests. These constraints hinge on the stumpage price, harvesting costs, transportation costs and competing users for materials. The combination of costs with the potential woody biomass quantity, sometimes known as economic availability, can be expressed using either roadside costs or delivered costs. Typically, roadside costs consist of stumpage and harvesting costs while delivered costs include the roadside cost and the cost of transporting the material from the forest to the production facility. Several studies have considered economic availability, especially the delivered cost of woody biomass, as major determinant affecting the feasibility of energy projects (Langholtz et al., 2006; Aguilar & Garrett, 2009; Galik et al., 2009). In addition to economic availability of woody biomass, analysis of competing users of woody biomass material is essential for a a complete assessment of the potential supply for a woody biomass energy facility project in a market economy (Sperling, 1984).

2.5.3.1 Stumpage Costs

Stumpage is the price paid to a forest landowner for the right to harvest some or all of their forest. Typically, stumpage cost is a relatively small part of the total delivered cost of woody biomass as compared to costs of harvesting and transportation (McDill et al., 2011), and typically it is lower than the stumpage cost for conventional products such as sawtimber (Perez-Verdin et al., 2009). Stumpage cost assumptions in previous woody biomass studies differ from one study to another. For example, Galik et al. (2009), in a study that explored the potential supply cost of woody biomass from three Southern states (i.e., South Carolina, North Carolina and Virginia), assumed stumpage costs of zero to $1 per green ton of biomass. Perez-Verdin et al. (2009), in a study that assessed woody biomass availability in Mississippi, used a stumpage cost of $4 per dry ton for the northern part of their study and $7 per dry ton for the south part. These prices were based on Timber Mart-South reports. The Manomet Center for Conservation Sciences (2010), on the other hand, used stumpage prices ranging from $1 to $2 per green ton, which, according to the authors, are prices commonly received by Massachusetts landowners. In the Billion-Ton update report, stumpage costs for private forestland were assumed to be

$4 per dry ton, and these were assumed to increase up to 90% of the pulpwood stumpage price if all the available logging residues are used (U.S. Department of Energy, 2011). For federal land, the study assumed no stumpage cost, as much of the harvesting activities related to fuel treatment or restoration activity. McDill et al. (2011), in a woody biomass harvest cost study conducted in Central Pennsylvania, used a stumpage cost of $3 per green ton.

2.5.3.2 Woody Biomass Harvest Costs

Estimating woody biomass harvesting costs can be challenging because harvest costs can vary depending on many factors including stand characteristics, silvicultural treatment methods, equipment or machinery used, harvesting system, scale of operations, costing method used, and human factors, among other things (Asikainen et al., 2002; Rummer, 2008).

Harvest costs are strongly dependent on the site conditions, largely because machine productivity is affected by factors such as the terrain or slope condition, average skidding distances, and the material volume and quality (Asikainen et al., 2002). In a conventional and biomass logging cost and production study on a variety of stand types and tract sizes, Cubbage and Greene (1989) found that tract volume, tree diameter, and hardwood percentage significantly affect harvest cost. The impact of these factors, however, varies depending on the harvesting machinery used (Cubbage & Greene, 1989).

Harvesting woody biomass can be costly, especially if the primary operation is to remove only woody biomass (i.e., small diameter trees) since in that case all fixed and administrative costs must be assigned to the biomass produced (Asikainen et al., 2002).Given the low market value of woody biomass and the high cost of harvesting, harvest operations often result in more cost than revenue (Han et al., 2004). In recent years, the use of integrated harvests, where all products, including timber, pulpwood, and biomass are harvested together, has gained attention as it offers the opportunity to reduce harvesting costs (Hudson & Mitchell, 1992; Hudson, 1995). There are two types of integrated systems: one-pass and two-pass. In the-one pass integrated harvesting system, all wood products, including woody biomass, are harvested in a single operation. In a two-pass system, the harvested woody biomass is piled and left in the forest to dry while the higher-value timber is extracted. Typically, the operation to collect woody biomass left in the forest is conducted several weeks after the commercial timber operation (Wilkerson & Perlack, 2009). Previous work evaluating integrated harvesting systems has determined that the one-pass harvest system results in higher productivity and recovery efficiency, and thus lower harvesting costs (Stokes & Watson, 1988; Han et al., 2004). A one-pass integrated harvesting system can involve two types of residue collection systems: whole-tree and cut-to-length. In the integrated whole-tree harvesting system, trees are felled mechanically using a feller-buncher or manually using a chain saw and a skidder machine is used to transport felled trees, with tops and limbs intact, to the landing area. The integrated cut-to-length system usually involves a highly mechanized approach in which a harvester is used to fell, delimb and cut trees into specified lengths at the stump and a forwarder is used to transport both merchantable and non-merchantable parts of trees to the landing area. With regard to harvesting costs, Adebayo and Johnson (2007) compared the two types of integrated residue collection systems and found that whole-tree harvesting systems had lower production costs than the cut-to-length system because of higher productivity.

Given the many factors that can affect harvesting costs, generalization about harvesting costs for woody biomass is difficult. This problem can be partly remedied by using harvest simulation cost models to predict harvesting cost for combinations of various harvesting systems and stand conditions. Unfortunately, few harvest simulation cost models have been developed specifically for harvesting woody biomass for a wide range of conditions, especially in the Northern U.S. Most woody biomass supply analyses, especially studies that have employed FIA plot data, have used the Fuel Reduction Cost Simulator (FRCS) (Fight et al., 2006), to estimate average harvest costs for woody biomass (Fried et al., 2005; Barbour et al., 2008; Becker et al., 2009; U.S. Department of Energy, 2011). FRCS is a spreadsheet-based harvest cost model derived from an earlier model called STHARVEST (Hartsough et al., 2001) that was originally developed in the western U.S., specifically for estimating fuel reduction treatment costs. The difference between these two models is that FRCS allows consideration of multiple products (logs and chips) and the multiproduct systems include chipping tops, limbs, and small trees (Fight et al., 2006). In 2008, FRCS was revised by (Dykstra et al., 2009) to include Southern and Northern (north-central and northeast) variants.

Another challenge in accurately estimating woody biomass production costs, especially in integrated harvesting system is selecting between two harvest costing approaches: marginal costing and joint product cost. The marginal costing approach assumes that woody biomass is a byproduct of harvesting the conventional products (e.g., sawlogs and pulpwood) and typically assigns little or zero cost to woody biomass production (Puttock, 1995; Saunders et al., 2012). The joint product cost approach, on the other hand, suggests that fixed and shared production costs should be allocated between conventional and woody biomass (Puttock, 1995). Although there is some debate on which costing method should be used in estimating woody biomass cost in an integrated harvest system, Puttock (1995) observed that the joint product cost more accurately reflects the "real" cost of producing woody biomass than the marginal cost. Nonetheless, integrated harvest studies have given little attention to using this approach in estimating woody biomass supplies (Puttock, 1995; Kellogg et al., 2006), and thus little has been done to develop woody biomass harvest cost models that use this approach.

2.5.3.3 Transportation Costs

Various methods can be used to transport woody biomass from the harvesting site to the end-use facility, including roads, railways, and water. Of these three, hauling the material on roadways using trucks or chip vans is the most common method used in the U.S. (Wilkerson & Perlack, 2009). Woody biomass is often transported in comminuted form, i.e., as wood chips or mulch, since this allows higher density loads (Jenkins & Sutherland, 2009) and can reduce the moisture content by 5 to 20 percent (Wilkerson & Perlack, 2009). Thus, some pretreatment at the harvest site can significantly reduce total delivery costs.

Woody biomass transportation costs are location-specific, as they depend on the distance between the location of the harvest site and the energy facility, the available transportation network, and other factors that can add significantly to the delivered cost of woody biomass. According to Perez-Verdin et al. (2009), transportation costs could account for 50–60 percent of total delivered cost of woody biomass, and these costs increase significantly as the procurement distance increases. In Nordic countries, half of the delivered cost of forest residues to heating plants is transportation over an average haul distance of 60 km (37.3 miles) (Andersson et al., 2002). A variety of transportation cost models have been developed specifically for assessing the cost of transporting biomass, including the Forest Residue Transportation Costing Model v.5 (USDA Forest Service Southern Research Station, 2005), the Biomass Transportation Model (BIOTRANS) (Han & Murphy, 2011), and the BioSAT Trucking Model (Purdue et al., 2013).

2.5.3.4 Competing Users of Woody Biomass

Having a consistent supply of woody biomass at a competitive price is critical for an energy facility to be viable in the market economy. Wood has a wide variety of applications, and several industries consume wood as their main feedstock, including lumber, panel products, and pulp and paper mills. While woody biomass energy facilities generally would not compete for high quality sawlogs, they could potentially compete with other industries that use lower-value wood such as oriented strandboard (OSB) and pulp and paper mills. Benjamin et al. (2009) noted that competition for woody biomass could occur, especially when wood procurement areas overlap, which can drive up the stumpage prices and, in the short term, harvesting costs. Sperling (1984) highlighted that competing wood user is an important factor that should be considered when analyzing the attractiveness and viability of a proposed energy facility investment.

2.6 Conclusions

This chapter reviewed the relevant literature pertaining to woody biomass supply studies with a focus on issues and factors that constrain availability. It began with a discussion of the terms used to define woody biomass, which then served as a basis to present the definition on woody biomass used in this study. Next, issues and concerns surrounding sustainable woody biomass harvest were highlighted with an emphasis on its potential adverse impacts on the environment. Various voluntary BMP’s and biomass harvesting guidelines have been developed to guide both timber and biomass harvesting to help minimize the impact of harvesting on the environment. Previous woody biomass supply studies have set operational sustainability criteria, which mostly have relied on the amount of harvestable biomass to leave in the forest for ecological sustainability reasons. The review also found that the FIADB is a critical data source for estimating woody biomass supplies. Finally, a review of various factors that constrain woody biomass availability identified variables that significantly affect biomass availability. Methods used in previous studies are recognized and were used as a guide for developing the analytical framework presented in the next chapter.

Based on the review, studies that focus on biophysical and social constraints have concluded that social constraints have greater impact on wood or forestland area available for harvest than biophysical constraints, especially in the Northern U.S. On the other hand, studies that concentrate on the economic supplies of woody biomass tend to conclude that economic constraints are more crucial in determining the feasibility of wood energy projects. While the literature on woody biomass supplies from natural forests is extensive, noticeably absent from the literature are studies that link all three factors – biophysical, social, and economic – into a common analytical framework. Yet, failure to recognize these three types of constraints in any woody biomass supply assessment will produce biased estimate of availability, and hence potentially create misleading information on supplies especially for the development of a woody biomass-based energy facility.

Chapter 3

Analytical Framework

Based on the literature review presented in Chapter 3, an analytical framework for estimating woody biomass supplies that considers biophysical, social and economic constraints is proposed (Figure 3-1). It will be used to present and analyze potential supplies that account for biophysical, social and economic constraints for a case study of siting a woody biomass energy facility in Pennsylvania. An objective/constraint of this study was to use, as much as possible, models and data that would be readily available and accessible to most analysts (i.e., business developers, wood procurement managers) so that the framework is easily replicated by others. Thus, approach used in this case study depends on publically accessible U.S Department of Agriculture Forest Service data and models.

Woody biomass supplies from natural forests can be produced through a variety of forest management and silvicultural activities. The case study presented in this work estimates woody biomass supplies assuming that only even-aged regeneration harvest systems based on clearcutting are used. As with nearly all woody biomass supply studies in the U.S., Forest Service FIA data are used to estimate supply within the procurement region of the proposed hypothetical woody biomass energy plant. Biophysical and social constraints are modeled as factors that limit forestland area accessible for harvest, whereas economic constraints are considered by estimating the cost of obtaining woody biomass material from each FIA plot at roadside and delivering it to the energy facility.

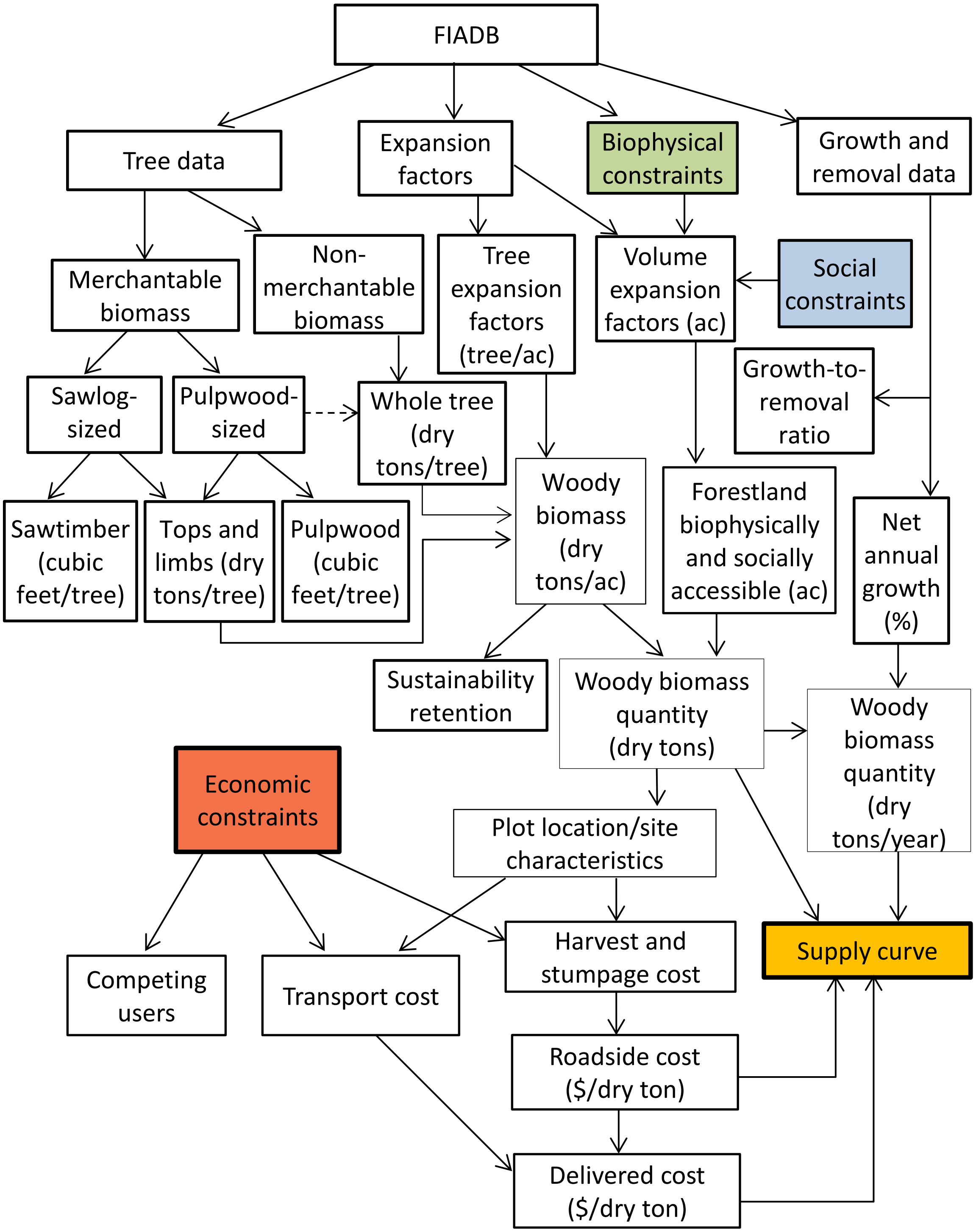

Figure 3-1: Analytical framework to estimate woody biomass supplies from natural forests for a potential energy facility location

Prior to estimating woody biomass supplies for a proposed energy facility, it is important to assess the overall resource condition and harvest sustainability within the facility's expected procurement region based on growth and removals data from the FIADB. Timber productivity measured by net annual rate of growth and harvest level sustainability measured by growth-to-removal ratio can be used for this assessment.

Next, the potential quantity of woody biomass that can be recovered from a plot is estimated by simulating a clearcut regeneration harvest on each FIA plot using an integrated harvest system, in which both woody biomass and conventional products (i.e., sawlogs and pulpwood) are harvested together in a single operation. Sources of woody biomass from integrated harvests include tops and limbs of merchantable trees that either meet sawlog or pulpwood-sized diameter and quality specifications[1] and non-merchantable biomass which consists of trees that are classified as saplings and non-growing stock trees (i.e., cull, rough and rotten trees) that can be whole tree chipped. At this point, information on woody biomass (tops and limbs and whole tree chips) for each FIA plot is expressed in dry tons per tree[2]. To scale the estimated amount per tree on a plot to a per-acre basis, the per-tree amount is multiplied by the respective tree expansion factor (Woudenberg et al., 2011). It is important to note that pulpwood-sized biomass can also be harvested and whole-tree chipped for energy use[3]. Nevertheless, the availability

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[1] Detailed explanations of diameter specifications for merchantable biomass and of the scenarios of pulpwood-sized utilization are provided in the methodology section.

[2] The green cubic-foot volume is converted to oven-dry tons using equation developed by Miles and Smith (2009).

[3] As noted in many studies (e.g., Pennsylvania Hardwoods Development Council, 2008; Wiedenbeck et al., 2010; U.S. Department of Energy, 2011), the number of traditional users of pulpwood-sized biomass has been decreasing in the region, especially pulp and paper mills. This suggests that considerable supply could be available for energy use from pulpwood-sized biomass.

would depend on current and projected consumption by traditional users of this material to make pulp for paper or composite panel products. Therefore, in this study, the supply of woody biomass is modeled using three pulpwood biomass utilization scenarios based on assumptions about utilization rates of pulpwood-sized biomass by traditional pulpwood users and the energy sector. The results are used to assess the impact on woody biomass supplies when different rates of pulpwood-sized biomass are used. Because harvesting woody biomass from natural forests has potential negative impacts on the environment, especially on soil productivity, wildlife and biodiversity (Burger, 2002; Lattimore et al., 2009; Janowiak & Webster, 2010), the estimated per-acre potential amount of woody biomass is reduced for ecological sustainability reasons (U.S. Department of Energy, 2011).

Next, acres of forestland area represented by each FIA plot as expressed by its expansion factor are modified as a function of biophysical and social constraints. In this analysis, when biophysical and social constraints apply to a given FIA plot, the number of forested area (acres) represented by a given plot is systematically reduced using a reduction formula adapted from Butler et al. (2010). Biophysical constraints are factors imposed by physical features of the landscape that can limit ground harvest operations (e.g., steep slope and physiographic class) and factors related to the inherent productivity of each plot’s site, which relate to productive capacity (i.e., capable of producing 20 cubic feet per acre per year) that can affect whether the forestland area represented by that plot can be managed sustainably for timber production.

Riparian buffers are considered a social constraint because society directly determines harvesting options expressed through voluntary BMPs and woody biomass harvesting guidelines. Reserved forestland is also considered a social constraint because legislation has set aside such. These areas are typically subject to various use regulations that preclude harvesting. In addition, the size of a forest holding is considered a social constraint because research has shown (Metcalf, 2010) that owners of smaller parcels are more opposed to harvesting timber and less likely to conduct a commercial harvest. This could also be an economic constraint because the economics of harvesting are less attractive on smaller parcels (Cubbage, 1983) which would limit landowner options to conduct harvest operations. The final variable considered a social constraint is landowner attitudes toward harvesting. Previous research has shown (Butler & Leatherberry, 2004; Butler, 2008) that many NIPFLs, especially in the northern U.S., hold their forestland for non-timber purposes such as aesthetics and privacy values and have no intention to sell timber. Thus, access to harvesting on these private forestland sites would be limited. In this analysis, attitude toward harvesting that limit access is based on opposition to harvesting derived from Metcalf (2010) and (Metcalf & Finley, 2011).

Economic constraints include estimating roadside and delivered costs. Roadside costs include the cost of harvesting woody biomass on each inventory plot plus the stumpage price. The delivered cost is a combination of roadside costs and the cost of transporting woody biomass from the roadside to an energy facility. Transportation costs are calculated assuming that all of the acres represented by a plot are located at the plot[4]; since some of those acres will be closer to the facility than the plot and others will be farther than the plot, this assumption should not introduce any bias into the analysis.

The combination of forestland area (acre) accessible for harvest (as modified by the various constraints) with the estimated woody biomass quantity suitable for energy use (dry tons/acre) generates an estimate of woody biomass quantity (dry tons) that is both biophysically and socially available for energy production on each plot. Then, for each plot, the associated roadside and delivered costs are combined with the estimated quantity to produce a supply curve to analyze characteristics of supplies with respect to biophysical, social and economic constraints. Also, the estimated woody biomass quantity (dry tons) can be converted into annual supply. For this reason, the estimated woody biomass quantity (dry tons) available at different price points is multiplied by the estimated timber annual rate of growth within the proposed procurement region.

Another economic constraint considered in the analytical framework is the presence of competing industries that use similar wood materials. To address this, an overlapping procurement area analysis among competing users could be conducted[5] to assess the overall attractiveness of siting woody biomass energy facility at a proposed location.

