TIMBER RESIDUE SUPPLY FOR BIOENERGY IN THE NORTHERN TIER OF THE GREAT LAKES: DETERMINANTS AND AVAILABILITY

By

Elena Dulys-Nusbaum

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ABSTRACT

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Timber residues, a timber byproduct, are a low-cost source of biomass that avoids the environmental and food market consequences of other energy feedstocks. We studied the effect that price, forest species mix, bio-energy attitudes, environmental amenities, and environmental disamenities have on the decision to harvest for non-industrial private forest owners (NIPFs) in northern Michigan and Wisconsin. Over 50% of landowners were willing to provide timber residues at timber harvest or stand improvement (tree thinning) at prices starting at just $15/acre. NIPFs with large, single-species tracts with fewer concerns over environmental disamenities were the most likely to harvest timber residues. We extrapolated the supply of timber residues for the Northern Tier and adjusted for forest owners' willingness harvest, finding that non-industrial private forest owners could provide 0.34 million oven dry tons of timber residue at $15/acre. At the same price of $15/acre, the 10 counties with the largest timber residue availability in the Northern Tier combine to have the potential to provide feedstock for 5.13 million gallons of ethanol per annum from non-industrial private forest sources.

To Lola and Levin.

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KEY TO ABBREVIATIONS

BP	Bivariate probit model
BTR	Billion Ton Report
DOE	US Department of Energy
DNR	Department of Natural Resources
EISA	Energy Independence & Security Act
EIA	Energy Information Administration
EPA	Environmental Protection Agency
FIA	Forest Inventory & Analysis Program
FIDO	Forest Inventory Data Online System
GHG	Greenhouse gases
GLBRC	Great Lakes Bioenergy Research Center
ILUC	Indirect land use change
IV	Instrumental variable
MI	Michigan
MLE	Maximum likelihood estimation
NIPF	Non-industrial private forest owner
NRC	National Research Council
ODT	Oven-dry short tons
RPS	Renewable Portfolio Standard
TBB	Tree and branch biomass
USDA	US Department of Agriculture
WI	Wisconsin

Chapter 1: What Drives the Potential Supply of Timber Residues from Private Lands in the Northern Tier of the Great Lakes? [1]

I. Introduction

Timber residues serve as a potentially significant biomass source in meeting growing U.S. energy needs. As low cost byproducts of existing wood production activities, timber residues provide an alternative to dedicated biomass crops while circumventing the environmental and food market consequences that come with growing dedicated energy crops on agricultural land (DOE, 2011).

The production of dedicated bioenergy crops (including tree crops) comes with several implications. Using edible crops as an energy feedstock contributes to food price changes that ripple worldwide. Most notably, some of the global cereal food price spikes that occurred from 2005 to 2011 are attributed to the shift of U.S. cropland into corn grown for ethanol production following the passage of the renewable fuel standards in 2005 and 2007 (DOE, 2011; IFPRI, 2010; NRC, 2011; Oladosu, 2013).

Rising food prices such as the cereal price spikes not only hurt low-income populations, they also create environmental harm via indirect land use change (ILUC). The conversion of existing forest to food crops causes a large, one-time release of CO_2 that may not be recovered by the consequent use of land to produce biofuels (NRC, 2011). This seriously undermines and potentially reverses the greenhouse gas (GHG) offset intended by the initial bioenergy mandate policy (Searchinger, 2010).

[1] Essay is adapted from Dulys-Nusbaum, E.M., Swinton, S.M., Klammer, S.S. (2016). What Drives the Potential Supply of Timber Residues from Private Lands in the Northern Tier of the Great Lakes?, Selected Paper. Agricultural & Applied Economics Association 2016 AAEA Annual Meeting, Boston, MA, July 31 - August 2, 2016.

Increasing productivity and conversion efficiency could alleviate food price and ILUC challenges (DOE, 2011), but increased corn production leads to other forms of environmental damage, including an increase of nitrates in waterways, erosion (Pimentel, 2009), hypoxia, algal blooms, eutrophication (NRC, 2011), and a decrease in wildlife (Fargione et al., 2009). The use of marginal agricultural lands in place of fertile lands for bioenergy feedstock production is another solution, but the economic availability of such lands remains questionable (Mooney et al., 2015; Skevas et al., 2016; Swinton et al., 2017).