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[4] FIADB provides coordinates for every plot location, but these are not precise due to "fuzzing and swapping" of actual plot location to ensure privacy of private landowners. Since these changes are random, they should not bias the results of the analysis

[5] Due to time constraints, the analysis of competing users of woody biomass is not included in this study. However, this analysis is retained in this framework.

Chapter 4

Methods

4.1 Introduction

This chapter describes the methods to estimate woody biomass supply for a hypothetical energy facility location using the analytical framework presented in chapter 3. Because delivered costs can only be assessed with regard to a specific location, a case study siting a hypothetical woody biomass energy facility located in Williamsport, Pennsylvania, serves to demonstrate the framework. The procedure to estimate woody biomass supplies for a potential woody biomass energy facility consists of six major analyses:

1. Evaluate forest resource sustainability based on growth and removal rates,
2. Estimate the potential amount of woody biomass produced per acre using a clearcut harvest,
3. Estimate the potential forestland area biophysically and socially accessible for harvesting,
4. Estimate roadside and delivered costs for woody biomass,
5. Develop supply curves, and
6. Analyze competing users of woody biomass.

4.2 Overview of the Case Study Area

The case study area in Williamsport, Pennsylvania was selected because of several factors: 1) the surrounding area is heavily forested and, for the most part, has low population densities, suggesting the land is available for harvesting, and 2) it has an existing logging industry and several wood-based industries. Nevertheless, the procedure developed should be applicable to any proposed energy plant location that has similar data. The hypothetical center point coordinates for the plant location are latitude 41° 14’40” N and longitude 77°1’17”W (41.247,-77.019).

Conventional wood-based manufacturing facilities procure their wood supply from within a procurement zone approximated by a concentric circle radiating from their facility (Brewington & Earl, 2000). This approach was used to describe woody-biomass supplies around the hypothetical energy plant location. Four procurement circles centered on the energy facility were considered: 1) a 50-mile radius, 2) a doughnut-shaped area with a 50 to 75-mile radius, 3) a doughnut-shaped area with a 75 to 100-mile radius, and 4) all areas within a 100-mile radius.

State and county boundary datasets for Pennsylvania were acquired from the Pennsylvania Spatial Data Access (PASDA) website (PASDA, 2013) and for New York State from the New York State Geographic Information System (GIS) clearinghouse website (NYSGIS Clearinghouse, 2013). All spatial datasets were processed using ESRI’s ArcGIS software (Version 10.1). A current census interval (2006-2010) of Forest Inventory and Analysis Database (FIADB) version 5.1 (Woudenberg et al., 2011) for

Pennsylvania and New York was obtained from the United States Forest Service (USFS) FIA website (USDA Forest Service, 2013a) to describe current forestland area, ownership, and forest-type groups within the procurement region.

Figure 4-1 shows the location of the hypothetical Williamsport, PA energy facility with three procurements radii at 50, 75, and 100 miles to define the four procurement areas around the energy facility. The figure also depicts the boundaries of the counties included in the zones defined by the procurement radii. A total of 47 counties from Pennsylvania and 14 counties from New York State are at least partially within the 100-mile radius around the hypothetical energy facility. County names for each procurement region are provided in appendix Table A-1.

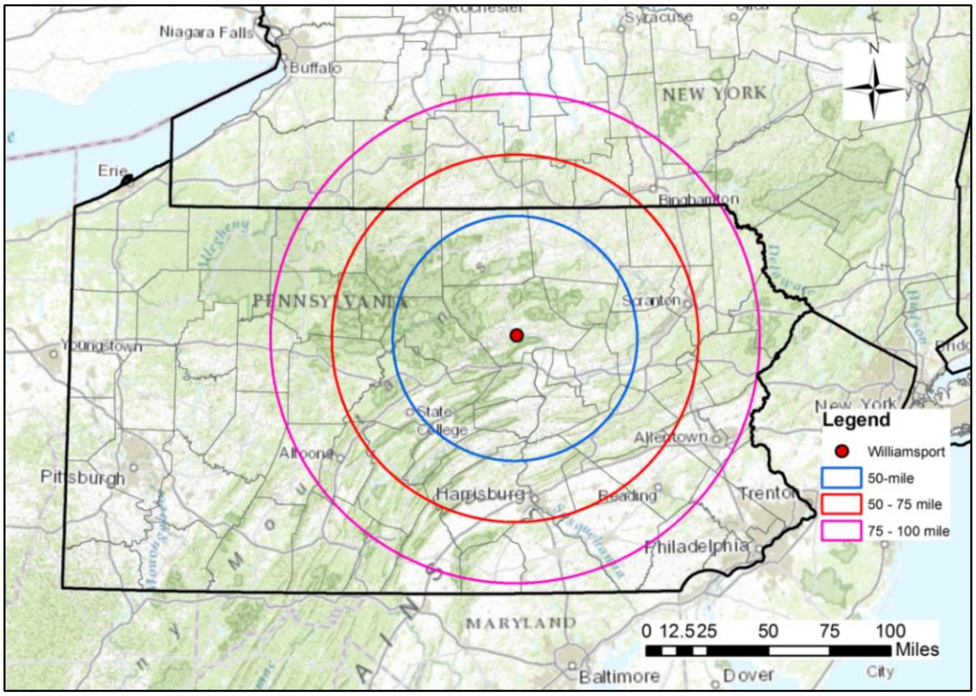


Figure 4-1: Map of the hypothetical woody-biomass-based energy facility located in Williamsport, PA, with three radii at 50, 75, and 100 miles used to define four procurement areas around the energy plant location.

The estimated forestland area within the 100-mile region is 12.35 million acres, with the majority (68%) belonging to private owners (Table 4.1). The public forestland (32%) is primarily state-owned. The portion of the forestland that is private is particularly high in the 50 to 75-mile (69%) and in the 75 to 100-mile (76%) procurement zones. The ownership pattern in the 50-mile zone is more evenly distributed, with private ownership of 56% of the forestland and 44% being publicly owned.

Table 4-1: Estimated forestland acres by ownership for the 50-mile region, the 50 to 75-mile region, the 75 to 100-mile region, and total 100-mile region around energy plant located in Williamsport, PA.

Procurement region (Miles)	Federal (Acres)	State (Acres)	Local (Acres)	Private (Acres)	Total (Acres)	% Private	% Public
50	-	1,408,753	79,038	,906,039	3,393,830	56%	44%
50-75	13,881	1,059,233	130,662	2,723,537	3,927,313	69%	31%
75- 100	230,323	799,355	182,368	3,815,848	5,027,895	76%	24%
Total 100-mile region	244,204	3,267,342	392,068	8,445,424	12,349,038	68%	32%

Across the 100-mile region, the majority (52%) of forestland is in oak dominated forest types such as oak-hickory, oak-pine, and oak-gum-cypress (Table 4-2). The second largest forest type in the region is “northern hardwoods” (42%), which includes maple-beech-birch, elm-ash-cottonwood, and aspen-birch. Softwood dominates only 5% of forestland in the region, which is mostly pine and eastern hemlock. A very small portion (1%) of the forestland is classified as “non-stocked” but still considered forestland (land at least 10% stocked by forest trees). A common situation where forests are classified as “non-stocked” is when the forest has just been clearcut prior to the inventory. Most of these areas will regenerate to some type of stocked condition over time.

Table 4-2: Forestland acres by aggregate forest type for the 50-mile region, the 50 to75-mile region, the 75 to 100-mile region, and the 100-mile region around energy facility located in Williamsport, PA.

Procurement region (Miles)	Oak Dominated (Acres)	Other Hardwoods (Acres)	Softwood (Acres)	Non-stocked (Acres)	Total (Acres)
0-50	1,899,924	1,296,119	186,021	11,766	3,393,880
50-75	2,194,446	1,545,726	167,296	19,844	3,927,313
75-100	2,332,160	2,353,395	311,479	30,861	5,027,895
100-mile region total	6,426,529	5,195,241	664,796	62,472	12,349,038
Percent	52%	42%	5%	1%	100%

4.3 Evaluate Forest Resources Condition Based on Growth and Removals

Before estimating the potential supply of woody biomass for the hypothetical energy facility, the first step is to evaluate current resource harvest levels relative to removal rates to evaluate whether the supply is sustainable over the long run. Net growth, the growth in tree volume minus the mortality, and removals (i.e., volume of forest inventory removed during timber harvesting or cultural treatments) are useful indicators of timber productivity and timber harvest sustainability (Smith et al., 2009). For this reason, the net annual rate of growth was used to measure timber productivity and the balance between net growth and removals was measured by the growth-to-removal ratio (G:R) to check timber harvest sustainability within the three procurement circles and the overall procurement region. The annual growth rate and G:R were calculated using the following equation:

$$\text{Annual rate of growth (\%)} = \left(\frac{\text{Net growth of all live trees on forestland (cubic feet)}}{\text{volume of all live trees on forestland (cubic feet)}}\right) * 100$$

$$\text{Growth} - \text{to} - \text{removal ratio (G: R)} = \frac{\text{Net growth of all live trees on forestland (cubic feet)}}{\text{Removals of all live trees on forestland (cubic feet)}}$$

A G:R ratio of 1 indicates an equal volume of wood is grown and harvested in the region. A G:R ratio greater than one means that standing inventory is increasing over time, and a G:R less than 1 indicates that more wood is being removed than grown

To calculate the annual rate of growth and G:R, data on live tree inventory, net growth, and removals for each procurement region were derived from the Forest Inventory Analysis Database (FIADB) version 5.1 (Woudenberg et al., 2011) using the current census cycle (2006-2010).

4.4 Estimate Potential Amount of Woody Biomass (Per Acre) from Regeneration Harvests

4.4.1 Silvicultural System Approach

After inventory G:R ratios have been assessed, the next step is to estimate the maximum potential amount of woody biomass available for harvest. The potential quantity of woody biomass that could be recovered from harvest was estimated using current (2010) plot-level data from FIADB version 5.1 (Woudenberg et al., 2011) on all ownerships within the procurement zones.

In this study, even-aged clearcut harvests were assumed to model woody biomass supply availability. It was assumed that all trees were removed in a single-pass operation to create a new, even-aged stand. Forest regeneration following clearcutting can be either natural or artificial (through planting), although in Pennsylvania landowners and forest managers usually rely on natural forest regeneration and planting is rare. For the purposes of this study, it is assumed that sufficient attention is given to regeneration conditions and seed sources and/or advance regeneration prior to harvest to ensure successful establishment of the next stand to ensure sustainability. This assumption, though clearly over-simplified, is made here because addressing the issue of how to ensure adequate regeneration occurs when Pennsylvania forests are harvested is too large an issue to include within the scope of this study. Related issues, such as the potential impact of biomass harvests on the future composition of Pennsylvania's forests are similarly beyond the scope of this study. These are, of course, critical issues in Pennsylvania, as the forests are at risk of regeneration failures due to lack of adequate advance regeneration, competitive plants, and widespread over-browsing of regeneration by deer (McWilliams et al., 2007). While alternative silvicultural systems, whether even-aged (e.g., shelterwood, seed tree) or uneven-aged (e.g., group selection), might be more suitable and better fit site conditions, species characteristics, landowner objectives (e.g., aesthetics, wildlife), regeneration conditions, and other ecological conditions in many cases, modeling these types of silvicultural systems is also beyond the scope of this study.

4.4.2 Types of Woody Materials Suitable for Energy Use

The amount of woody biomass recovered from the clearcutting regeneration harvests was estimated by assuming an integrated harvesting system, where both conventional products and biomass would be harvested in a single operation and processed at the landing area. Because different parts of trees have different economic values and likely end uses (e.g., sawlogs, pulpwood, and wood chips), the wood from harvestable trees was categorized into two groups: 1) merchantable biomass, 2) non-merchantable biomass (Figure 4-2).

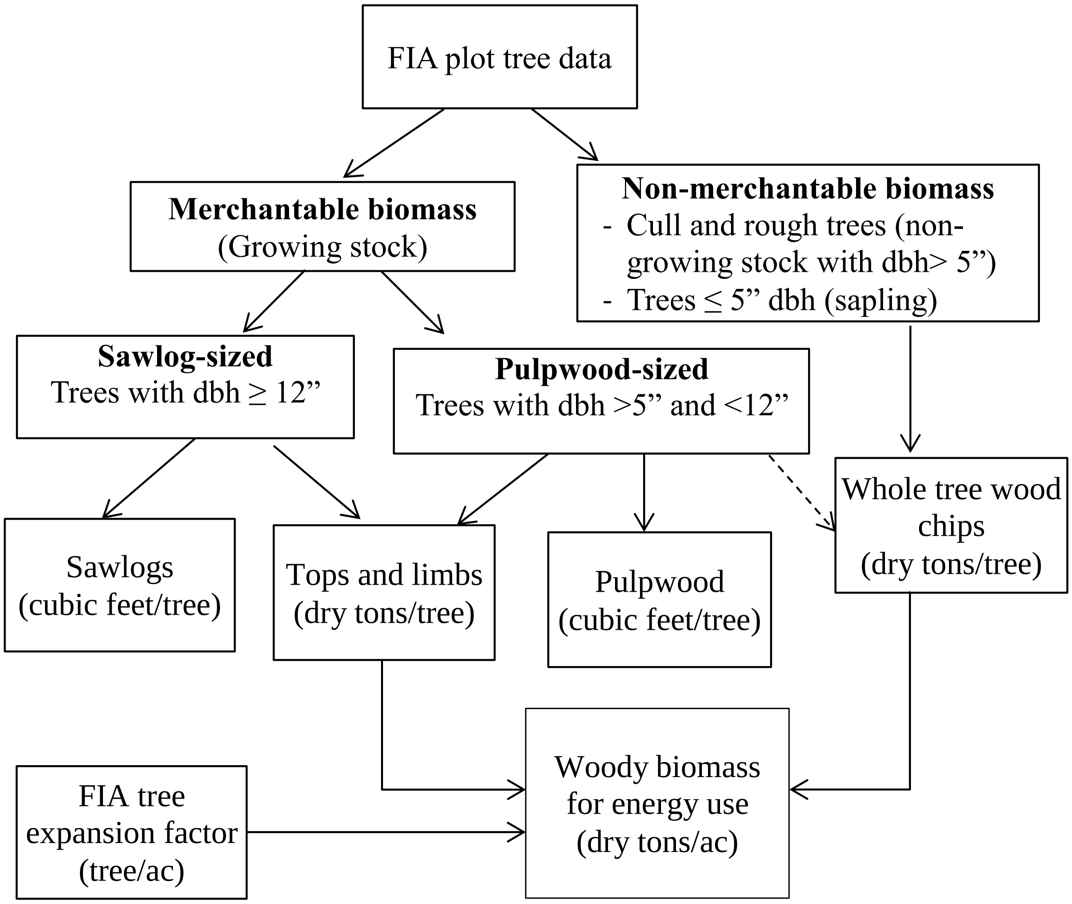


Figure 4-2: Potential woody biomass recovered from clearcutting regeneration harvests using whole tree integrated harvest system on a given FIA plot.

Merchantable biomass includes growing stock trees (trees that qualify for commercial merchantability) that meet either sawlog or pulpwood market specifications, and for this reason was partitioned into sawlog- and pulpwood-sized biomass (Figure 4-2). Sawlog-sized biomass consists of growing stock trees with dbh greater than or equal to 12 inches. The stem portion can be processed into commercial timber products and is unlikely to be used for energy because of its higher value. However, the tops and limbs of sawlog-sized trees can be processed into wood chips for energy use. Pulpwood-sized biomass consists of growing stock trees that have a dbh less than 12 inches and greater than 5 inches. The stem portion can be used as feedstock for making pulp and the tops and limbs can potentially be chipped for energy use.

To derive sawlog- and pulpwood-sized biomass stem volume (cubic-foot/tree) in each FIA plot, the sound cubic-foot volume (VOLCFSND) variable was queried from the FIADB Tree Table. For the quantity of tops and limbs (dry tons/tree) in each merchantable biomass category, the dry biomass in the top of tree (DRYBIO_TOP) variable was used. The tree data were filtered according to the sawlog- and pulpwood-sized biomass diameter specification, categorized as growing stock (TREECLCD = 2) and live (STATUSCD =1), and being on plots that are forested (10% stocked by tree) and accessible for inventory (COND_STATUS_CD=1). To scale the estimated per-tree amount to per-acre basis, tree expansion factors (i.e., trees per acre unadjusted (TPA_UNADJ) derived from Tree Table) were used.

The non-merchantable biomass can be harvested and whole-tree chipped for biomass. It consists of trees that are classified as non-growing stock trees (e.g., rough and cull trees with dbh >5 inches) and saplings (trees ≤5 inches in diameter) (Figure 4-2).

To derive the non-merchantable biomass quantity (dry tons/tree) in each FIA plot, VOLCFSND and DRYBIO-TOP data were queried from the FIADB Tree Table using the same filtering method described earlier for the merchantable biomass, except for the tree class code where non-growing stock tree (TRECLCD = 2 and 3) was used. For the sapling biomass quantity (dry ton/tree), the dry biomass of sapling (DRYBIO_SAPLING) variable from the Tree Table was used. The TPA_UNADJ variable was used to scale the estimated per-tree amount on each plot to a per-acre basis.

Pulpwood-sized biomass can also be harvested and whole-tree chipped, using both stem and tops and limbs for energy use. The use of this material for energy depends on the demand for this material for pulp for paper production or composite panel products such as medium-density fiber board (MDF) and oriented strand board (OSB). As noted earlier, there has been a significant decline in the traditional pulpwood-using industries in the northeastern U.S. in the past two decades (Baker et al., 2005; Piva, 2010; Wiedenbeck et al., 2010), especially for pulp and paper production in Pennsylvania (Pennsylvania Hardwoods Development Council, 2008). Various factors have contributed to the downturn of the pulpwood-using industry in the region, including the 2007-2009 economic recession, declines in housing construction that utilizes composite panel products, lack of global competitiveness of U.S. print paper manufacturing companies, the growing use of electronic media (Woodall et al., 2011), and increased paper recycling (USDA Forest Service, 2012b). Recent projections from the 2010 Resource and Planning Act Assessment (RPA) indicate that U.S. consumption of pulp and paperboard is likely to decline over time primarily in the newsprint and printing and writing paper grades. At the same time, production of pulp and paper board is projected to remain relatively low when there is strong competition from the wood energy market for pulpwood-sized biomass (USDA Forest Service, 2012b). Therefore, there likely will be excess pulpwood-sized biomass available for energy production in the region, and there is room to expand the use of this material for producing energy (U.S. Department of Energy, 2011). For this reason, three scenarios were developed using different assumptions regarding the potential amount of woody biomass available for the hypothetical energy facility. These scenarios are explained in the following section.

4.4.3 Supply Scenarios Based on Pulpwood-Sized Harvest Utilization

Three scenarios were considered in estimating the potential supply of woody biomass for use by the energy facility: base, low and high-supply scenarios. These scenarios are based on different assumptions about the utilization rates of pulpwood-sized biomass by traditional pulpwood using industries (i.e., pulp and composite panel producers) versus the energy sector. The base case scenario uses an approximation of current pulpwood-sized biomass consumption rates by the traditional pulpwood using industries in Pennsylvania. The high and low case supply scenarios explore the effect on potential woody biomass supplies and costs when pulpwood-sized biomass is fully utilized either by the energy sector or by the traditional pulpwood using industries, respectively. Each supply scenario and the corresponding pulpwood utilization rates are explained below and summarized in Table 4-3.

Table 4-3: Utilization rate of pulpwood-sized biomass and the potential woody biomass that could be derived from the integrated harvest for the low, base, and high case woody biomass supply

Woody biomass supply scenario	**Pulpwood-sized biomass utilization rate**	**Potential woody biomass derived from integrated harvest harvest**
Low	No pulpwood-sized biomass used for woody biomass	1. Whole tree chips of non-merchantable biomass 2. Tops and limbs from sawlog- and pulpwood-sized biomass
Base	70% of pulpwood-sized biomass used for woody biomass	1. Whole tree chips of non-merchantable biomass and pulpwood-sized biomass 2. Tops and limbs of sawlog- and pulpwood-sized biomass
High	100% of pulpwood-sized biomass used for woody biomass	1. Whole tree chips of non-merchantable biomass and pulpwood-sized biomass 2. Tops and limbs of sawlog-sized biomass

4.4.3.1 Pulpwood-sized Biomass Utilization for Base Case Supply

The base-case scenario assumes that current utilization of pulpwood-sized material by the traditional pulpwood industries is about 30% of the available pulpwood-sized biomass supply and that the remaining 70% of the pulpwood-sized biomass supply is available for energy use. This approximation of pulpwood-sized biomass utilization between the two industries is not based on the actual market use of the material; rather, it is based on expert opinion. Furthermore, it does not account for potential changes in demand for pulpwood-sized biomass over the longer term. Thus, the assumption is only intended for the short term and assumes no significant changes in the demand for pulpwood-sized biomass from conventional industries using this material. To implement the scenario, 30% of the FIA plots in each procurement region were selected randomly and the simulated integrated harvest was assumed to produce wood products for three different markets: sawtimber, pulpwood and woody biomass. For these plots, all sawlog-sized and pulpwood-sized biomass was harvested for the respective markets, and potential woody biomass recovered for energy use includes only chipping the tops and limbs of the harvested sawlog and pulpwood-sized biomass and whole tree chips of the non-merchantable biomass. For the remaining 70% of the plots in each procurement region, the integrated harvest produced only two types of wood products: sawtimber and woody biomass. In these harvests, all sawlog-sized biomass is harvested for the sawtimber market and woody biomass is recovered from whole tree chipping of the pulpwood-sized biomass and non-merchantable biomass and from chipping the tops and limbs of the harvested sawlog-sized biomass.