Obtaining bioenergy feedstocks from byproducts can avoid the price feedback problems associated with dedicated bioenergy crops. Literature local to Michigan and Wisconsin support this claim. Skevas et al. (2016) found that the use of corn stover as an energy feedstock was more profitable than other perennial cellulosic crops such as switchgrass and carried less risk.

Common feedstocks other than corn stover include wheat straw and timber residues. Timber residues, also known as "thinnings," "removal residues," "logging residues," "timber residue," or "timber slash," is the material left after timber harvest or stand improvement (thinning) on forested land (DOE, 2011). Byproducts such as timber residues provide this profit advantage over dedicated bioenergy crops because their production costs are already covered by the sale price of the base product.

Timber residues have the advantage of dynamic end-use and show promise as a low-cost avenue toward meeting CO_2 emission reduction goals. Timber residues may be processed into ethanol at a dedicated bio-refinery (NRC, 2011) or burned for bio-electricity. Burning timber residues in a power plant can be done in an existing plant with a relatively low-cost retrofit (Hughes, 2000). The use of timber residues for bio-electricity could be one of the most cost-effective ways of meeting voluntary CO_2 reductions due to the utilization of existing infrastructure (De & Assadi, 2009). Moreover, co-firing timber residues along with coal has the potential to create positive local economic impact for areas that both ship coal from far away and have abundant timber resources, such as Mississippi (Perez-Verdin et al., 2008).

How available is energy biomass from timber residues? This remains a key question. Timber residue supply remains uncertain and limited (EPA, 2015). The potential for a large national timber residue supply is relatively modest due to high marginal costs and the lack of federal subsidies to ameliorate these costs. Market uncertainties such as these are likely to curtail private investment (NRC, 2011). Many studies have been conducted to estimate the biophysical availability of wood and timber residues in the past (Butler et al., 2010; DOE, 2011), but less is known about the economic determinants of that availability. As much of the U.S. timber supply grows on land owned by non-industrial, private forest owners (NIPFs), the contribution of large quantities of timber residue to meet demands for renewable energy is not possible without the voluntary cooperation of these NIPFs.

Understanding NIPF landowner behavior and willingness to harvest timber residues is crucial to understanding the availability of the material. Considerably less attention in the literature has been given to forest residue harvesting preferences of NIPFs, though this literature has grown substantially in recent years. Existing studies indicate that socio-demographic characteristics, forest management objectives, and stand characteristics are all important determinants of the NIPF's decision to harvest timber residues from their forested land (Joshi & Mehmood, 2011; Gruchy et al., 2012; Becker et al., 2013). In their study of the availability of logging residues for bioenergy production by NIPFs in the southern United States, Joshi & Mehmood (2011) found that characteristics such as age, acreage, ownership objectives, and species were all important determinants of the landowner's decision. However, their study omitted biomass price, a key economic variable. Knowledge of wood-based bioenergy is another key driver according to Joshi et al. (2013), who call for developing strong extension services to inform landowners with small tracts of land of the potential for woody biomass as an energy feedstock. Landowner attitudes towards forest management and bioenergy as well as opinions about the importance of climate change are also important drivers of willingness to supply timber residues (Gruchy et al., 2012; Markowski et al., 2012).

A large share of existing research on the availability of timber residues for energy biomass comes from the southern United States (Gruchy, 2012; Joshi & Mehmood, 2011; Joshi et al., 2013), which is home to 80% of U.S. forest cover (NRC, 2011). While the Midwest is represented in the literature (Aguilar et al., 2014; Becker et al., 2013), the presence of economic drivers in these papers' models are largely absent except for Aguilar et al. (2014). Aguilar et al. (2014) found that marginal willingness to supply timber residues was far more sensitive to the offer price for saw logs than to changes in the price of timber residues. Although they include one variable related to environmental disamenities as well as one related to energy attitudes, the study lacks a rich set of covariates that cover environmental amenities and disamenities. Moreover, it omits controls for level of knowledge regarding bioenergy concepts, zoning restrictions, or tree types. The addition of these variables could better isolate the effect of timber residue price on the decision to harvest.

The goal of this study is to shed light on what drives the supply of timber residues by NIPFs in a region underrepresented in the literature as well as to test the effects of price, bioenergy attitudes, acreage, amenities, and disamenities while controlling for stand and socio-demographic characteristics. In this study, we focus on the Northern Tier of the Great Lakes, the sub-region that includes northern Michigan and northern Wisconsin. This area has a well-established wood products industry that produces saw logs, biomass for paper pulp, and other forest products (Dickmann & Leefers, 2003).

II. Conceptual Model

We assume that all private forest owners are seeking to maximize their utility with respect to the use of their forested land. Utility is driven in part by the forest owner's consumption behavior as well as the environmental amenities and disamenities associated with the harvest of timber residues. Empirically, a forest owner's utility is also conditioned upon variables such as demographic characteristics, knowledge of timber residues, beliefs about bioenergy, and concerns about the removal process.

Define the utility that the forest owner derives from their forested land as U, as in equation (1). The function U is assumed to be differentiable and increasing concavely in marketed consumer goods, c, environmental amenities, a, and personal integrity that aligns actions with beliefs and attitudes toward bioenergy, i. Utility, U, is decreasing in disamenities, d. For each individual forest owner $[n = 1 \dots, N]$, all other observable variables that affect the forest owner's utility in this choice scenario are denoted by the vector $\boldsymbol{X_n}$, whose components are described in table (1).

(1)
$$\max_A U = [\boldsymbol{c}, a, i, d|\boldsymbol{X_n}]$$
$$s.t. \quad A = \{\bar{A}, 0\}$$
$$\boldsymbol{p_c c} \leq \pi + m$$
$$\pi = pAY(ft_s, ft_m) - AC(ft_s, ft_m)$$
$$a = a(A)$$
$$d = d(A)$$
$$i = i(b)$$

The forest owner's decision on whether to harvest timber residues from A acres of land at the time of a normally scheduled timber harvest is assumed to hinge on maximization of the utility function subject to the associated constraints in equation (1). The variable A is limited by the total number of timberland acres available, $\bar{A}$. This choice is represented by the first constraint in equation (1). Due to the nature of the harvest of timber residue, the forest owner only has the choice to harvest all of her or his timberland acres, $\bar{A}$, or none. The second constraint, the budget constraint, limits the consumption of all market goods (the vector **c** with its corresponding price vector, $\boldsymbol{p_c}$) by the amount of income the forest owner has from both timber residue income, π, and all other income, m. Timber residue income is represented by the third constraint, where the forest owner's profit from timber residues at payment p per acre for the area of timber residues that is made available, A. The timber residue profit is a function of the quantity yield, Y, from available acres $\bar{A}$. The yield depends on the species makeup of the given forest, which is a mix of single species acres, ft_s, and multispecies acres, ft_m. The levels of environmental amenities, a, and disamenities, d, that are experienced by the forest landowner also depend on A. Integrity, i, depends on the owner's beliefs regarding bioenergy, b.

The maximization of equation (1) with respect to the chosen number of acres to allow timber residue harvest, A, leads us to equation (2), the forest owner's optimal decision of whether to supply A^* land area for timber residue harvest. Timber residue harvest is treated as all-or-nothing; it is not economically feasible to selectively harvest several forested acres due to the associated cost. Because of this, the decision of A^* is binary, with the option of either providing timber residues from the fixed total available number of acres, $\bar{A}$, or providing none (0 acres). The decision variable A^* then represents either $\bar{A}$ or 0 acres, depending upon the utility that a given forest owner derives from her or his available land, $U(\bar{A})$. The expression $U(0)$ represents the utility a forest owner derives from supplying no acres for residue harvest.

Factors that contribute to $U(\bar{A})$ include price, environmental amenities, disamenities, bioenergy attitudes, and the vector $\boldsymbol{ft}$. This vector represents the combination of single and mixed forest types, and the vector $\boldsymbol{X_n}$, which corresponds to other conditioning variables (see table (1)).

(2)
$$A^* = A(p, a, b, d, \boldsymbol{ft} | \bar{A}, m, X_n) = \begin{cases} \bar{A}, & U(\bar{A}) > U(0) \\ 0, & U(\bar{A}) \leq U(0) \end{cases}$$

Table 1: Class vectors of the control variable vector, $\boldsymbol{X_n}$

Component of X_n	Description
$\boldsymbol{dem}$	Demographic variables such as age and education
$\boldsymbol{for}$	Forest characteristics such as tree age
$\boldsymbol{use}$	Existing uses that the forest owner has regarding her/his forest and participation in forest programs
$\boldsymbol{beliefs}$	Beliefs that the forest owner has about energy issues relating to timber residues
$\boldsymbol{concerns}$	Concerns that the forest owner has about the process or consequences of harvesting timber residues