4.4.3.2 Pulpwood-sized Biomass Utilization for Low Case Supply

The low case-supply scenario assumes there is strong competition from the traditional pulpwood industries for pulpwood-sized biomass, and all of this material is assumed to be utilized by the traditional users of pulpwood. In this scenario, all FIA plots are harvested to produce three wood products: sawtimber, pulp, and woody biomass. The potential woody biomass recovered from this scenario includes only the tops and limbs of sawlog- and pulpwood-sized biomass and whole tree chips of non-merchantable biomass.

4.4.3.3 Pulpwood-sized Biomass Utilization for High Case Supply

The high-case scenario assumes there is no demand from the traditional pulpwood products market and all pulpwood-sized biomass is utilized by the energy market. Therefore, in the high-supply case, integrated harvests simulated in all FIA plots were set to produce only two products: sawtimber and woody biomass. The potential woody biomass recovered for energy use in the high case includes tops and limbs of sawlog-sized biomass and whole tree chips from pulpwood-sized and non-merchantable biomass.

4.4.4 Conversion Factors

For each plot, the potential amount of woody biomass suitable for energy production was estimated using oven-dry tons per acre. In the FIADB, the biomass weight of small trees less than 5 inches diameter and of tops and limbs can be calculated using DRYBIO_SAPLING and DRYBIO_TOP, respectively, from the Tree Table; the units of these variables are oven-dry tons (Heath et al., 2008; Woudenberg et al., 2011). However, the stem volume for sawlog- and pulpwood-sized biomass was in green cubic-foot volume (Woudenberg et al., 2011). The following equation was used to convert the cubic-foot volume stem volume to oven-dry ton units (Miles & Smith, 2009).

$$B_{odw} = (V_{gw} * SG_{gw} * W)/2000$$

Where; B_{odw} = oven-dry biomass (tons) of wood

V_{gw} = net volume (cubic-foot) of green wood in the central stem

SG_{gw} = green specific gravity of wood

W = weight of cu. ft. of water (62.4 pounds/cubic-foot)

The green specific gravity of wood was obtained from the Reference Species Table of FIADB. A weighted average of the specific gravity was used based on the share of wood volume in each species within each procurement region. The estimated weighted specific gravities for the 50-mile, 50 to 75-mile, and 75 to 100-mile region were 0.516, 0.519, and 0.507, respectively.

4.4.5. Sustainability Reduction

To mitigate the ecological impacts of woody biomass harvests, especially on soil productivity, we assume that 30% of harvested woody biomass would be left in the forest on each FIA plot to recycle soil nutrients and provide habitat for wildlife (U.S. Department of Energy, 2011). This reduction in potential woody biomass production comes from tops and limbs of sawlog- and pulpwood-sized biomass and non-merchantable tree biomass. Also, 15% of trees scheduled for harvest were assumed to be retained and left in the forest for plots on state forest land (i.e., land managed by the Department of Conservation and Natural Resources (DCNR) Bureau of Forestry (BoF)). In this context, “trees” consist of stems and tops and limbs of both merchantable and non-merchantable biomass. This reflects the BoF’s policy of leaving retention trees on all overstory removal harvests.

Because the FIADB does not categorize state forest ownership by the associated agencies (e.g., Bureau of Forestry, Game Commission), ESRI’s ArcMap (version 10.1) was used to identify FIA plots located on state forest land. The Pennsylvania DCNR BoF state forest boundaries were obtained from PASDA (PASDA, 2013) and used to clip FIA plots categorized as non-reserved state forest ownership. The clipped FIA plots within the BoF state forest for each procurement region were then transferred back to the FIADB to apply the 15% harvest retention factors.

4.5 Biophysically and Socially Accessible Forestland Area

4.5.1 The Approach

Biophysical and social constraints affect the accessibility of forestland for harvesting and reduce the potential availability of woody biomass. To estimate the forestland area biophysically and socially accessible for harvest, the following formula, adapted from Butler et al. (2010), was used to reduce the forestland area (acres) represented by each FIA plot to reflect acres that are unavailable for harvest.

$$Forestland_{A} = \sum_{i=1}^{n}\left(\prod_{j=1}^{m} VEF_i(1 - ReductionRate_{ij})\right)$$

Where; $Forestland_A$: Forestland area potentially accessible for harvesting

VEF_i: Volume expansion factor for plot *i*

Reduction $rate_{ij}$: Accessibility reduction rate for constraint *j* on plot*i*

In the formula, Forestland_A, is equal to the sum of the forestland area represented by each FIA plot volume expansion factor, VEF_i, reduced by each constraint that applies to each plot. This reduction is accomplished by multiplying the expansion factor by the product of each reduction factor corresponding to each constraint. The volume expansion factor represents the number of forested acres that each plot represents (Van Deusen, 2005). The area represented by the volume expansion factors can differ greatly from one plot to another because of varying weight given to the sampled plots that fall within a county (Van Deusen, 2005). Nonetheless, the sum of expansion factors for the sampled plots within a county usually matched closely with the county's forested acres (Van Deusen, 2005). There are some limitations associated with using the expansion factor. First, the plot expansion factor is susceptible to change, especially when inventory data are restratified (Woudenberg et al., 2011). Second, sampling errors cannot be calculated when using these factors (Bechtold & Patterson, 2005).

The biophysical and social constraints included in this study are based on availability of data and constraints cited in the literature. In this study, slope, physiographic class, and site productivity are considered to be biophysical constraints. Reserved forest, riparian buffers, size of forest holding, and private forest landowner opposition to harvesting were identified as social constraints. For each of these factors, the threshold levels used to represent the accessibility constraint are described in the next section. In addition, a sensitivity analysis was conducted to assess the impact of using different combinations of constraint thresholds on accessible forestland to simulate high and low woody biomass supply.

The reduction rate for constraints on a given plot, Reduction rate$_{ij}$, can take a value between 0 and 1. A value of 1 means that a constraint applies to the plot, which then causes the forestland represented by that plot to be considered inaccessible for harvest. In contrast, a value of 0 implies that no constraint applies and the forestland area represented by the plot is fully accessible for harvest (Butler et al., 2010). In this study, a reduction rate of 1 was used for all constraints, except for size of forest holding where a reduction rate of 0.9 was used.

4.5.2 Biophysical Constraint Thresholds

The biophysical constraints on woody biomass availability considered in this study were slope, physiographic class, and site productivity. These constraints are measured condition attributes in the FIADB (USDA Forest Service, 2006) and are measured at the plot level. For each FIA plot, the variables were obtained from the FIADB Condition Table.

Steep slopes can limit harvesting potential. In some states, harvesting on steep slopes is restricted by the BMPs. For example, Butler et al. (2010), based on Kittredge and Parker (1999), note that harvesting on slopes greater than 60% is restricted by Massachusetts's BMPs. Nevertheless, in Pennsylvania, there is no restriction on conducting harvest on steep slopes (Metcalf, 2010). In addition to increased soil disturbance and other ecological impacts, steep slopes make timber harvesting more difficult and expensive (Butler et al., 2010; Metcalf, 2010) and limit the use of ground-based harvesting systems. Thus, for this study, plots on average ground slopes greater than 40% were constrained from harvest.

Physiographic class is a variable measured by the FIA that identifies the general effect of physical land form, topographical position and soil moisture available on a site (USDA Forest Service, 2006; Woudenberg et al., 2011). Plots are assigned one of three physiographic class codes: xeric (low or deficient moisture to support tree growth), mesic (moderate or adequate moisture available to support growth), and hydric (abundant or overabundant moisture) (Woudenberg et al., 2011). Hydric physiographic sites such as swamps and low, wet, boggy sites were constrained for harvest (Butler et al., 2010). Therefore, this variable was used as a biophysical constraint in this analysis.

The last biophysical factor is site productivity level, which is used by FIA to classify forestland in terms of its capacity to produce wood for industrial use (Woudenberg et al., 2011). In general, forestland that can produce in excess of 20 cubic feet per acre per year is considered productive forest land (USDA Forest Service, 2006). Forestland that is incapable of producing 20 cubic feet per acre per year is categorized as unproductive land due to adverse site condition such as infertile or rocky soils, dry climate, or poor drainage (USDA Forest Service, 2006). Butler et al. (2010) classified unproductive forestlands as constrained because they believed such lands could not be managed sustainably for timber production. For this reason, plots with site productivity less than 20 cubic feet per acre per year were considered constrained in this study.

4.5.3 Social Constraints Thresholds

Various social variables have been identified in previous studies that may affect the availability of forestland for harvest. Four social factors were chosen to represent social constraints on forestland area accessible for harvesting: reserved forest, riparian buffers, size of forest holding, and private forest landowner opposition to harvesting.

For reserved forest, a reduction rate of 1 was used when a plot was categorized as reserved forestland, which means it was considered inaccessible for harvest. Examples of reserved forest land include national and state parks and designated federal wilderness areas. Reserved forest status was derived from the FIADB Condition Table.

There are some areas where forest harvesting practices are limited or restricted. Most of these areas are restricted through BMPs and/or woody biomass harvesting guidelines that focus on riparian buffer zones to protect water quality and aquatic habitat or to control soil erosion. The National Hydrography Datasets (NHD) from the U.S. Geological Survey (USGS) website (U.S. Geological Survey, 2012) were used in this study to create buffers around streams, rivers, lakes, ponds, reservoirs, canals, dams, stream gages and other water bodies included in the dataset. This study considered plots that are within a 100 ft. riparian buffer zone as inaccessible for harvest (Butler et al., 2010).

Size of forest holding and opposition to harvest are key factors that affect the accessibility of private forestland to harvesting. These constraints, especially opposition to harvest, are known to limit access for harvesting for approximately 10 to 20% of private forestland in Pennsylvania (Metcalf & Finley, 2011). However, one of the major challenges in accounting for these variables in this study is a lack of data available for a plot-level analysis. Previous work that analyzed similar constraints on the FIA plot level used the National Woodland Owner Survey (NWOS) survey response that is not publicly available. Although the NWOS results can be accessed through FIA national program website (USDA Forest Service, 2013b), the available data are summarized at a statewide level. County-specific results on these two factors from Metcalf (2010)and Metcalf and Finley (2011) were used for this study. Those studies examined several biophysical and social factors that affect access to timber on private forest in Pennsylvania. In particular, the variables used were: 1) the proportion of private forestland by size of holding and by county, referred to as county-specific proportion of holding (CSP_H), and 2) the proportion of private forest land inaccessible for harvest due to opposition to harvesting by county, referred to as county-specific opposition (CSP_O). These variables were used to reduce the area available for harvest represented by each FIA plot within each procurement region. In Metcalf (2010) and Metcalf and Finley (2011), the distribution of size of forest holding in each county was measured using GIS ownership parcel data and Landsat imagery of land use and land cover data. To measure acres of forestland owned by NIPFLs opposed to harvesting in each county, they used owner's opposition or willingness to harvest responses (a five-point Likert scale with options "very opposed, opposed, neither opposed nor willing, willing, or very willing") to a survey of Pennsylvania NIPFLs. From these responses, they used percent of NIPFLs opposed and very opposed in each county to calculate the acres of forestland inaccessible for harvest due to NIPFLs attitudes opposed to harvesting.

Because the hypothetical energy facility's procurement region is large, covering 47 counties in Pennsylvania and 14 counties in New York, and the CSP_H and CSP_O values from Metcalf (2010) and Metcalf and Finley (2011) covered only 26 counties in Pennsylvania, specific values were not available for 35 counties in the region. These counties were classified into four county clusters (highly developed, developed/developing, quasi-rural, and rural forested) produced in Metcalf and Finley (2011), and average values of CSP_H and CSP_O in each cluster from those counties where data were available were used to impute values for counties where data were not available.

Initially, Metcalf (2010) aggregated counties into clusters because insufficient data were available for a county-scale analysis of PFL attitudes and behavior in his study. (Metcalf, 2010) used hierarchical cluster analysis to group all counties in the state into sets of counties reflecting parcelization or development of private forestland, based on county area, percent forest, and percent private forest. He found four groups of counties: 1) developed, 2) developed/developing, 3) developing/undeveloped, and 4) undeveloped. Based on these clusters, the amount and percentage of acres inaccessible for harvest due to PFL opposition to harvest was estimated for two counties. Similarly, Metcalf and Finley (2011) employed the same methods and produced four distinct clusters of counties: 1) highly developed, 2) developed/developing, 3) quasi-rural, and 4) rural forested. Variables used in the cluster analysis were county size, urbanization (i.e., population and population growth rates), percent forest, and percent of private forest. Based on these clusters, amount and percentage of acres inaccessible for harvest due to PFLs opposition to harvest was estimated for 24 counties. The average values of CSP_H

and CSP_O by clusters of counties and the specific CSP_H and CSP_O values by county from Metcalf (2010) and Metcalf and Finley (2011) are shown in Appendix Table A-2.

A distance analysis was used to assign counties that were not included in Metcalf (2010) and Metcalf and Finley (2011) to a cluster so that the average CSP_H and CSP_O values for that cluster could be assigned to those counties. Similarity was determined by calculating the Euclidian distance between that county's values for the clustering variables and the average values of the variables for each cluster based on the counties originally classified in that cluster. The unclassified county was assigned to the cluster for which this distance was the smallest. The variables used in this analysis were as similar as possible to those used by Metcalf and Finley (2011): county size, urbanization (population 2000 and population 2010), forested acres, and private forest. After each county was assigned to a cluster, the average CSP_H and CSP_O values for the cluster were assigned to counties in that cluster. The CSP_H and CSP_O values for all the counties for each of the procurement regions are shown in Appendix Table A.3.

To accomplish the area reduction analysis using the county-specific information on CSP_H and CSP_O, ownership information and the county name where the plot is located was derived from the FIADB and added to the spreadsheet used for the area reduction analysis. For size of forest holding, the private land in the county in holdings smaller than 10 acres (CSP_H) was considered constrained. The reduction rate for this constraint is 0.9, meaning that 90 percent of the holdings smaller than ten acres in size were considered unavailable. In order to use this reduction rate in the formula presented previously, this rate is multiplied by the CSP_H. As an example, if CSP_H is 30%, the applied reduction rate would be $0.9\times0.3=0.27$.

The CSP_O values indicate the estimated proportion of landowners who are opposed to harvest. The reduction rate for this constraint takes a value of 1. This reduction rate (1) was multiplied by the CSP_O value before the adapted reduction formula presented previously was applied to estimate forestland area accessible for harvest.

4.5.4 Sensitivity Analysis

A sensitivity analysis was conducted to assess the impact of different combinations of constraint thresholds on accessible forestland area. In general, a more restrictive set of constraint thresholds from the base values was used to simulate a lower woody biomass supply and less restrictive constraint thresholds were used to simulate higher supply. Table 4-4 summarizes the biophysical and social constraint variables, reduction rates and constraint thresholds values used for the base, low and high case supply.

Biophysical constraint thresholds: For slope variable, slopes greater than 30% were tested for the low supply case. On the other hand, the base slope threshold value (i.e., 40%) was retained for the high case because ground harvest systems in the Fuel Reduction Cost Simulator, the harvest cost model used in this study, are limited by this slope threshold. Beyond this slope threshold, a cable yarding system would be needed (U.S. Department of Energy, 2011), which would not be economical, especially for extracting woody biomass (Fried et al., 2005; Fight et al., 2006). Also, skidding on steeper slopes, especially whole-tree skidding, can cause excessive soil disturbance (Fight et al., 2006). Hydric sites were considered constrained for the low case, whereas no limitation on these sites was applied for the high case. Although harvesting these sites is unrealistic, especially in the region, harvesting on land inundated by water is possible as these areas could be logged under frozen conditions (Butler et al., 2010). For site productivity, the 20 cubic feet per acre per year threshold was kept for the low case and no limitation on site productivity level was set for the high case.

Table 4-4: Descriptions of biophysical and social variables, reduction rate and the threshold for the base, low, and high case supply.

Constraint	Units/codes	Reduction rate on VEF	Constraint threshold		
			Low supply	Base supply	High supply
Biophysical					
Slope	Percent	1	≥30	≥40	≥40
Physiographic class	1 = Xeric 2 = Mesic 3 = Hydric	1	Hydric	Hydric	No limitation
Site Productivity	Cubic feet/ac/year 1 = 225+ 2 = 165-224 3 = 120-164 4 = 85-119 5 = 50-84 6 = 20-49 7 = 0-19	1	<20	<20	No limitation
Social					
Reserved forest	0 = Not reserved 1 = Reserved	1	1	1	1
Riparian buffers	Feet	1	≤150	≤100	≤50
Size of forest holding	Acres	$0.9*CSP_H$	<20	<10	<10
Opposition to harvest	Acres	$1*CSP_O$	$CSP_O * 1.5$	CSP_O	$CSP_O * 0.5$

Note: VEF: Volume expansion factor
CSP_H: County specific holding
CSP_O: County specific opposition

Social constraint thresholds: In this study, plots categorized as reserve forestland were considered constrained for both the low and high case. Following Butler et al. (2010) riparian buffer zones of 150 ft. and 50 ft. were used to test the low and high case, respectively. For size of forest holding, a size of less than 20 acres was used for the low case, and size of less than 10 acres used in the base case was retained to simulate high case supply. For opposition to harvest variable, the base CSP_O value was multiplied by 0.5 and 1.5 in the low and high cases, respectively. This multiplication allows a 50 percent decrease and a 50 percent increase relative to the base CSP_O estimates.

4.6 Roadside and Delivered Cost of Woody Biomass

This study provides both roadside and delivered cost estimates of woody biomass for the hypothetical energy facility in order to examine the impact of transportation cost on the potential supply of material delivered to the energy facility at a given cost. In this study, roadside cost consists of stumpage and harvest costs. Delivered cost combines roadside costs with transportation costs, which consist of the cost of loading and hauling woody biomass from each FIA plot to the energy facility.

4.6.1 Stumpage Costs

Assumptions for woody biomass stumpage costs in the literature vary by study and by region or state. This study used a stumpage cost of $3 per green ton ($6 per dry ton, 50% moisture content) for woody biomass chips in all supply scenarios. This price is based on a recent Pennsylvania woody biomass cost study (McDill et al., 2011).

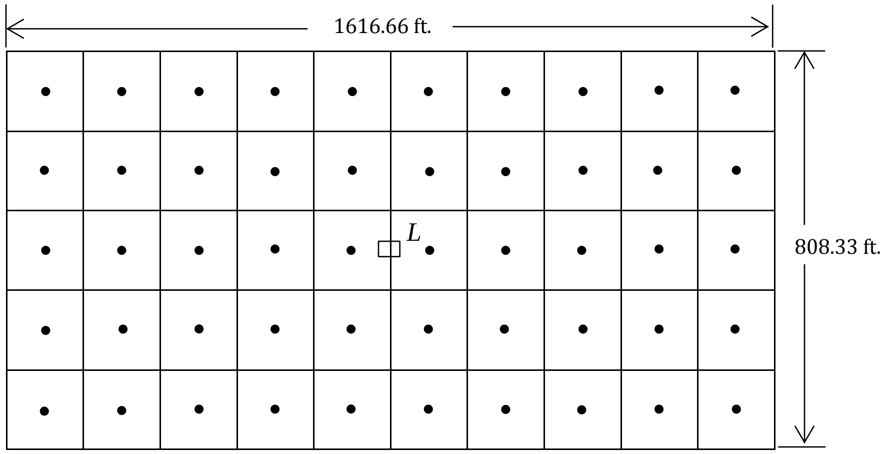
4.6.2 Harvest Costs

The costs of harvesting woody biomass with clearcut regeneration harvests using an integrated harvest system were estimated for all FIA plots using FRCS Northern variant (Fight et al., 2006; Dykstra et al., 2009). A key challenge in using the FRCS model is its costing method. When estimating the cost of whole-tree chips, the model includes all harvesting activities, including felling, skidding and chipping the non-merchantable biomass (i.e., cull trees and saplings) and the pulpwood-sized biomass. On the other hand, for the tops and limbs from merchantable biomass trees (sawlog- and pulpwood-sized trees), the model includes only the cost of one activity, chipping the material at roadside, and the cost of felling and skidding are fully allocated to the merchantable stem volume produced. The latter costing approach is known as marginal costing, where tops and limbs were assumed to be a byproduct of producing the merchantable stem for conventional products (Puttock, 1995). To accurately estimate the harvest cost for tops and limbs, a similar costing approach for producing whole-tree chips should be used where felling and skidding cost along with other fixed cost items are also allocated to the tops and limbs. This allocation of cost would increase the estimated costs of harvesting the tops and limbs while lowering the cost of producing the merchantable stems for conventional products (Puttock, 1995). Estimating tops and limbs using the joint product costing approach from FRCS is beyond the scope of this study.