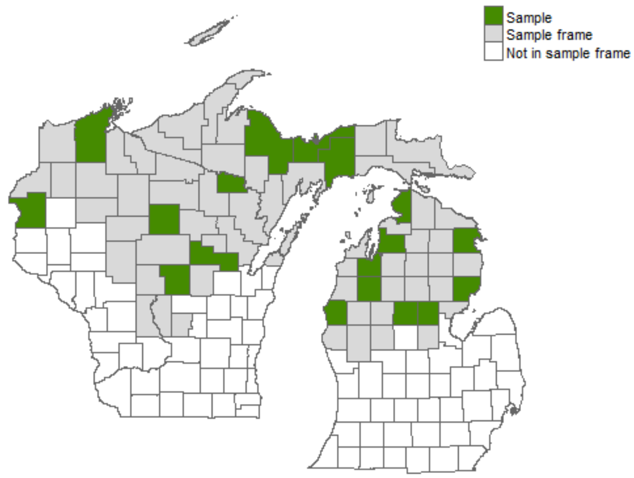
III. Data

This study utilizes data from a stated choice survey distributed by the Great Lakes Bioenergy Research Center (GLBRC) researchers, from October-November 2014 with responses received until May 2015. The geographical area for the sample frame is the Northern Tier of the Great Lakes: a 76-county sub-region of northern Michigan and Wisconsin with ample forested land and limited agricultural growing capacity. The sample was stratified at both county and household levels. At the county level, the GLBRC stratified the 76 counties by high (>20%) and low (<20%) grassland cover, randomly selecting six counties in Wisconsin and twelve in Michigan (Michigan counties are approximately half the size of Wisconsin's) (Swinton et al., 2017).

Within each county, GLBRC researchers targeted 96 (Michigan) or 192 (Wisconsin) non-institutional landowners that owned ten or more acres of rural land, identified from county-level property tax records (Swinton et al., 2017). GLBRC investigators stratified the second stage of the sample by large (>100 acres) and small (10-100 acres) landholdings as well as participation or non-participation in forest management programs such as Michigan's Qualified Forest Program or Wisconsin's Managed Forest Law. This created four strata within each county from which GLBRC selected 24 and 48 participants for Michigan and Wisconsin, respectively, with the goal of creating a balanced sample (see sample counties in figure (1)). GLBRC Researcher Sophia Tanner calculated survey weights as the inverse of sampling probabilities (see table (6) in the Appendix). Forest program participant landowners with over 100 acres were over-sampled due to their low incidence in the population.

After culling the 2304 addresses mailed for 134 undeliverable surveys, the final sample of 2170 achieved a 51.8% response rate (Swinton et al., 2017). Of these respondents, 91.5% of the sample owned at least some forested land. For this analysis, non-forest owners were dropped from the original sample because they are not participants in the timber residue market and are not relevant for this study.

Figure 1: Sample frame for the 2014-2015 GLBRC survey



The survey included questions about demographics such as age, income sources, and education level, as well as forest characteristics, plans, and management practices. The survey also included belief variables associated with opinions regarding the environmental amenities offered by harvesting timber residues. In addition, the survey included concern variables that pertained to levels of comfort surrounding the disamenities that come with the harvest of timber residues such as noise, smell, and privacy. Respondents were asked to react to the 11 belief and nine concern statements on a Likert scale that ranged from 1 (strongly disagree) to 5 (strongly agree). The explanatory variables that we include in this study and their descriptive statistics are in table (2).

The stated choice section for timber residues included two scenarios where forest owners were asked (1) "if [the company harvesting your timber] offered you a contract for $___ per acre to remove woody biomass from your forested land at the time of your next <u>timber harvest</u>, would you agree to the offer?" and (2) "if [the company harvesting your timber] offered you a contract for $___ per acre to remove woody biomass from your forested land at the time of your next <u>stand</u>

improvement, would you agree to the offer? (such as forest thinning, junk wood removal, or habitat restoration).” The dollar payment for timber slash varied randomly across surveys ($15, $30, $60, $ 90). For each of the timber residue questions, respondents could answer (a) “yes, I would be willing to sell my woody biomass,” (b) “no, I do not have plans to harvest timber/conduct stand improvement from my forested land,” (c) “no,” with no detail, (d) “no, I would sell my biomass if the payment were higher,” or (e) “I would never sell woody biomass from a timber harvest.”