To estimate harvest cost per dry ton for each type of woody biomass, tops and limbs and whole tree chips, in each FIA plot, a ground-based whole tree (WT) harvest system was assumed. Two types of harvesting systems were used: ground-based mechanical WT and ground-based manual WT. Note that in an actual harvesting operation, both manual and mechanical harvest systems might be used where larger diameter trees are felled with a chainsaw and smaller trees are felled with a feller buncher. However, FRCS can only simulate one harvest system for a plot, so this study considered only one of the two ground-based WT harvest systems to simulate harvest cost for a plot. Based on expert opinion, the manual system was used for plots stocked with large sawtimber trees and have a growing stock volume greater than 2,000 board feet (bdft) and the mechanical system was used for plots that have growing stock volumes of 2000 bdft or less.

With a ground-based manual WT system, it is assumed that trees are felled by hand using a chainsaw and a rubber-tired skidder (choker and grapple) is used to collect and transport the whole trees to the landing area. With a ground-based mechanical WT system, it is assumed that trees are felled and bunched using a feller buncher and a rubber-tired grapple skidder is used to transport the material to the landing area. For both harvest systems, manual and mechanical, trees are assumed to be sorted according to final products – sawlog, pulpwood, and biomass – in the landing area. For conventional products, logs are assumed to be processed mechanically using a stroke or single grip processor and loaded onto trucks. For woody biomass, trees that are categorized as non-merchantable, pulpwood-sized biomass (according to pulpwood-sized utilization scenario) and tops and limbs of the sawlog- and pulpwood-sized biomass are chipped using a disk chipper. This chipping process produced wood chips with bark (i.e., dirty chips). Typically, larger stems can be economically debarked using a chain flail, or a drum or ring debarker before the in-woods chipping process to produce higher value clean chips which are bark free and typically used to produce pulp, oriented strand board (OSB), and possibly liquid fuels. However, the FRCS includes no option to produce clean chips; therefore, woody biomass cost estimates in this study were for producing dirty wood chips.

Input variables in FRCS for slope, number of trees per acre harvested, wood density, hardwood fraction, bole volume per tree, and residue fraction were derived from the FIADB. Residue fraction was calculated using the ratio of the stem volume (dry tons) and the tops and limbs volume (dry tons). Treatment area, move in cost, and average skidding distance for each FIA plot were assumed to be 30 acres, 30 miles, and 476.36 feet respectively. The average skidding distance, 476.36 feet, used as input in the model was calculated based on geometric shape of the treatment area and location of the landing. In this study, the 30-acre treatment area was assumed to have a rectangular shape with a landing (L) located in the middle (Figure 4-3). For a 30-acre treatment area, the rectangular dimension was assumed to be 1616.66 ft. by 808.33 ft. In order to estimate the average skidding distance, the rectangle was divided equally into 50 squares with a center point assigned to each. The distance between each point to the landing area was calculated and averaged over all points to obtain the average skidding distance of 476.36 feet used for this study. Summary of inputs used in FRCS for estimating harvest cost on each FIA plot are shown in Table 4-5.



L = Landing

Figure 4-3: A 30-acre treatment area having a rectangular shape with landing in the middle

Table 4-5: Summary of selected inputs used in FRCS for estimating harvest cost on each FIA plot

Variable	**Value**	**Prescription/unit**
Logging system	1. Ground-based mechanical WT 2. Ground-based manual WT	Growing stock volume > 2000 bdft Growing stock volume ≤ 2000 bdft
Slope	Range from 0 to 40	Percent
Treatment area	30	Acres
Move in cost	30	Mile
Average skidding distance	476.36	feet

The cost data for logging wages, fuel price and equipment in FRCS were based on 2008 cost data. Therefore, these costs were updated for Pennsylvania and New York to reflect the latest cost condition, for the year when the harvesting costs were simulated. Logging wages for Pennsylvania and New York were updated using 2012 logging occupation (NAICS 113310) data obtained from Bureau of Labor Statistics (2012b). The default benefit rate (35%) in the cost model was retained. Fuel price was updated to \$4.14/gallon using the December 2012 diesel price for the Central Atlantic Region (PADD 18) taken from Energy Information Administration (EIA) (2012). The base December 2002 equipment costs were updated using the 2011 producer price index (PPI) for construction and machinery (PCU333120333120) obtained from the Bureau of Labor Statistics (2012a).

4.6.3 Transportation Costs

Roundtrip transportation costs for woody biomass were estimated using Forest Residue Transportation Costing Model v.5 (FoRTSv5) (USDA Forest Service Southern Research Station, 2005). FoRTSv5 is a spreadsheet calculator developed by Forest Service Southern Research Station to assist in analyzing woody biomass transportation costs from the forest to an end-use facility using different combinations of equipment and hauling routes. In this study, transportation costs consist of two operations: 1) loading comminuted woody biomass into trucks and, 2) hauling the materials from the forest to the energy facility. The equipment selected for the loading process was a knuckleboom loader, and a chip van was used for hauling. Wood chips are generally not discharged from the chipper onto the ground and then loaded into a van with a loader. Normally, the wood is chipped through a wood chipper and directly blown into a van. Since the loading process was included as part of the transportation cost in this study, it can be regarded as an additional cost, which likely causes an overestimate of the total cost of transportation.

The 2005 cost assumptions for fuel, trucking wages, and equipment price were updated to the most current available data. The fuel/gasoline cost ($4.145) was updated to December 2012 U.S using highway diesel fuel price for Central Atlantic Region obtained from the Energy Information Administration (EIA) (2012). Oil and lube was assumed to be 10% of the fuel price (Han & Murphy, 2011). The trucking wage rate (NAICS 484110) for Pennsylvania ($15.9/hour) was obtained from the Bureau of Labor Statistics (2012b). The default 33% benefits rate in the model was retained. The loader and chip van prices base year were updated using the 2011 producer price index (PPI) for construction and machinery (PCU333120333120) and heavy duty truck manufacturing (PCU3361203361202).

Knuckleboom productivity for loading wood chips (46.53 tons/ productive machine hour (PMH)) was obtained from McDill et al. (2011) studies on woody biomass harvests in Pennsylvania. The machine utilization rate for the loader was 0.65 PMH/ scheduled machine hour (SMH) (Brinker et al., 2002).

Chip van loads depend on weight limits and vehicle capacity regulations; therefore, the chip van load was assumed to be 20 green tons (Wu et al., 2011) (a 50% moisture content was used to convert to dry ton). The hauling distances and travel time between FIA plots and the energy facility were computed using the ArcMap Network Analyst origin-destination (OD) cost matrix. A detailed street network data set was obtained from the 2007 Tele Atlas North America (ESRI, 2007). Since empty travel time is generally shorter than loaded travel time, the empty travel time was assumed to be 10% less than the loaded travel time (Han & Murphy, 2011). The default 20 minutes chip van standing time (hooking, drop, other task) used in the transportation cost model was retained.

4.7 Develop Supply Curve

The next step in the procedure is to develop supply curves. For each plot, the estimated quantity of tops and limbs and whole tree chips in dry tons per acre produced by the harvest was multiplied by the associated acres accessible for harvest and were combined to derive the maximum potential quantities of woody biomass biophysically, socially, and both biophysically and socially available for energy use represented by that plot. Then, roadside costs of woody biomass per dry ton for each type of potential woody biomass quantities (biophysically, socially and both biophysically and socially available) in that plot were calculated. This was done by dividing the total cost of woody biomass by the potential woody biomass quantities (biophysically, socially and both biophysically and socially available). To derive the total costs of woody biomass for each potential woody biomass quantity (biophysically, socially and both biophysically and socially available), the per dry ton cost of stumpage and predicted harvest costs for tops and limbs and whole tree chips per dry ton were multiplied by the potential quantities biophysically, socially, and both biophysically and socially available in each plot and were then combined. The delivered cost of woody biomass from each FIA plot to the energy facility was derived by adding the transportation cost to the roadside cost. Then, the potential quantity available from each plot was combined with the estimated roadside and delivered costs, and the list of plots was sorted from the cheapest to the most expensive.

Supply curves were then constructed using Microsoft Excel. The supply curve was constructed so that the x-axis represents the cumulative sum of potential quantities and the y-axis shows the estimated roadside and/or delivered cost.

These supply curves show key characteristics of supplies within the energy facility procurement region. In particular, the curves show how increases in resource use result in higher marginal costs due to having to go farther to get biomass and due to having to get the biomass from sites where it is more costly to harvest. In addition, for the base case scenario, arc elasticity of supply can be calculated to examine how much quantity supplied changes with respect to a change in delivered cost/price. The arc elasticity was calculated as the average elasticity around three delivered cost levels: $50, $75, $100, and $150 per dry ton. Two declines and increases from each cost level were considered in the calculation, a $5 per dry ton decline or increase and a $10 per dry ton decline or increase. For example, arc elasticity around the $50 per dry ton delivered cost level was calculated as the average elasticity for $40 to $50, $45 to $50, $50 to $55, and $50 to $60 per dry ton. This was done to minimize the effect of irregularities in the supply curve.

In addition to the supply curve of woody biomass developed using information on maximum potential quantities and cost from each FIA plot, annual supply can also be estimated. To derive woody biomass supplies available on an annual basis, the estimated annual growth rate within the 100-mile radius around the energy facility are multiplied by the estimated maximum potential quantities of woody biomass both biophysically and socially available. Note that the FIA definition of growth focuses on growing stock volume and does not account for the rate of growth for biomass as a whole. Therefore, in this study it was assumed that the net annual growth rate of total biomass is proportionate to the net annual growth rates of all live trees on forestland.

4.8 Analysis of Competing Users of Woody Biomass

The final step in the analytical framework is to analyze competing users of woody biomass to assess the attractiveness of introducing the energy industry in the market area. It is important to note that assumptions made about the pulpwood-sized biomass utilization rate for the base case were based on observation of pulpwood consumption in Pennsylvania. In reality, however, a woody biomass-based energy facility competes for raw material when the proposed wood procurement area overlaps with those of similar wood using industries. A high degree of overlapping wood procurement areas would intensify the competition for raw material, which could drive up stumpage prices.

Analysis of overlapping wood procurement areas between existing and proposed competing woody biomass users can be conducted using spatial analysis. The degree of intersection with other facilities' procurement areas can be combined with the estimated potential supply of woody biomass to assess the degree of raw material competition. To conduct this analysis, spatial data would be needed on the wood biomass using companies in the region whose procurement zones overlap the study area and on the wood consumption of those facilities. Due to time constraints this analysis was not conducted for this study.

Chapter 5

Results and Discussion

5.1 Introduction

This chapter presents the results from applying the proposed woody biomass supply analytical framework to the hypothetical energy facility located in Williamsport, PA. The first section assesses the overall resource condition within the energy facility's procurement region using information about timber growth and removals. The second section summarizes the amount of woody biomass (per acre) that can be recovered by conducting the hypothetical clearcutting regeneration harvest on all FIA plots in the region. The third section shows the effects of applying the biophysical and social constraints on harvest accessibility resulting from the forestland area reduction analysis. The fourth section analyzes the estimated roadside and delivered costs of woody biomass. Each cost component that makes up the estimated costs is described separately. The fifth section presents and analyzes the woody biomass supply curves that were constructed. The first supply curve is for the base-case set of biophysical and social constraint thresholds and the base-case pulpwood biomass utilization scenario. It illustrates the impact on potential supplies of woody biomass for the energy facility due to biophysical, social, and economic constraints (i.e., cost). In addition, supply curves are used to assess the sensitivity of supplies to changes in biophysical and social constraint thresholds and to explore the impact on woody biomass quantity and cost from using different assumed utilization rates of pulpwood-sized biomass.

5.2 Timber Growth and Removals within the Procurement Region

In assessing sustainable supplies of woody biomass for a proposed energy facility it is essential to begin with an appraisal of resource conditions and sustainability within the expected wood procurement region. Timber volume inventory, net growth and removals data from a complete FIADB inventory cycle (2006-2010) were used to assess and describe current resource conditions with respect to timber productivity and harvest level sustainability within the procurement regions around the hypothetical energy facility located in Williamsport, Pennsylvania.

Table 5-1 shows the wood inventory volume, annual net growth, annual rate of growth, and the growth to removals ratio (G:R) for each of the study's procurement regions. Within a 100-mile radius around the energy facility, the total timber inventory volume is 26.81 billion cubic feet. As expected, the estimated timber inventory volume increases as one moves to the outer procurement regions due to the larger areas of forestland included in those regions. The net annual growth within the 100-mile radius is 567.71 million cubic feet, with annual removals of only 279.11 million cubic feet.

Table 5-1: Growth rate and growth-to-removals ratio for the procurement regions around energy facility located in Williamsport, PA: the 50-mile region, the 50 to 75-mile region, the 75 to 100-mile region, and the total 100-mile region.

Procurement area	Live tree inventory (cubic feet)	Net growth (cubic feet/year)	Removals (cubic feet/year)	Growth rate	Growth to removals ratio
50-mile	7,393,566,496	133,611,889	65,674,063	1.8%	2.03
50 to 75-mile	8,154,509,967	173,488,783	97,345,360	2.1%	1.78
75 to 100-mile	11,263,228,817	260,605,479	116,090,295	2.3%	2.24
Total for 100-mile region	26,811,305,280	567,706,151	279,109,717	2.1%	2.03

Analysis of the annual rate of growth showed that within the 100-mile region the net growth rate (gross growth minus mortality) of the forest is about 2.1% annually (Table 5-1). This estimate is consistent with, albeit slightly lower than, the average annual rate of growth in the northern forest (2.4%) reported by Smith et al. (2009). The growth rates vary by procurement zone partly due to the different mix of species and sites across the procurement region. The highest annual rate of growth was in the 75 to 100-mile region, followed by the 50 to 75-mile region, and then the 50-mile region with annual growth rates of 2.3%, 2.1%, and 1.8%, respectively.

The estimated G:R ratio is greater than one in all procurement regions, suggesting that more wood is being grown in the forest than harvested (Table 5-1). On average, the G:R in the 100-mile procurement zone is 2.03. Within the procurement region, the highest G:R ratio was in the 75 to 100-mile region with estimated growth around 2.24 times removals. The 50-mile region follows with growth 2.03 times removals, and in the 50 to 75-mile region growth exceeds the amount of wood removed at a ratio of about 1.78:1. Based on this simple G:R analysis, overharvesting is not occurring at a landscape level within the procurement region and results suggest that the standing timber inventory will likely continue to increase and current harvest level could be doubled without reducing inventories from current levels.

5.3 Potential Amount of Woody Biomass (Per Acre)

Table 5-2 provides descriptive statistics for the potential amount (in dry tons per acre) of woody biomass (whole-tree chips and tops and limbs) and conventional products (i.e., sawlogs and pulpwood for fiber) that could be produced by clearcutting the 491 FIA plots in the 50-mile region, the 603 plots in the 50 to 75-mile region, and the 812 plots in the 75 to 100-mile region for the three different pulpwood utilization scenarios. These estimates reflect the harvest retention requirement for ecological sustainability purposes (i.e., 15% of trees be left standing for plots located on state forest land and the 30% of harvestable woody biomas left on the ground at harvesting sites for all inventory plots to provide soil nutrients and wildlife habitat).

Table 5-2: Dry tons of biomass per acre in sawlog- and pulpwood-sized stems, tops and limbs, and whole-tree chips produced by clearcutting FIA plots expressed as the maximum, median, and mean weight, by three pulpwood utilization scenarios for three procurement regions around a hypothetical energy facility located in Williamsport, PA.

Supply scenario based on pulpwood utilization	Procurement region (mile)	No. of plots	Conventional products						Woody biomass						Stem to chip ratio
			Sawlog-sized biomass (Dry tons/acre)			Pulpwood-sized biomass (Dry tons/acre)			Tops and limbs (Dry tons/acre)			Whole tree chips (Dry tons/acre)			
			Max	Median	Mean	Max	Median	Mean	Max	Median	Mean	Max	Median	Mean	
Low	0 - 50	491	75.71	11.87	14.23	37.31	9.96	11.03	13.93	4.40	4.47	28.83	4.14	5.07	2.65
	50 - 75	603	58.35	9.04	12.69	38.30	7.52	8.56	13.35	4.04	4.15	33.35	4.43	5.55	2.19
	75 - 100	812	75.32	11.87	15.08	48.05	8.94	8.94	36.07	4.32	4.47	16.07	4.35	4.47	2.69
Base	0 - 50	491	75.71	11.87	14.23	28.79	0.00	3.20	11.35	2.23	2.81	44.21	10.31	11.68	1.20
	50 - 75	603	58.35	9.04	12.69	38.30	0.00	2.66	11.36	2.03	2.58	69.23	12.31	12.31	1.03
	75 - 100	812	75.32	11.87	15.08	48.05	0.00	2.04	11.81	2.34	2.87	77.67	10.33	12.39	1.12
High	500 - 50	491	75.71	11.87	14.23	-	-	-	10.23	1.87	2.12	44.21	13.35	14.42	0.86
	50 - 75	603	58.35	9.04	12.69	-	-	-	58.34	7.75	1.89	46.46	13.29	13.98	0.80
	75 - 100	812	75.32	11.87	15.08	-	-	-	48.74	1.84	2.20	48.75	13.65	14.65	0.90

In the three regions, removal of sawlog-sized biomass stems provides on average 14.23, 12.69, and 15.08 dry tons per acre, respectively, from the smallest to the largest region (Table 5-2). As expected, the amount of biomass produced from pulpwood-sized stems varies greatly depending on the pulpwood biomass utilization scenario. For the base case, when 70% of pulpwood-sized biomass was whole-tree chipped and another 30% was processed for traditional pulpwood using industries, the mean amount of whole-tree chips produced ranges from 11.68 to 12.39 dry tons per acre. At the same time, the mean amount of biomass recovered from tops and limbs ranged from 2.58 to 2.87 dry tons per acre. For the high case, because all pulpwood-sized biomass is used for energy, the mean amount of whole-tree chips recovered for all procurement regions increased slightly from the base case. On the other hand, the mean quantity of biomass produced from tops and limbs in all regions dropped slightly from the base case because it is only derived from sawlog-sized biomass. For the low case, since all pulpwood-sized biomass in each procurement region was harvested for pulp production, the mean amount of biomass from tops and limbs almost doubled from the base case, but the mean amount of biomass from whole-tree chips decreased substantially and mainly comes from non-merchantable biomass sources (i.e., saplings, and cull and rough trees).

5.4 Acres of Forestland Unavailable due to Biophysical and Social Constraints

5.4.1 Estimated Reduction in the 100-Mile Region around Energy Facility

As noted in Table 4-1, there are about 12.35 million acres of forestland within a 100-mile radius around the hypothetical energy facility. Using the reduction formula adapted from Butler et al. (2010), 29.53% (3.65 million acres) of the total forestland was unavailable for harvest due to both biophysical and social constraints (Table 5-3). The social constraints had the most impact, with an estimated reduction of 20.76% (2.56 million acres) while the biophysical constraints account for only a 10.84% (1.33 million acres) reduction. These reduction estimates are not additive due to the multiplicative nature of the formula (Butler et al., 2010). This finding is consistent with the literature that suggests that social constraints have substantially more effect in reducing access to harvest than the biophysical constraints (Metcalf, 2010; Metcalf & Finley, 2011).

Of the four social constraints considered in this study, PFLs opposition to harvesting had the greatest impact, with an estimated reduction of 10.39% (1.28 million acres) of the total forestland (Table 5-3). This represents about 15.35% of the total private forestland within the region (Table 5-4).While large portions of private forestland are accessible for harvest due to a lack of owner opposition; there is no guarantee that private forestland will actually be harvested by the unopposed owners. As noted by Metcalf and Finley (2011), PFLs who were unopposed to harvesting or even willing to harvest might not be able to as many factors might affect their harvest behavior or decision including forest stand characteristics (quality and value of the timber), ownership objectives, market value and expectations about future market values, time, and beliefs, among other factors.

Table 5-3: Estimated reductions in forestland area within 100-mile radius around the hypothetical energy facility located in Williamsport, PA, for a low, a base, and a high case supply scenario due to changes of biophysical and social constraints thresholds.

Constraints	Reduction in forestland (%)		
	Low	Base	High
Biophysical factors			
Slope	20.16	10.20	10.20
Site productivity	0.25	0.25	-
Physiographic class	0.51	0.51	-
Cumulative reduction due to biophysical constraints	20.80	10.84	10.20
Social factors			
Reserved status	2.16	2.16	2.16
Riparian buffers	1.63	2.38	3.19
Size of forest holding	13.49	7.62	7.62
Opposition to harvesting	15.59	10.39	5.20
Cumulative reduction due to social constraints	29.11	20.76	16.96
Cumulative reduction due to biophysical and social constraints	44.37	29.53	25.58

Table 5-4: Estimated reduction in forestland area due to opposition to harvest, private forestland holding less than 10 acres, and reserved forest for base case supply constraint threshold for the 50-mile region, 50 to 75-mile region, 75 to 100-mile region, and total 100-mile region around hypothetical energy facility.

	Private forest					Public forest		
Procurement region (miles)	Total private forestland (acres)	Total acres of private forestland opposed	Percent of private forestland opposed	Total private forestland <10 acres	Percent of private forestland <10 ac	Total public forestland (acres)	Total acres of reserved forest	Percent reserved forest
50	1,906,039	282,706	14.83%	185,643	9.74%	1,487,791	143,068	9.62%
50 - 75	2,639,416	418,652	15.86%	308,294	11.68%	1,287,897	96,435	7.49%
75 - 100	3,815,848	577,705	15.14%	442,455	11.60%	1,212,047	27,237	2.25%
Total 100-mile	8,361,303	1,283,065	15.35%	940,997	11.25%	3,987,735	266,739	6.69%

The next largest social reduction factor was size of forest holding which limited access to approximately 7.62% (0.94 million acres) of all forestland (Table 5-3), or 11.25% of the total private forestland within the 100-mile radius (Table 5-4). For the base-case analysis, county-specific proportions of forestland in holdings smaller than 10 acres are based on information from Metcalf (2010) and Metcalf and Finley (2011). These proportions were used to reduce the FIA plot expansion factor because below this threshold private forestland owners would have limited options to conduct harvesting, largely due to high harvesting costs. Kittredge et al. (1996) showed that tracts below10 acres could still be economically harvested, but it would largely depend on the quality and value of the timber within the tract. Nonetheless, since many of the private forests contain a large volume of low quality timber or “low-use-wood” resulting from past high grading practices (Kenefic & Nyland, 2005; Pennsylvania Hardwoods Development

Council, 2008), harvesting on small parcels would be uncommon. For these reason, even many larger properties would be uneconomical to harvest. A study conducted in the southern U.S. suggested that most economies of scale in harvesting are achieved on parcels ranging from 20 to 40 acres, especially when highly mechanized harvesting system are used (Moldenhauer & Bolding, 2009). With private forestland expected to become more parcelized due to inheritance, development and other pressures that divide parcel sizes into multiple owners (Butler & Leatherberry, 2004; Butler, 2008), forest holding size will likely become an increasingly important constraint on woody biomass supplies.

Riparian buffers and reserved status had comparable impacts on access, with estimated reductions of 2.38% (0.29 million acres) and 2.16% (0.27 million acres) of total forestland within the 100-mile region, respectively (Table 5-3). Riparian buffers were applied on both public and privately owned FIA plots to comply with forest harvesting guidelines to protect water quality and riparian habitat. Reserved status removes FIA plots located on public forests designated as Natural Areas, Wild Areas, Wild Plant Sanctuaries, and other special use areas. As indicated in Table 5.4, of the total 3.99 million acres public forest within the 100-mile region, about 6.7% of the total public forestland was constrained by reserved forest status, which means a large proportion would remain accessible for harvest. Nonetheless, the access to public forestland for harvesting will ultimately be affected by various policies and regulation related to the management of public forestlands. For example, the DCNR Bureau of Forestry (BoF) is currently reexamining policies limiting whole tree harvest practices on state forest land (Pennsylvania Bureau of Forestry, 2007). Such a change in policy that limits whole tree harvesting on BoF land would have an impact on woody biomass supplies from these forests. Although the BoF has implemented a timber harvest allocation model in the 20 state forest districts using scheduled silvicultural treatments, estimating woody biomass harvests from state forests using that model is beyond the scope of this study (Pennsylvania Bureau of Forestry, 2007).

Of the biophysical constraints, slope had the greatest impact, with an estimated reduction of 10.2% (1.26 million acres). Physiographic class and site productivity had little influence, with estimated reductions of 0.51% (0.063 million acres) and 0.25% (0.031 million acres), respectively (Table 5-3). These findings were consistent with previous studies in which slope had the greatest influence in limiting availability compared to other biophysical factors (Butler et al., 2010; Metcalf, 2010; Metcalf & Finley, 2011).

In the biophysical and social constraint threshold sensitivity analysis, using more restrictive constraint thresholds in the low case increased the amount of forestland unavailable for harvest compared to the base case to an estimated reduction of 44.37% (5.48 million acres) of all forestland within the 100-mile region (Table 5-3). On the other hand, using less restrictive biophysical and social constraint thresholds for the high case reduced the estimated impact on availability slightly, with only 25.58% (or 3.16 million acres) unavailable for harvest. Similar to the base case, social constraints collectively had greater impact on accessibility for harvest than the biophysical constraints for both low and high availability scenarios.

5.4.2 Estimated Area Reductions within the Three Procurement Regions around the Energy Facility

Table 5-5 shows the amount of forestland lost due to biophysical and social constraints in each of the three procurement regions. For the base case, social constraints again reduced the amount of forestland available for harvest more than the biophysical constraints in all the procurement regions, albeit at different levels. Of the social constraints, opposition to harvest, followed by size of forest holding, had the largest impacts on the forestland available for harvest in each procurement region. Although the area reduction caused by opposition to harvest and size of forest holding seems to increase as the procurement area expands, the reduction estimates in the table were based on total forestland within each region. This occurs because as the radius of the procurement region is increased an increasing proportion of the area in the procurement region is private. If the reduction percentages were calculated using only the private forestland within each procurement region, variation due to opposition and size of forest holding would not be noticeably different among the procurement regions (Table 5-4). Similarly, the reduction due to reserved forest status within public forestland varied from one procurement region to another, with the largest reduction in the 50-mile region (9.62% or 0.143 million acres), followed by the 50 to 75-mile region (7.49% or 0.096 million acres), and then the 75 to 100-mile (2.25% or 0.027 million acres). Again, this is largely explained by the larger portion of publicly-owned forestland in the regions with the smaller radii. From Table 5-5, in each procurement region, riparian buffers had the least impact on forestland availability. Reduction due to riparian buffers was slightly higher in the 75 to 100-mile region with a reduction of about 2.93% (0.147 million acres), followed by the 50-mile region with a 2.17% (0.0736 million acres) reduction, and then the 50 to 75-mile region with a 1.85% (0.050 million acres) reduction.

Of the biophysical variables, slope largely influenced access, with the highest reduction in the 50-mile region (14.50% or 0.49 million acres) followed by the 50 to 75-mile region (11.34% or 0.445 million acres) and then the 75 to 100-mile region (6.58% or 0.331 million acres) (Table 5-5). Site productivity and physiographic class had only minor impacts. Most of the reductions were less than 0.5%, except for physiographic class in the outer most procurement region where the reduction was 0.9% (0.0452 million acres).

The sensitivity analysis for each procurement region shows that using more restrictive constraint thresholds in the low case increased the amount of inaccessible forestland area attributed to both biophysical and social constraints. These reductions ranged from 42.05 to 45.69% (Table 5-5). On the other hand, less restrictive constraint thresholds in the high case resulted in smaller reductions in all procurement regions with cumulative reductions due to both biophysical and social constraints ranging from 23.09 to 28.20%. In both the low and high supply cases, cumulative reductions due to social constraints result in higher reductions than biophysical constraints, with the exception of the low-supply case in the 50-mile region where the reduction due to biophysical constraints (28.67% or 0.973 million acres) outweighed the social constraint reductions (25.11% or 0.852 million acres). This was primarily due to the slope variable. In the high case, the 40% slope threshold used in the base case was retained because FRCS does not accommodate ground-based harvesting for slopes over 40% (which generally reflects actual limitations).

Table 5-5: Estimated reductions in forestland due to biophysical and social constraints for three procurement regions around hypothetical energy plant: a 50-mile region, a 50 to 75-mile region, and a 75 to 100-mile region.

Procurement region (miles)	Constraints	Reduction in forestland area (%)		
		Low	Base	High
50	Biophysical factors			
	Slope	28.18	14.50	14.50
	Site productivity	0.27	0.27	-
	Physiographic class	0.35	0.35	-
	Cumulative reduction due to biophysical constraints	28.67	14.99	14.50
	Social factors			
	Reserved status	4.14	4.14	4.14
	Riparian buffers	1.25	2.17	3.73
	Size of forest holding	10.07	5.47	5.47
	Opposition to harveting	12.50	8.33	4.17
	Cumulative reduction due to social constraints	25.11	18.62	16.20
	Cumulative reduction due to biophysical and social constraints	46.44	30.58	28.20
50 - 75	Biophysical factors			
	Slope	21.03	11.34	11.34
	Site productivity	0.13	0.13	-
	Physiographic class	0.15	0.15	-
	Cumulative reduction due to biophysical constraints	21.31	11.62	11.34
	Social factors			
	Reserved status	2.41	2.41	2.41
	Riparian buffers	1.43	1.85	2.53
	Size of forest holding	13.97	7.85	7.85
	Opposition to harveting	16.00	10.66	5.33
	Cumulative reduction due to social constraints	30.07	21.15	17.12
	Cumulative reduction due to biophysical and social constraints	45.69	30.58	26.65
75 - 100	Biophysical factors			
	Slope	14.38	6.58	6.58
	Site productivity	0.34	0.34	-
	Physiographic class	0.90	0.90	-
	Cumulative reduction due to biophysical constraints	15.39	7.59	6.58
	Social factors			
	Reserved status	0.71	0.71	0.71
	Riparian buffers	2.02	2.93	3.37
	Size of forest holding	15.29	8.80	8.80
	Opposition to harveting	17.24	11.49	5.75
	Cumulative reduction due to social constraints	30.91	21.83	17.32
	Cumulative reduction due to biophysical and social constraints	42.05	28.06	23.09

5.5 Woody Biomass Costs Estimates

5.5.1 Stumpage Costs

In all scenarios, the assumed stumpage price paid to landowners was $6 per dry ton. This assumption was based on a recent woody biomass harvest cost study in Pennsylvania ($3 per green ton) (McDill et al., 2011). Nonetheless, stumpage prices are dynamic and can be location-specific. In an expanding woody biomass market, forest landowners might receive higher stumpage payments for woody biomass. The impact of rising or falling stumpage prices on roadside and delivered biomass costs is straightforward: if stumpage prices rise or fall by X dollars, then all woody biomass costs rise or fall by an equal amount.

5.5.2 Harvest Costs

The costs of harvesting woody biomass with clearcut regeneration harvests using an integrated harvest system were estimated for all FIA plots within the energy facility procurement region using the Northern Variant of FRCS (Fight et al., 2006; Dykstra et al., 2009). Harvest operations were simulated using the manual method on high-volume plots (≥2,000 bdft/acre) and using the mechanical method on low-volume plots (<2,000 bdft/acre). Table 5-6 summarizes the estimated whole-tree chip and the tops and limbs costs. In the base pulpwood utilization scenario, the mean cost for harvesting tops and limbs ranges from $9.82 to $10.08 per dry ton across the three procurement regions. The median cost of chipping tops and limbs is consistently about $11 per dry ton. The mean cost of whole-tree chips is much higher than the tops and limbs cost since it includes the cost of all harvest activities, not just the chipping cost. The estimated mean cost for whole-tree chips in the base case ranges from $75.74 to $92.90 per dry ton, and the median cost ranges from $60.89 to $67 per dry ton. The median cost is probably more meaningful in this case since half of the supply can be harvested at this cost or less.

The variation in cost estimates across plots was higher for the whole-tree chipping cost compared to the tops and limbs cost. The range of the whole-tree chipping harvest cost was the highest in the 50 to 75-mile region with a range of $6,048 per dry ton, followed by the 75 to 100 mile region with a range of $2,096 per dry ton. Even in the 50-mile region the range was $1094 per dry ton. These variations could be due to differences of site conditions found on each plot (i.e., slopes), harvest systems (i.e., manual or mechanical), or due to differences in the volume of the trees harvested per acre, as these are the key inputs for simulating the harvest costs. An investigation of the plot data showed that the extreme harvest cost estimates mainly occurred on plots with only a few small trees, which might have been recently harvested or early in successional development.

Table 5-6: Summary of stumpage and harvest costs of woody biomass supply scenario based on pulpwood utilization rate and by procurement regions around energy facility in Williamsport, PA

Supply scenario based on pulpwood utilization	Region (miles)	Stumpage cost ($/dry ton)	Estimated woody biomass harvest cost ($/dry ton)											
			Whole-tree chips						**Tops and limbs**					
			Range	1st quartile	3rd quartile	Interquartile range	Median	Mean	Range	1st quartile	3rd quartile	Interquartile range	Median	Mean
Low	0 - 50	6.00	0 - 1097.04	54.07	90.34	36.27	70.68	80.93	0 - 12.87	11.06	11.07	0.05	11.08	10.98
	50 - 75	6.00	0 - 5854.70	54.20	94.60	40.50	72.44	94.00	0 - 12.84	11.06	11.28	0.22	11.09	10.95
	75 - 100	6.00	0 - 2070.61	50.21	92.69	42.48	67.71	84.16	0 - 14.70	11.06	11.59	0.50	11.11	10.96
Base	0 - 50	6.00	0 - 1097.04	45.14	86.58	41.44	60.89	75.74	0 - 12.87	11.06	11.11	0.13	11.11	10.08
	50 - 75	6.00	0 - 6048.00	47.20	93.10	46.00	67.00	92.90	0 - 12.45	11.06	11.25	0.19	11.12	9.47
	75 - 100	6.00	0 - 2095.87	44.73	92.91	48.18	63.07	84.44	0 - 13.31	11.08	11.58	0.53	11.14	9.82
High	0 - 50	6.00	0 - 1125.16	43.43	85.66	42.23	58.55	75.22	0 - 12.87	11.08	11.20	0.13	11.12	9.69
	50 - 75	6.00	0 - 6048.00	44.30	92.70	48.40	61.90	93.80	0 - 12.53	11.08	11.25	0.17	11.14	9.05
	75 - 100	6.00	0 - 2095.27	42.53	89.65	47.13	60.20	81.47	0 - 12.20	11.08	11.51	0.43	11.15	9.39

Harvesting costs vary across the three pulpwood utilization scenarios. As discussed previously, when all pulpwood-sized biomass is assumed to be fully utilized by the traditional pulpwood-using industries in the high case, a higher proportion of tops and limbs and less whole-tree chips are used for energy (Table 5-2). The mean harvest cost for both sources was higher than the base and low case scenarios. In the low case, with a higher proportion of tops and limbs chipped, chipping costs were higher, with estimated means of $10.95 to $10.98 per dry ton across procurement regions (Table 5-6). This result was expected, as chipper machine productivity is largely dependent on the volume of wood chipped (Hartsough et al., 2001). By contrast, when a smaller proportion volume requires chipping, the cost of whole-tree chips increases compared to low and high case and mean costs range from $80.93 to $94.00 per dry ton. This observation was analogous to the finding by Cubbage et al. (1989), where harvest costs are highly influenced by the volume of wood removed since higher move-in and set-up costs need to be spread over a smaller harvested volume.

In the high case, where all pulpwood-sized biomass is taken for energy production, the estimated harvest cost means were much lower than the base and low case scenario across procurement regions, especially for the tops and limbs (Table 5-6). This is due to a smaller amount of tops and limbs being chipped, mainly because the source was only contributed by the sawlog-sized biomass (See Table 5-2, high case for tops and limbs). The cost estimates for whole-tree chips in the high case were somewhat lower than in the base case with means ranging from about $75.22 to $81.47 per dry ton across procurement regions (Table 5-6). This was probably due to slightly higher volumes of whole-tree chips harvested in the high-case scenario.

Many factors can influence costs in a harvest operation. For example, the size of the harvest tract was assumed to be 30 acres for all plots. Using different harvest tract sizes would affect the harvest cost estimates, as it would directly affect the skidding distance estimation. Other factors that can affect harvest costs that were not considered in this study include the harvest system (e.g., cut-to-length system) (Adebayo & Johnson, 2007) and silvicultural treatments (Kellogg et al., 1996).

5.5.3 Transportation Costs

Table 5-7 summarizes the estimated loading costs, hauling costs, and transportation costs from FIA plots to the energy facility in each procurement region. In this study, transportation costs were calculated as the sum of costs for loading woody biomass chips into a chip van at the FIA plot location and for hauling to the energy facility and to return to the plot site. Road access was assumed to exist to each FIA plot location.

The estimated loading cost was $7.27 per dry ton. Within the 50-mile radius, the average estimated woody biomass transportation cost was $20.74 per dry ton with an average one-way travel distance of 47.08 miles and an average roundtrip travel time of 124.26 minutes. The average transportation cost increased to $30.39 per dry ton in the 50 to 75-mile region and to $37.70 per dry ton in the 75 to 100-mile region. This result was expected and consistent with Han and Murphy (2011), who found that transportation cost increased with increasing travel distance. Within the total 100-mile radius around the energy facility, average transportation costs were $29.61 per dry ton and ranged from $8.80 per dry ton to $74.35 per dry ton. The estimated average transportation cost per mile from within each procurement region was $0.51 per dry ton per mile in the 50-mile procurement region, $0.35 per dry ton per mile for the 50 to 75-mile region, and $0.30 per dry ton per mile for the 75 to 100-mile region. On average, the cost per mile within the total 100-mile procurement region was around $0.37 per dry ton per mile. Average costs per ton per mile decreases by distance because the loading cost and other fixed costs are spread over more miles.

Table 5-7: Summary of estimated transportation costs for hauling woody biomass from three procurement regions, a 0 to 50-mile, a 50 to 75-mile, and a 75 to 100-mile region, to the hypothetical energy plant located in Williamsport, PA.

Procurement region (miles)	Travel distance mean (miles)	Round trip travel time mean (minutes)	Loading cost ($/dry ton)	Hauling cost mean ($/dry ton)	Transportation cost mean ($/dry ton)	Transportation cost range ($/dry ton)	Transportation cost mean ($/dry ton/mile)
0-50	47.08	124.26	7.27	13.47	20.74	8.80 - 41.98	0.51
0-75	88.36	214.36	7.27	23.12	30.39	22.37 - 74.35	0.35
0-100	125.53	272.23	7.27	30.43	37.70	28.29 - 52.75	0.30

5.5.4 Roadside and Delivered Costs

Roadside costs for each plot were estimated by dividing the total cost of stumpage and the estimated harvest cost for tops and limbs and for whole-tree chips by the total volume of biomass produced on the plot. The estimated average roadside cost for woody biomass within the 100-mile radius was estimated to be about $72 per dry ton (Figure 5-1). This estimate was within the range of $37.06 to $110.00 per dry ton ($18.53 to

$55.00 per green ton) estimated by McDill et al. (2011) based on an actual integrated harvest system of four different silvicultural system (clearcut, shelterwood, thinning, salvage thinning) in Pennsylvania. Nonetheless, the roadside cost in the FIA plots tends to vary greatly, ranging from $11 to $6,051 per dry ton due to the variability of the estimated harvest costs.

The delivered cost of woody biomass from each plot was estimated by combining the roadside and transportation costs for each FIA plot. Roadside cost was the major component of delivered cost in all procurement regions, accounting for 75% in the 50-mile region, 73% in the 50 to 75-mile region, and 65% of delivered cost in the 75 to 100 mile region (Figure 5-1). For the 100-mile radius, on average, about 70% of delivered cost was accounted for by roadside cost. The share of the delivered cost due to transportation costs was 35% in the 75 to 100-mile region, followed by 27% in the 50 to 75 mile region, and 25% in the 50-mile region. Within the 100-mile radius around the energy facility, transportation costs accounted for about 30% of the total delivered cost.

As the cost estimate did not include any profit that might be earned by the loggers, actual harvesting costs could be somewhat higher. Also, the diesel fuel price reflects the current price conditions (in December 2012). A change in the fuel price would affect the estimated delivered cost, as it directly affects both the transportation cost and harvest cost estimates. Labor and equipment costs are also subject to change, but are less volatile than fuel prices.

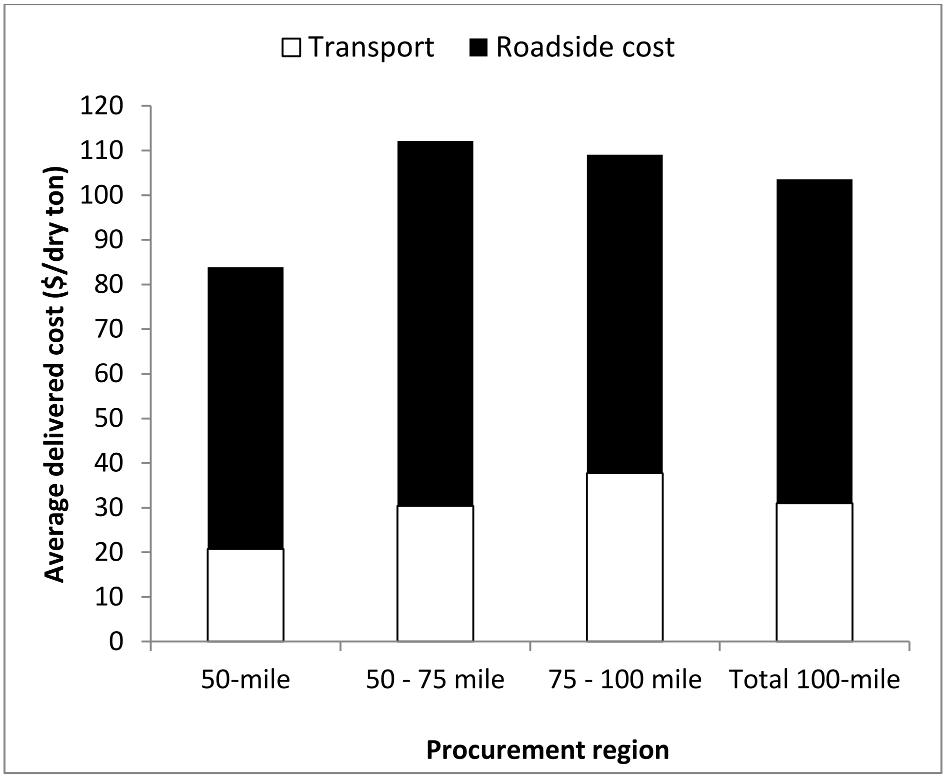


Figure 5-1: Average delivered cost composition of woody biomass by procurement regions.

5.6 Estimated Supply Curves

To develop supply curves, the estimated per-acre quantity for each type of woody biomass, whole-tree chips and tops and limbs was multiplied by the acres represented by the plot expansion factors determined as accessible for harvest based on biophysical and social constraints. Total woody biomass biophysically, socially, and both biophysically and socially available in each plot were derived by combining the estimated volume of whole-tree chips and tops and limbs. The per-acre roadside cost of woody biomass for each type of availability on each plot was then determined by dividing the total cost, which consists of stumpage and harvest costs for each type of woody biomass, by the total potential quantity of woody biomass available. Transportation costs were then added to the estimated roadside cost to derive the delivered cost of woody biomass from each plot to the energy facility. Supply curves were then constructed using information about the potential quantity of woody biomass biophysically, socially, and both biophysically and socially available with the associated roadside and delivered costs for each plot. Plots were sorted from least cost to highest cost, and cumulative quantities were calculated for successively higher costs.

5.6.1 Base Case Supply Curve

Woody biomass supply curves for the total 100-mile region, the 50-mile region, the 50 to 75- mile region, and the 75 to100-mile region around energy facility are shown in Figures 5-2, 5-3,5-4, and 5-5, respectively. The supply curves in the figures assume that the biomass is produced through clearcut regeneration harvests using the base-case biophysical and social constraint thresholds and the base-case pulpwood-utilization scenario. The supply curves show how the roadside and delivered costs progressively increase as a larger amount of woody biomass is utilized. As expected, adding transportation costs to the roadside costs shifts the supply curves upward.

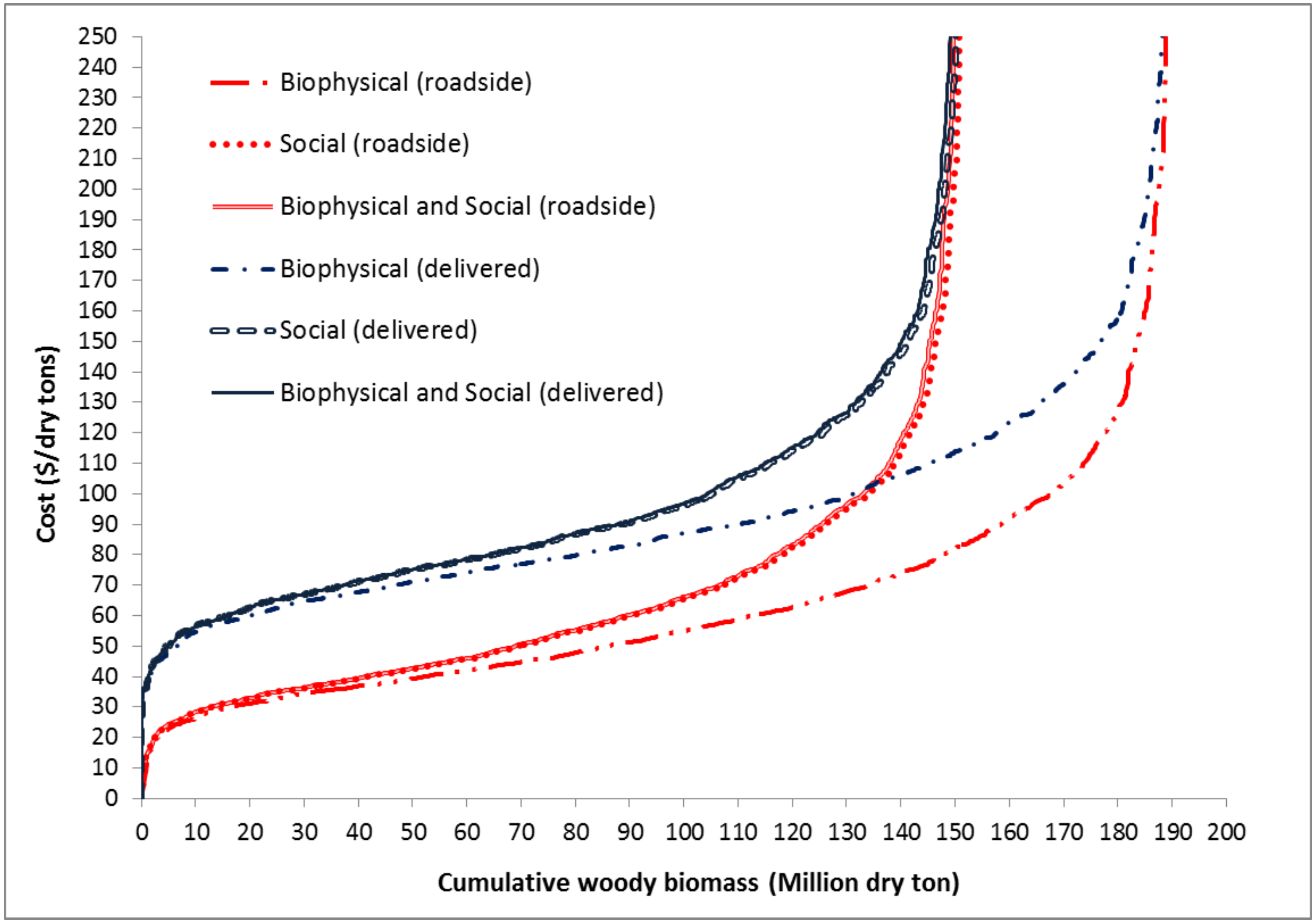


Figure 5-2: Woody biomass supply curve for the 100-mile region. The supply curve assumes the biomass is produced with clearcut regeneration harvests, base-case biophysical and social constraints thresholds, and the base-case pulpwood utilization scenario. The different curves show delivered vs. roadside supply and the impact of social and biophysical constraints.

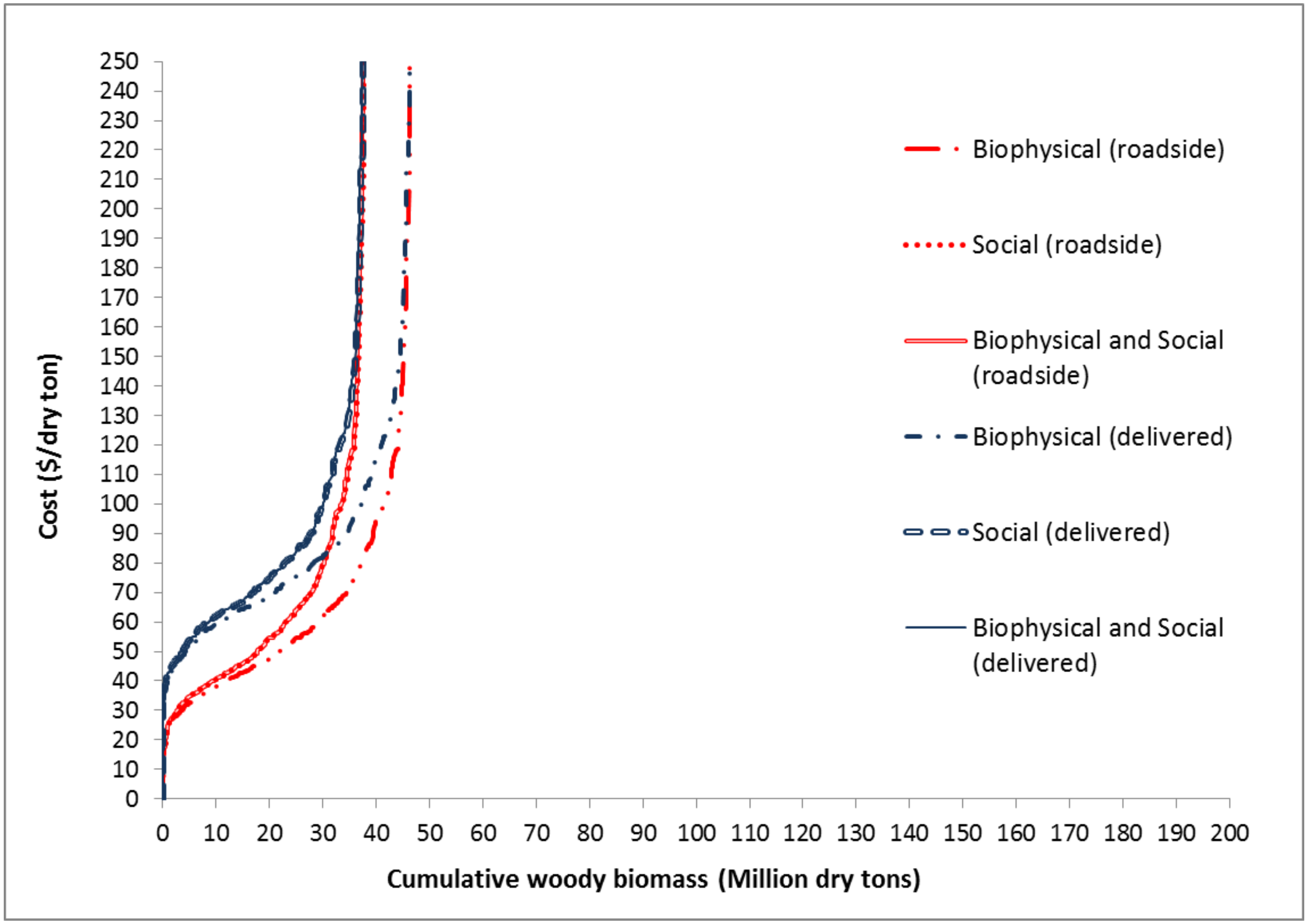


Figure 5-3: Woody biomass supply curve within 50-mile radius around hypothetical energy facility. The supply curve assumes the biomass is produced with clearcut regeneration harvests, base-case biophysical and social constraints thresholds, and the base-case pulpwood utilization scenario.

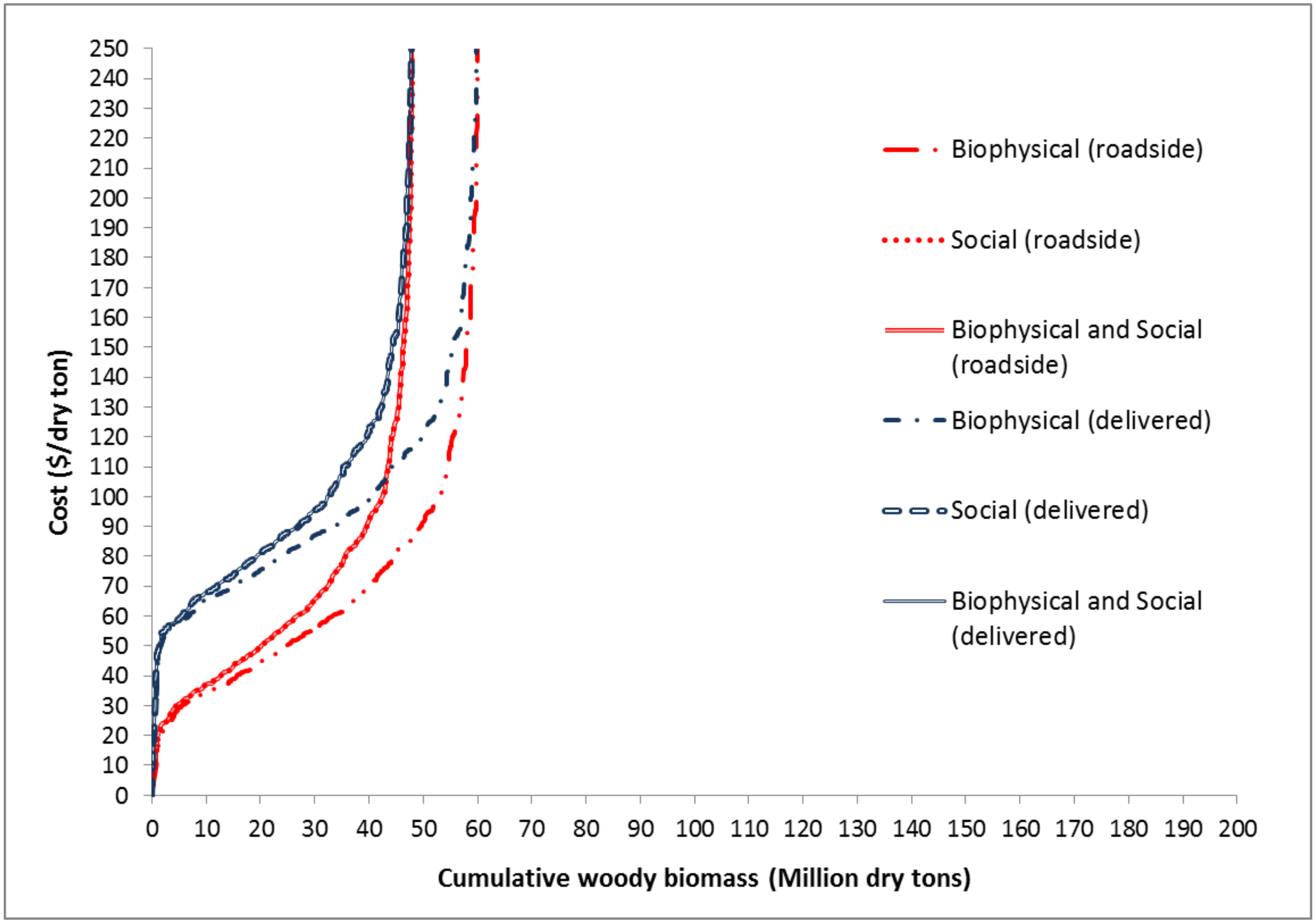


Figure 5-4: Woody biomass supply curve within 50 to 75-mile radius around hypothetical energy facility. The supply curve assumes the biomass is produced with clearcut regeneration harvests, base-case biophysical and social constraints thresholds, and the base-case pulpwood utilization scenario.

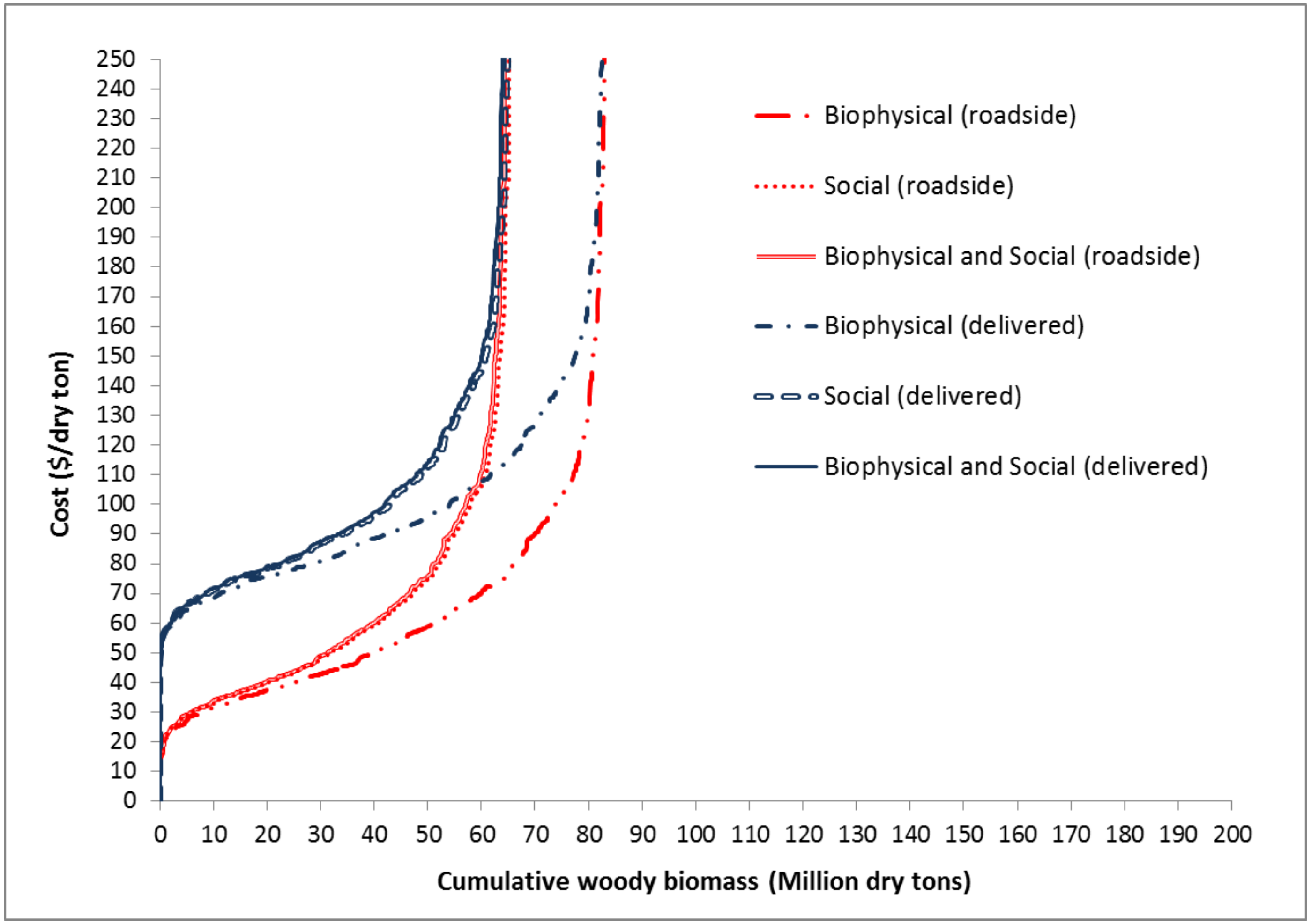


Figure 5-5: Woody biomass supply curve within 75 to 100-mile radius around hypothetical energy facility. The supply curve assumes the biomass is produced with clearcut regeneration harvests, base-case biophysical and social constraints thresholds, and the base-case pulpwood utilization scenario.

Biophysical and social constraints limit the amount of forestland that is accessible for harvesting. This reduction in turn reduces the total potential quantity of woody biomass available for energy use, shifting the supply curve to the left and reducing the estimated amount available at a given cost. Within the entire 100-mile radius, the maximum potential quantity of woody biomass available at any price after accounting for biophysical (i.e., slope, site productivity, physiographic class), social (reserved forest, riparian buffers, size of forest holding, and PFLs opposition to harvest) and both biophysical social constraints was 189.48, 151.06, and 149.96 million dry tons, respectively (Figure 5-2). The quantities of woody biomass supplied from the three procurement circles, 50-mile, 50-75 mile, and 75-100 mile are shown in Figures 5-3, 5-4, and 5-5, respectively. The estimated maximum potential quantity after applying biophysical, social and both constraints were 46.33, 37.67, and 37.51 million dry tons, respectively, in the 50 mile region, 60.03, 47.98, and 47.89 million dry tons in the 50-75 miles region, and 83.12, 65.41, 64.56 million dry tons in 75-100 mile region.

Of course, the quantity that would be economically available for use in the energy facility depends on the price the facility is willing to pay for biomass. To show the collective effect of biophysical, social, and economic constraints on the potential supply of woody biomass to the energy facility, a supply schedule was developed for three cost levels: $50, $100, and $150 per dry ton. At a roadside cost of $50 per dry ton, the estimated quantity that would be supplied from the total 100-mile region, after accounting for both biophysical and social constraints, was 69.00 million dry tons (Table 5-8). However, for a delivered cost of $50 per dry ton, the estimated quantity of woody biomass that would be delivered was notably less, only 4.60 million dry tons. The results show that economic constraints (i.e., cost and willingness/ability to pay) strongly influence the total potential quantity of woody biomass that would be supplied to the energy facility. The degree to which economic constraints limit the amount supplied depends on the price the facility is willing to pay for biomass.

Table 5-8: Estimated quantities of woody biomass that can be supplied from clearcutting regeneration harvests within the energy facilities procurement regions at three roadside/delivered cost levels: $50, $100, and $150 per dry ton. Results are for the base-case constraint thresholds and the base-case pulpwood biomass utilization scenario.

Roadside/ delivered cost per dry ton	Constraint	Potential quantity at roadside (million dry tons)				Potential quantity delivered (million dry tons)			
		50-mile	50-75 mile	75-100 mile	Total 100 mile	50-mile	50-75 mile	75-100 mile	Total 100 mile
$50	Biophysical	21.77	24.73	39.81	86.31	4.25	1.59	0.12	5.96
	Social	17.64	20.15	31.74	69.54	3.21	1.27	0.12	4.60
	Biophysical and social	17.62	20.11	31.27	69.00	3.21	1.27	0.12	4.60
$100	Biophysical	42.19	52.58	73.30	168.07	37.26	40.40	54.07	131.66
	Social	34.37	42.29	57.56	134.22	30.04	32.44	42.85	105.33
	Biophysical and social	34.21	42.21	56.71	133.12	30.10	32.39	41.89	104.38
$150	Biophysical	44.90	57.81	80.67	183.39	44.60	55.32	77.50	177.42
	Social	36.64	46.35	63.43	146.42	36.31	44.27	60.84	141.36
	Biophysical and social	36.47	46.27	62.58	145.32	36.14	44.19	59.92	140.25

As expected, the social constraints reduce the potential quantity of woody biomass available more than the biophysical constraints (Table 5-8). Much of the reduction due to social factors is due to PFLs opposed to harvest (See Table 5-3). This finding is consistent with previous work that found social constraints have a greater effect on the amount of forestland accessible for harvest and thus the quantity of wood available than biophysical constraints (Butler et al., 2010; Metcalf, 2010; Metcalf & Finley, 2011). This study adds to the previous work by including economic constraints that potentially have an even greater effect on the economically, socially and biophysically feasible supply of biomass for energy production.

Not surprisingly, at $50 per dry ton almost 70% of the delivered supply comes from the 50-mile region (Table 5-8). At this price, the 50 to 75-mile region provided only 27% of the delivered quantity, and the outer-most region (75 to 100-miles) contributed only about 2% of the supply. This shows the importance of transportation costs in limiting the size of the procurement region when woody biomass prices are low. This suggests that at relatively low biomass prices, an energy facility that uses woody biomass from natural forests must be optimally located near to the potential supply. Even so, delivered cost is a function of both harvest and transportation cost and is highly variable. Thus, while much of the supply was sourced from within 50-mile region some wood would still be delivered from as far away as 75 miles. When biomass is hauled from these longer distances, this was made possible by lower roadside costs at those sites, which largely depend on harvesting costs. These variations of roadside and transportation cost were noted by Galik et al. (2009) in attributing greater influence to the economic feasibility of woody biomass as an energy feedstock. This study has shown how both roadside and transportation costs can be accounted for by incorporating potential quantity and delivered cost, and the distribution of potential supplies within the procurement region with the least cost can be identified. This enables interested stakeholders to make more informed decisions as information on the amount of woody biomass that could be available at a given cost can be obtained from the supply curve.

5.6.1.1 Base Case Supply Response

Delivered supply curves for woody biomass within the 100-mile region (See Figure 5-2) have three notable regions of supplies. The first region – between delivered costs of about $25 and $59 per dry ton – shows a gradual increase of supply. Anecdotal evidence suggests that current market price for wood chip is $56 per dry ton ($28 per green ton). This means that wood chip users are currently exploiting the first low-cost supply region. However, supply within this region is relatively small as compared to the second region, between $60 and $110 per dry ton, which is a more elastic region. This suggests that at a slightly higher price than the current market price, abundant of supplies could be available. In the final region – greater than $110 per dry ton – the supply curve becomes steep and highly inelastic. This indicates that the resource is becoming exhausted and supply moves to the most expensive material.

To investigate supply response at different price points, arc elasticity of supply at four delivered cost levels – $50, $75, $100, and $150 per dry ton – were estimated (Table 5-9). Results showed that at about $50 per dry ton, the supply is elastic and sensitive to price changes. The arc elasticity estimates for the biophysical, social, and both biophysical and social supply functions are all greater than 1 at this price level. This indicates that at this price level, the amount supplied to the market is quite sensitive to price changes and higher prices will result in substantially higher supplies. The result also showed that the supply becomes highly elastic at delivered costs around $75 per dry ton with arc elasticity estimates above 7. This indicates that at this price level, the amount supplied is very sensitive to price changes. At a delivered cost of $100 and $150 per dry ton, however, all estimated arc elasticity are less than 1, meaning that supply is inelastic and the potential supply cannot be not greatly influenced by increasing the price.

Table 5-9: Arc elasticity estimates at three different delivered cost levels for biophysical, social and both biophysical and social constraint supply functions. The results are based on base case pulpwood utilization scenario.

Delivered cost/dry ton	Biophysical	Social	Biophysical and social
$50	1.72	1.69	1.67
$75	7.01	7.84	7.87
$100	0.47	0.48	0.48
$150	0.11	0.11	0.11

5.6.1.2 Woody Biomass Annual Supply

To provide an annual supply estimate for woody biomass within a 100-mile radius around the hypothetical energy facility, the estimated delivered supply of woody biomass for the base-case biophysical and social constraint thresholds and base-case pulpwood utilization scenario (See Figure 5-2, biophysical and social (delivered)) were converted to annual supplies using estimated annual rate of growth (2.1%) (See Table 5-1). The estimated annual supply curve for woody biomass is shown in Figure 5-6. The shape of the curve is similar to the supply curve depicted in Figure 5-2. Almost 97,000 dry tons of woody biomass could be supplied annually to the hypothetical energy facility at a delivered cost of $50 per dry ton (Table 5-10); at $75 per dry ton, the potential annual supply increased to 1.32 million dry tons.

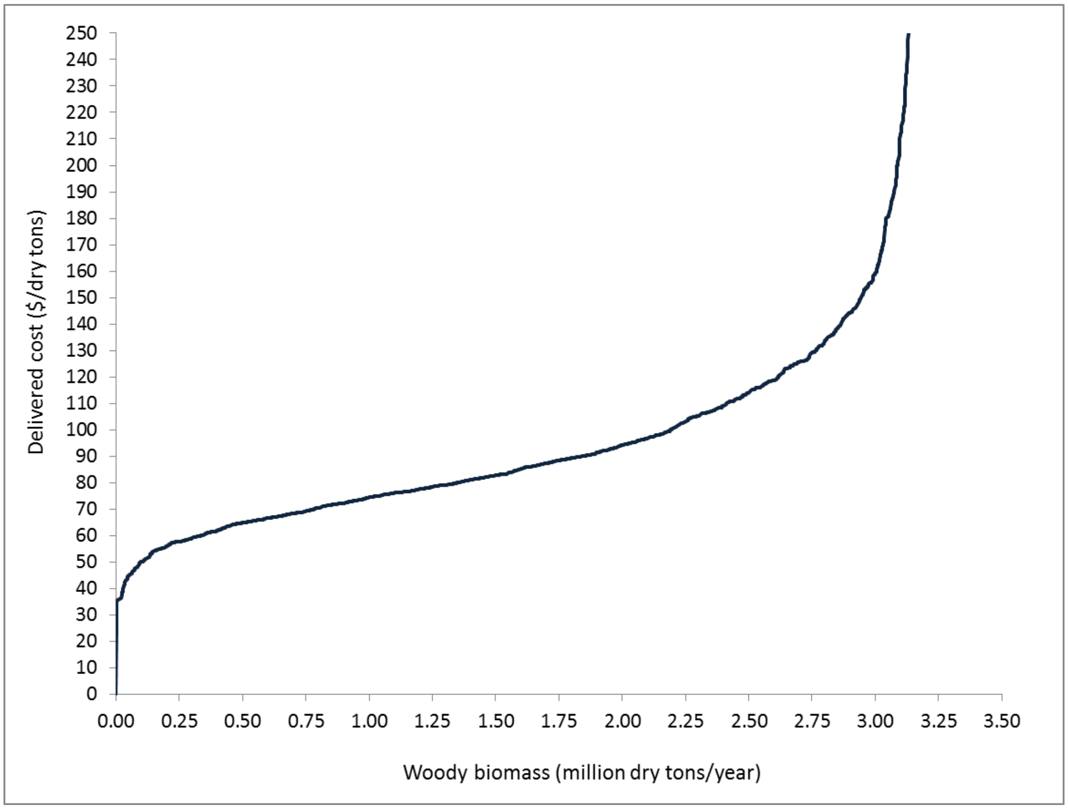


Figure 5-6: Annual supply of woody biomass and delivered cost within the 100-mile for base-case pulpwood utilization scenario and base-case biophysical and social constraint thresholds.

Table 5-10: Annual supply of woody biomass at four delivered cost levels. The results are based on base-case pulpwood utilization scenario and base-case biophysical and social constraint thresholds.

Delivered cost/dry ton	Estimated quantity (million dry tons)	Estimated quantity (million dry tons/year)
$50	4.60	0.097
$75	62.70	1.317
$100	104.38	2.192
$150	140.25	2.945

The estimated annual supply of woody biomass provided in this study would be a lower bound in this region, as the region has a large inventory of low use wood and reducing this inventory by harvesting more than the amount grown each year would likely be desirable. As indicated by the G:R estimated earlier (2.03) (See Table 5-1), the current inventory level is expected to continue to grow given the current harvest rate. Thus, if current low-use wood inventories levels are higher than desired, it would be prudent to increase the harvest rate to up to twice as much as the current growth rate over the medium term (~ 50 years). Applying this harvest regime, annual supplies of woody biomass in the medium term could be doubled relative to the estimates presented here. However, in the long run, the harvest rate would need to be reduced and should not exceed growth if one would like to maintain the standing inventory for sustainability.

5.6.2 Supply Sensitivity to Biophysical and Social Constraints Threshold

In this study, biophysical and social variables representing constraints on access for harvesting in both public and private forestlands were based on the literature and available data. The reduction formula from Butler et al. (2010) was adapted to systematically reduce the volume expansion factors for each inventory plot when a constraint or multiple constraints were observed at that plot to determine the area accessible for harvest represented by that plot. The previous section discussed the sensitivity of inaccessible forestland area within a 100-mile radius around the energy facility due to changes of biophysical and social constraint thresholds. Not surprisingly, using less restrictive biophysical and social constraint thresholds in the high case increased the amount of forestland assumed accessible for harvest, whereas using more restrictive thresholds in the low case decreased the assumed area of forestland assumed to be accessible. This section assesses the effects on the potential woody biomass supplies due to changes in the biophysical and social constraint thresholds using a supply curve approach.

More forestland is inaccessible for harvest in the low case because the constraint thresholds are more restrictive. This results in a lower quantity of woody biomass available for energy use compared to the case with the base constraint thresholds. Similarly, more forestland is accessible in the high case, and more biomass is projected to be available when less restrictive thresholds are applied. Figure 5-7 shows how the supply curves move to the left of the base-case curves when the low-case thresholds are applied and to the right of the base case when the high-case thresholds are applied.

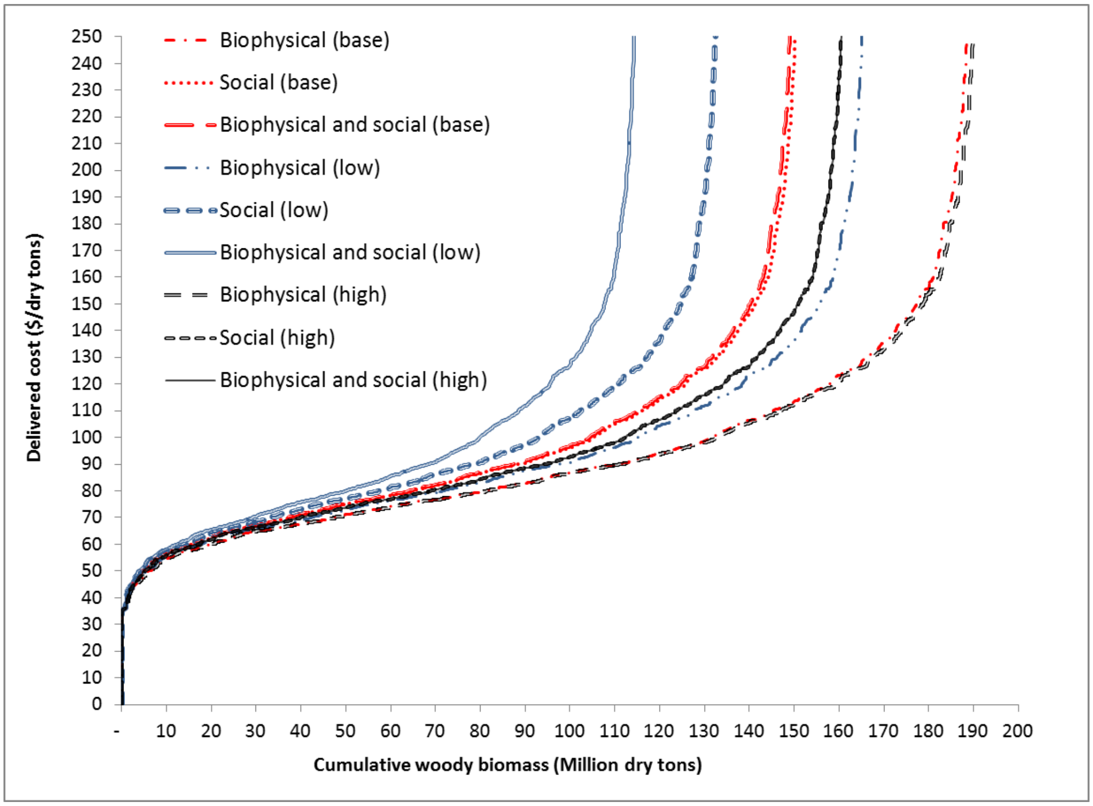


Figure 5-7: Sensitivity of woody biomass quantity and delivered cost within 100-mile radius around energy facility to biophysical and social constraint thresholds. Results are based on the base-case pulpwood biomass utilization scenario.

The maximum potential quantity available was reduced in the low case by 12.4% (to 166.03 million dry tons) by the biophysical constraints and by 11.8% (to 133.22 million dry tons) for by the social constraints, and by 23% (to 115 million dry tons) when both biophysical and social constraints are applied. Figure 5.7 shows that the low-case curves are significantly to the left of the base-case curves. As has been shown previously in the sensitivity analysis of forestland accessible for harvest in the low case analysis, slope and opposition to harvest were the most important biophysical and social factors.

For the high case, using less restrictive constraint thresholds increased the estimated quantity supplied for energy production only slightly relative to the base case, as only slightly more forestland would be accessible for harvest with these constraint thresholds. Figure 5-7 shows that the high case curves are only slightly to the right of the base case curves. The increases in potential quantities relative to the base case were rather small, with an increase of about 0.7% at the maximum (190.86 million dry tons) for the curve with only biophysical constraints, an increase of 6.4% (161.41 million dry tons) at the maximum for the curve with only social constraints, and an increase of 7.1% (151.41 million dry tons) for the curve with both biophysical and social constraints. This occurs mainly because in the high case some of the key thresholds were the same in the high case as the base case. For example, the slope threshold was kept at 40% mainly due to the ground-based harvest machine limitation in the FRCS cost model. Since the supply curve is quite sensitive to slope changes, as illustrated by the low case, future studies could potentially analyze a slope constraint threshold up to 50% or higher for the high case and estimate harvest costs in FRCS using a cable yarding system for slopes above 40%. This, would increase the maximum potential quantity but only at very high costs since cable yarding systems are expensive (Fried et al., 2005). Also, the amount of woody biomass left on site would need to be increased for slopes greater than 40% for environmental sustainability purposes (U.S. Department of Energy, 2011).

Table 5-11 shows the sensitivity of estimated woody biomass supplies within the100-mile radius around the energy facility to changes of biophysical and social constraint thresholds at delivered costs of $50, $100, and $150 per dry ton. Similar to the base case, in both the low and the high case, the estimated woody biomass supplied at $50 per dry ton is relatively small compared to the total estimated quantity potentially available with no price restrictions. At a delivered cost of $100 per dry ton the estimated quantity supplied increases dramatically, and nearly all of the potential supply within 100 miles of the energy facility can be delivered at cost of less than $150 per dry ton. Supplies in the low-threshold case were between 18 and 24% lower when all constraints were applied than in the base case, with the difference between the low and the base case increasing as the price increases. Supplies in the high-threshold case were 7 to 8% higher when all constraints were applied. Again, the differences between the high and the base case increased as the price increased. At all cost levels and in both the low and the high constraint threshold cases, social constraints had greater effect on estimated supplies than the biophysical constraints.

Table 5-11: Estimated woody biomass supplied from a 100-mile radius around the energy facility for low, base, and high case biophysical and social constraint thresholds at three different delivered cost levels: $50, $100, and $150 per dry ton. The results are for the base-case pulpwood biomass utilization scenario.

Delivered cost/dry ton	Constraint	Potential quantity at different biophysical and social constraint threshold supply scenarios (million dry tons)		
		Low supply	Base supply	High supply
$50	Biophysical	5.61	5.96	5.99
	Social	4.06	4.60	4.96
	Biophysical and social	3.74	4.58	4.90
$100	Biophysical	115.25	131.67	132.89
	Social	93.03	105.33	112.37
	Biophysical and social	79.93	104.38	112.01
$150	Biophysical	155.65	177.42	178.80
	Social	124.74	141.36	151.01
	Biophysical and social	106.47	140.25	150.91

5.6.3 Pulpwood Biomass Utilization Scenario

Recall that in the high-case woody biomass supply scenario, all pulpwood-sized biomass was assumed available for the energy use, whereas for the low-case supply scenario, all pulpwood-sized biomass was assumed utilized by the traditional pulpwood using industries. In the base case, the assumption was that the traditional pulpwood using industries used 30% of the pulpwood-sized material in the supply region. The following analysis uses the base-case thresholds for both the biophysical and social constraints.

Figure 5-8 shows that under the base-case pulpwood-sized biomass (PU) supply scenario, the maximum potential quantity available was 149.96 million dry tons. In the low-case PU supply scenario the maximum quantity reduced from the base case by 23.1% to 115.25 million dry tons. The maximum supply increased by 8.3% to 162.43 million dry tons in the high case. The supply curves also show that at low quantities and prices the low-case curve lies below the base-case curve before it crosses the base-case curve, at about $70 per dry ton, and rises more rapidly as quantities increase. In contrast, the high-case curve is slightly above the base case curve at low quantities but rises more gradually as more quantity is supplied. From this observation it is likely that pulpwood is a complementary material at lower price level. This is evident by a rightward shift of the supply when pulpwood-sized biomass is produced for the traditional pulpwood industry due to the competitive market, which in turn generates more biomass as a byproduct. Another interesting observation is that there is no competition for material at lower cost since the amount of material supplied or supplied together relatively small. However, as the curves begin to diverge, competition for material becomes apparent.

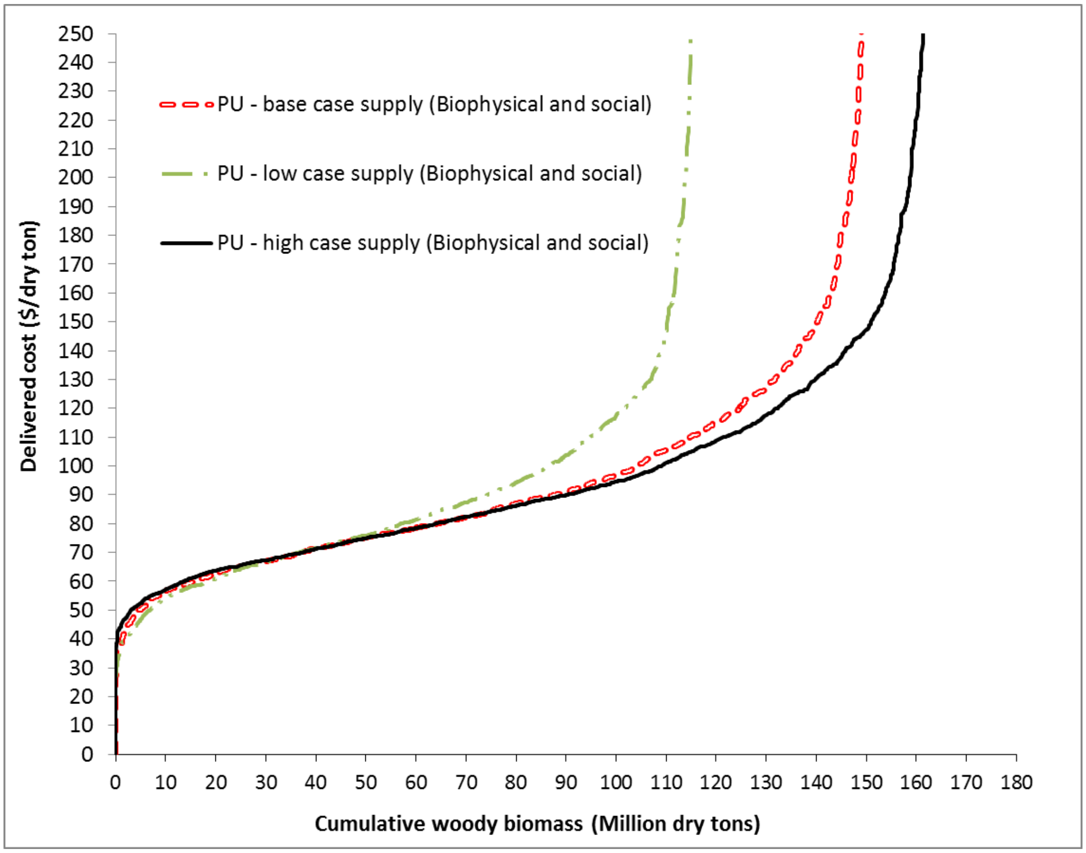


Figure 5-8: Estimated woody biomass delivered cost supply curves for the 100-mile radius around the energy facility for three pulpwood-sized biomass utilization (PU) supply scenarios. The results are based on base case constraint thresholds for both biophysical and social constraints.

A supply schedule was developed for three delivered cost levels – $50, $100, and $150 per dry ton – for each of the PU supply scenarios to describe the supply curves in greater detail (Table 5-12). At a delivered cost of $50 per dry ton, the potential supply of woody biomass is greater in the low-case PU supply scenario than the base case, with an estimated quantity supplied at this price of 6.83 million dry tons versus 4.60 in the base case. In contrast, in the high case, the quantity supplied at $50 per dry ton is only 3.03 million dry tons. However, at higher delivered prices – $100 and $150 per dry ton – the amount supplied to the energy plant for the low case is notably lower than in the base case and the base-case supply is lower than the high case, as expected. The reason for the higher quantity supplied in the low-case scenario at low prices is that more biomass is being produced from the tops and limbs from the pulpwood-sized trees. Since only chipping costs are attributed to tops and limbs, this material is much cheaper. However, the amount of material produced this way is relatively small, so when larger quantities are needed, the chips must be obtained with more expensive whole-tree chips. In general, supplies of chips for energy are less when some of the potential biomass is used by traditional users of pulpwood-sized material. These results suggest that having a competitive traditional pulpwood using industry results in a small low-cost supply of chips for energy, but when larger supplies are needed conventional users of pulpwood are competitive with the energy market.

Table 5-12: Estimated potential quantity of woody biomass at different delivered cost levels for three pulpwood-sized biomass utilization (PU) supply scenarios. The results are based on base case constraint thresholds for both biophysical and social constraints.

Delivered cost /dry ton	Potential quantity biophysically and socially available (million dry tons)		
	PU (low case supply)	PU (base case supply)	PU (high case supply)
$50	6.83	4.60	3.03
$100	86.41	104.38	109.09
$150	110.19	140.25	150.98

Chapter 6

Conclusions

Many factors affect the availability of woody biomass supplies from natural forests. This study looked at the factors that affect the supply of woody biomass for a hypothetical energy facility located in Williamsport, PA. Biophysical and social constraints affect the accessibility of forest for harvesting. Economic constraints include factors that determine the cost of harvesting woody biomass from the forest and delivering it to the energy facility, as well as the presence and impact of competing industries that use similar material. Few studies have attempted to account for the full suite of factors that constrain woody biomass availability for a potential energy location. As a result, business developers and wood procurement managers often struggle to estimate potential supplies of woody biomass within a potential wood procurement area. This study has developed and applied an analytical framework for a systematic assessment of sustainable woody biomass supplies for a potential energy facility location that takes into account biophysical, social, and economic constraints. By applying the framework to a case study of siting woody biomass on a hypothetical energy facility, this study explores the characteristics of the potential supplies with respect to biophysical, social and economic constraints.

The procedure to implement the framework starts with an assessment of the resource condition within the proposed energy procurement region. The results suggest that forests within the proposed energy facility’s procurement region are productive and growing at an annual rate of 2.1% and indicate that at landscape level overharvesting is not occurring and that harvest levels could be more than doubled without reducing current inventories.

After the initial assessment of forest conditions, key information was identified and developed that was instrumental for developing supply curves for the energy facility's procurement regions. This included estimating the potential woody biomass volume per acre on each FIA plot that could be harvested in a clearcut regeneration cut while accounting for environmental sustainability retention factors. Plot expansion factors were then adjusted, using reduction analysis, to estimate the area of forestland represented by each plot that was estimated to be accessible for harvest based on biophysical, social, and both biophysical and social constraints. The forestland area reduction analysis performed for this study corroborates other researchers' conclusions that, in the Eastern US, at least, social constraints have a larger impact on the accessibility of forestland for harvest than biophysical constraints. The study found that of all the social constraints, PFLs' opposition to harvest has a greater impact on available forestland area. Of the biophysical constraints, slope was found to be the most important factor. The total volume that can be supplied that is represented by a plot is equal to the volume of biomass that can be produced per acre times the adjusted plot expansion factor.

The next step was to estimate the roadside and delivered costs. Roadside costs were calculated by combining stumpage and harvest costs, and the delivered cost is the sum of roadside and transportation costs. The results of this analysis show that harvest and transportation costs are highly variable. Simulated harvest cost estimates based on whole-tree integrated harvesting employing both mechanical and manual harvest systems for both tops and limbs and whole-tree chips across the 100-mile procurement region ranged from $9.05 to $6,048 per dry ton. Variation in the harvest cost estimate is due to differences in site conditions found on each plot (i.e., slope), the harvest system used (i.e., manual or mechanical), and especially the harvest volume per acre, as these are the key input variables used to simulate harvesting costs. Variation in the estimated transportation cost estimates is primarily due to different FIA plot locations relative to the energy facility. The distance and type of road between the plot and the energy facility affects travel time, which is a function of distance and speed travelled on each road segment. Estimated transportation costs across the 100-mile procurement region ranged from $8.80 to $74.35 per dry ton. While transportation costs are significant, this study found that average roadside cost accounted for a greater portion of the average delivered cost component. Cost estimates are subject to change, particularly the stumpage cost and fuel price, which could vary depending on location and market conditions. Also noteworthy, cost estimate did not account for any profit to loggers.

The last step in applying the analytical framework proposed here was to combine the estimated quantity of biomass represented by each plot with the estimated roadside and delivered cost to develop woody biomass supply curves. The supply curves in this study show the estimated cost as a function of the quantity of woody biomass that needs to be delivered to the hypothetical energy facility after accounting for the various factors that constrain availability. In addition, the curves show the cumulative effect of the biophysical, social, and economic constraints modeled in this study on potential woody biomass supplies. Within the 100-mile radius around energy facility at a roadside cost of $50 per dry ton, 69.00 million dry tons can be produced under both biophysical and social constraints. At a delivered cost of $50 per dry ton the quantity available for use in the energy facility drops dramatically with only 4.60 million dry tons. At same price level, about 97,000 dry tons per year of woody biomass could be supplied to the hypothetical energy facility. At $50 per dry ton almost 70% of the delivered material was from within the 50- mile region, 27% was from the 50 to 75-mile region, and only about 2% was from the 75 to 100-mile region. This clearly shows the effect of delivered cost on affordable woody biomass that could be hauled to the energy plant, which, at this low price, is largely a function of transportation cost. At all cost levels selected for the supply schedule, social constraints had greater impact on the available quantity of woody biomass than biophysical constraints, which confirms other researchers' findings for the eastern US. This study has refined previous studies by incorporating economic constraints (i.e., cost). The study also shows that the degree to which economic constraints affect supplies depends on the ability or willingness of the facility to pay for material.

The supply curve analysis can also be used to assess the sensitivity of woody biomass supplies to changes in the biophysical and social constraint thresholds. The study demonstrated how the supply curve analysis can be used to assess the effects of using more or less restrictive thresholds on the potential woody biomass quantity available at a given cost. Supply curves were also used to assess the effect on cost and quantity resulting from different assumptions about pulpwood-sized biomass utilization by traditional pulpwood users and the energy sector. In the low case, where all pulpwood-sized biomass was assumed to be used by traditional pulpwood users, the supply of low-cost chips is actually greater, largely because more biomass is being procured from the tops and limbs of the pulpwood-sized trees, which is a much cheaper material. For the high case, in which all pulpwood was used for energy generation, at higher prices at least, more biomass would be available compared to the base case scenario.

There are some fairly significant uncertainties in some of the parameters used in our study, especially for the social constraints. These include uncertainties about the number of NIPFLs opposed to harvest and regarding the number who are not opposed but will not actually conduct harvest on their land due to factors beyond the scope of this study. In particular, NIPFLs willingness to harvest woody biomass as part of a timber harvests can be influenced by various factors, especially price. The potential supplies provided in this study are based on the assumptions that landowners would participate in woody biomass market given stumpage price of $6 per dry ton of woody biomass. Although this price assumption is based on the current market price, however, it is uncertain whether landowner would be willing to enter woody biomass market for this price. Also, some landowners may be willing to conduct harvesting at a loss if the treatment increases the future profitability of their land (e.g., improvement thinning or rehabilitation of high-graded stands). Therefore, better information on factors that affect landowner decisions to engage in woody biomass markets in Pennsylvania would improve the supply estimates provided in this study. In addition, although a large amount of public forestland was assumed potentially accessible for harvest, the actual accessibility would depend on the public policies that govern the way the agencies manage public forests, in particular, their polices related to timber harvest practices such as whole-tree harvesting. Nonetheless, the BoF and Pennsylvania Game Commission, which are the public agencies that manage the state forest, do offer timber for sale as part of their forest management practices.

One of the challenges in conducting this study was finding a good woody biomass harvest cost model suitable for forest conditions in Pennsylvania and that has flexibility in how joint product costs are modeled in an integrated harvest setting. How these costs are modeled would affect the cost estimates used here. Thus, a better cost model that can appropriately predict harvest cost from an integrated harvest system in the region, especially in Pennsylvania, should be developed that can be accessed publicly. Also, as stated earlier, this study provides cost estimates for dirty chips due to limitation of the FRCS cost model. Typically, larger diameter stems can be debarked to produce clean chips, which are more expensive due to the additional equipment required for the debarking process but have higher value than dirty chips.

Although it was assumed that a certain percentage (70%) of pulpwood-sized biomass is available for energy use for the base case, this estimate was based on subjective expert opinion regarding pulpwood consumption in Pennsylvania. Woody biomass supplies likely would be influenced by competition from existing and potential competitors for the same raw material within the expected wood procurement area. Typically, a large percentage of the procurement area that overlaps with the procurement areas of several competing users would indicate a high level of competition for raw materials and would suggest that increasing the demand in the region will lead to increases in stumpage costs in the region. This could threaten the viability of the proposed energy plant. Thus, an analysis of overlapping procurement areas from potential competing users of woody biomass, both for the traditional pulpwood users and for energy facilities is needed to ensure that introducing a new energy facility in the proposed location will not lead to strong competition for the existing resource. Due to time constraints, however, such analysis was not included in this study. Future studies should include a competing user's analysis, and this analysis is retained in the woody biomass supply analysis framework proposed in this study.

Future work on model improvement could include modeling harvest costs using variable harvest tract sizes for FIA plots based on county-specific parcel-size information to improve the accuracy of the harvest cost estimates. In Pennsylvania, a significant portion of private forests, especially in more developed area of the state, belong to NIPFLs owning smaller parcels. Since harvesting smaller parcels is much more expensive than larger ones, different results can be expected if a different parcel size distribution was modeled. In particular, we expect that the estimated supply curve would become less elastic. Additional work could also consider other harvest systems such as cut-to-length methods and cable yarding for slopes greater than 40%. Also, since stumpage and fuel prices can change considerably depending on market conditions, it would be interesting to consider the effect on delivered cost estimates and elasticity of the supply curve due to changes in stumpage and fuel prices assumptions. In this study, the analytical framework is designed to estimate woody biomass supply from conducting regeneration harvest focusing on cleacutting method. Thus, future studies could also develop supply estimates based on other silvicultural systems commonly used in the region such as shelterwood harvests. A life-cycle analysis is another area of research that could be incorporated into the analytical framework to address the carbon neutrality issue. A computer-aided tool to facilitate data entry, perform analyses, and generate results could also be developed.

This study is unique in terms of the procedure developed to estimate woody biomass supply that integrates biophysical, social, and economic factors that limit the availability of the material for energy use. To my knowledge, such an approach has not been applied in any studies designed to address woody biomass supply from natural forests in the eastern U.S. The procedure is flexible and allows analysts to change most of the assumption used in this study. For example, it is relatively easy to change the biophysical and social constraint thresholds and reduction rates used in this study, as well as the assumption about the current pulpwood utilization rate. Although the results presented in this study are specific to the case study area, the procedure developed in the analytical framework can be applied in other potential market areas where similar data are available. The proposed procedure can be utilized, using publicly available data and models, by organizations interested in evaluating initial feasibility and subsequent operation of woody biomass-based energy facilities that require accurate and dependable information on supply within their expected wood procurement area. In addition, the results from this study will be useful to policy makers, forest landowners, forest planners, and public agencies, to understand better the collective impact of biophysical, social and economic constraints toward the potential supplies of woody biomass for energy use. This will help them develop strategies or policies to support the future development of woody biomass-based energy systems.

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Appendix

Table A.1: List of counties within 100-mile radius around the energy facility located in Williamsport, Pennsylvania

Pennsylvania counties				New York counties	
1	Adams	25	Lebanon	1	Allegany
2	Bedford	26	Lehigh	2	Broome
3	Berks	27	Luzerne	3	Cattaraugus
4	Blair	28	Lycoming	4	Chemung
5	Bradford	29	McKean	5	Chenango
6	Bucks	30	Mifflin	6	Cortland
7	Cambria	31	Monroe	7	Livingston
8	Cameron	32	Montgomery	8	Ontario
9	Carbon	33	Montour	9	Schuyler
10	Centre	34	Northampton	10	Seneca
11	Clearfield	35	Northumberland	11	Steuben
12	Clinton	36	Perry	12	Tioga
13	Columbia	37	Pike	13	Tompkins
14	Cumberland	38	Potter	14	Yates
15	Dauphin	39	Schuylkill		
16	Elk	40	Snyder		
17	Franklin	41	Sullivan		
18	Fulton	42	Susquehanna		
19	Huntingdon	43	Tioga		
20	Indiana	44	Union		
21	Jefferson	45	Wayne		
22	Juniata	46	Wyoming		
23	Lackawanna	47	York		
24	Lancaster				

Table A.2: County specific proportion of private forestland opposed by PFLs, county specific proportion opposed (CSP_O), and proportion of private forest by size of forest holding, county specific holding (SCP_H), by county and clusters of counties.

Clusters	Counties	County specific opposition (CSP_O)	County specific holding (CSP_H)				Mean of CSP_O	Mean of CSP_H, <10 ac	Mean of CSP_H, <20 ac
			1-9.9 acres	10-19.9 acres	<20 acres	20-49.9 acres			
Highly developed	Montgomery	0.488	0.482	0.202	0.684	0.196	0.488	0.482	0.684
Developed/ developing	Berks	0.215	0.290	0.151	0.441	0.235	0.228	0.260	0.399
	Chester	0.282	0.357	0.161	0.518	0.215			
	Westmoreland	0.187	0.132	0.107	0.239	0.207			
Quasi-rural	Adams	0.154	0.135	0.107	0.242	0.223	0.149	0.134	0.233
	Armstrong	0.124	0.047	0.046	0.093	0.128			
	Carbon	0.141	0.131	0.070	0.201	0.127			
	Clinton	0.119	0.057	0.056	0.113	0.118			
	Cumberland	0.172	0.195	0.166	0.361	0.260			
	Dauphine	0.172	0.223	0.147	0.370	0.207			
	Forest	0.135	0.092	0.060	0.152	0.136			
	Greene	0.123	0.035	0.042	0.077	0.141			
	Lackawanna	0.139	0.096	0.072	0.168	0.170			
	Lawrence	0.170	0.176	0.147	0.323	0.287			
	Lehigh	0.198	0.331	0.186	0.517	0.236			
	Perry	0.150	0.116	0.097	0.213	0.221			
	Pike	0.132	0.112	0.041	0.153	0.094			
	Union	0.158	0.134	0.140	0.274	0.249			
Rural/ forested	Bradford	0.146	0.090	0.100	0.190	0.245	0.137	0.095	0.175
	Centre	0.122	0.062	0.060	0.122	0.137			
	Erie	0.187	0.187	0.146	0.333	0.306			
	Huntingdon	0.115	0.068	0.057	0.125	0.124			
	Lycoming	0.110	0.029	0.052	0.081	0.127			
	Monroe	0.147	0.142	0.072	0.214	0.131			
	Washington	0.145	0.104	0.090	0.194	0.206			
	Wayne	0.127	0.079	0.063	0.142	0.142			

Source: Table adapted from *Human dimensions of private forestland ownership: sampling, estimation, decision making process, and implication* (p.212) by Metcalf A.L., 2010, unpublished doctoral dissertation, The Pennsylvania State University, University Park and from *Timber availability assessment: an analysis of biophysical and social constraints in Pennsylvania* (p. 8-54) by Metcalf A.L., and Finley J.C., 2011, The Pennsylvania State University, University Park. Adapted with permission.

Table A.3: Calculated county specific proportion that are opposed for harvest by PFLs and county specific size of forest holding <10 acres and <20 acres within 100-mile procurement radius around energy facility located in Williamsport, PA.

Clusters	State	Counties	County specific opposition (CSP_O)	County specific holding (CSP_H)	
				1-9.9 acres	<20 acres
Highly Developed	PA	Bucks	0.488	0.482	0.684
	PA	Montgomery	0.488	0.482	0.684
Developed/Developing	PA	Berks	0.215	0.290	0.440
	PA	Lancaster	0.228	0.260	0.400
	PA	Luzerne	0.228	0.260	0.400
	PA	York	0.228	0.260	0.400
Quasi-Rural	PA	Adams	0.154	0.135	0.240
	PA	Blair	0.149	0.134	0.230
	PA	Cambria	0.149	0.134	0.230
	PA	Cameron	0.149	0.134	0.230
	PA	Carbon	0.141	0.131	0.200
	PA	Columbia	0.149	0.134	0.230
	PA	Cumberland	0.172	0.195	0.360
	PA	Dauphin	0.172	0.223	0.370
	PA	Franklin	0.149	0.134	0.230
	PA	Fulton	0.149	0.134	0.230
	PA	Jefferson	0.149	0.134	0.230
	PA	Juniata	0.149	0.134	0.230
	PA	Lackawanna	0.139	0.096	0.170
	PA	Lebanon	0.149	0.134	0.230
	PA	Lehigh	0.198	0.331	0.520
	PA	Mifflin	0.149	0.134	0.230
	PA	Monroe	0.149	0.134	0.230
	PA	Montour	0.149	0.134	0.230
	PA	Northampton	0.149	0.134	0.230
	PA	Northumberland	0.149	0.134	0.230
	PA	Perry	0.150	0.116	0.230
	PA	Pike	0.132	0.112	0.150
	PA	Snyder	0.149	0.134	0.230
	PA	Sullivan	0.149	0.134	0.230
	PA	Union	0.158	0.134	0.270
	PA	Wyoming	0.149	0.134	0.230
	NY	Chemung	0.149	0.134	0.230
	NY	Cortland	0.149	0.134	0.230
	NY	Livingston	0.149	0.134	0.230
	NY	Ontario	0.149	0.134	0.230
	NY	Schuyler	0.149	0.134	0.230
	NY	Seneca	0.149	0.134	0.230
	NY	Tioga	0.149	0.134	0.230
	NY	Tompkins	0.149	0.134	0.230
	NY	Yates	0.149	0.134	0.230

Table A.3 (Continued)

Rural/forested	PA	Bedford	0.137	0.095	0.180
	PA	Bradford	0.146	0.090	0.190
	PA	Centre	0.122	0.062	0.120
	PA	Clearfield	0.137	0.095	0.180
	PA	Clinton	0.137	0.095	0.180
	PA	Elk	0.137	0.095	0.180
	PA	Huntingdon	0.115	0.068	0.130
	PA	Indiana	0.137	0.095	0.180
	PA	Lycoming	0.110	0.029	0.080
	PA	McKean	0.137	0.095	0.180
	PA	Potter	0.137	0.095	0.180
	PA	Schuylkill	0.137	0.095	0.180
	PA	Susquehanna	0.137	0.095	0.180
	PA	Tioga	0.137	0.095	0.180
	PA	Wayne	0.127	0.079	0.140
	NY	Alleghany	0.137	0.095	0.180
	NY	Broome	0.137	0.095	0.180
	NY	Cattaraugus	0.137	0.095	0.180
	NY	Chenango	0.137	0.095	0.180
	NY	Steuben	0.137	0.095	0.180

VITA

Norzanalia Saadun was born on 1979 in Perak, Malaysia. In 1997, she gained admission to the Universiti Putra Malaysia in Serdang, Malaysia and received a Forestry Diploma in 2000 and a Bachelor of Science in Forestry in 2002. In January 2004, she joined Universiti Putra Malaysia and worked as a tutor in the Faculty of Forestry. With a scholarship from her employer, she enrolled in graduate studies at Universiti Putra Malaysia, Serdang, Malaysia and was awarded a Master of Science in Wood Industry Management in 2007. For her master's degree, she studied foreign direct investment in the Malaysian furniture industry.

In August 2008, she was awarded a scholarship from the Ministry of Higher Education of Malaysia and a study leave from her employer, Universiti Putra Malaysia, to enroll in a Doctor of Philosophy degree in Forest Resources at The Pennsylvania State University. For her doctoral research, she focused on estimating woody biomass supplies from natural forests for an energy facility. Upon completion of her studies, she will go back to Malaysia and continue to work for Universiti Putra Malaysia as a lecturer at the Faculty of Forestry.

Her current research interests focus on wood-based industry management, international business and foreign direct investment, forest resource management, and bioenergy.