The wording of the questionnaire and the inherent uncertainty behind what the questionnaire is asking are worth noting. In the questions of interest above, the term “woody biomass” is used in place of “timber slash,” “timber residue,” and “harvest residue.” Due to the wide variety of terms used in this area of the literature, “woody biomass” was chosen out of convenience and its broad application by the questionnaire’s authors. However, in a strictly technical sense, the term “woody biomass” refers to all aboveground biomass in a forested area, whereas “timber residue” or “slash” only refers to branch and tree top material. This discrepancy in language challenges the construct validity of the study from the viewpoint of forest scientists and is worth noting.

Additionally, in both questions, it is uncertain when the “next timber harvest” or “next stand improvement” will take place. There is no realistic way of knowing when exactly the “next” logging event will be. The implications are that the forest owners’ attitudes could change substantially between now and this “next” event date. We impose the assumption that the attitudes will not change before the next event to draw meaningful conclusions from this study with the information that we have.

Table 2: Selected explanatory variables from the 2014-2015 GLBRC survey

Variable	Description	Units	N	Mean	Std. Dev.
<u>Decisions</u>					
harvestDecision	Agree to harvest biomass next harvest	0/1*	946	0.526	0.500
standDecision	Agree to harvest biomass next stand improvement	0/1	950	0.476	0.500
<u>Income</u>					
price	Price offered	$/acre	1019	49.7	28.6
income	Household income	$/year	1019	83400	47800
<u>Demographics</u>					
age	Age	years	1019	60.4	11.2
male	Male gender	0/1	959	0.799	0.401
farmer	Farmer	0/1	955	0.219	0.414
education	Education	years	1019	0.436	0.496
duration	Duration of land ownership	years	950	24.9	16.0
resident	Resides on land	0/1	967	0.686	0.464
<u>Forest Characteristics</u>					
agZone	Agriculture zoning	0/1	981	0.341	0.474
resZone	Residential zoning	0/1	981	0.149	0.357
mixed	Mixed natural forest	acres	971	82.0	931.828
single	Single-species tree plantations	acres	980	8.49	74.7
other	Other forest	acres	986	1.79	49.7
oldMix	Mixed forest is over 10 years old	0/1	1019	0.829	0.376
oldSing	Single-species tree plantation is over 10 years old	0/1	1019	0.393	0.489
<u>Uses</u>					
prevHarv	Has previously harvested timber	0/1	993	0.594	0.491
personal	Forested land used for personal use	0/1	1015	0.844	0.363
forestProg	In a forest program	0/1	1019	0.295	0.456
<u>Knowledge</u>					
bioenergy	Landowner has heard of bioenergy	0/1	1009	0.893	0.310
slashEthanol	Knows forest slash could be used for bioenergy	0/1	999	0.495	0.500
seenSlash	Landowner has seen forest slash	0/1	1000	0.629	0.483
<u>Beliefs</u>					
renewableBelief	Renewable energy important to future of the US	0-5†	990	4.23	0.914
bioenergyBelief	Bioenergy should be prioritized over other renewables	0-5	987	2.99	0.839
noCoalBelief	Bioenergy should be burned over coal even with extra cost	0-5	984	3.14	0.872
climateChangeBelief	Substituting bioenergy feedstocks for fossil fuels will help mitigate climate change	0-5	986	3.10	0.938
foodIssueBelief	Growing bioenergy feedstocks on cropland will increase competition with food needs	0-5	986	3.37	0.909

Table 2 (con't)

Variable	Description	Units	N	Mean	Std. Dev.
forestLossBelief	Bioenergy will result in forest loss	0-5	985	2.95	0.820
publicForBelief	Government should allow harvesting of public forest and CRP land for bioenergy	0-5	985	3.11	1.02
biodiversity	Biodiversity should be maintained when land use is changed	0-5	977	3.55	0.842
biofuelsBelief	Liquid biofuels are a promising alternative energy technology	0-5	977	3.24	0.636
fossilHarmBelief	The use of fossil fuels can be harmful to health and the environment	0-5	982	3.40	1.02
fossilLimitBelief	The world will run out of fossil fuels in the next 50 to 120 years	0-5	985	2.86	0.919
Concerns					
smell	The potential smell	0-5	917	2.56	0.919
noise	Noise from harvesting, planting, or other activities	0-5	918	2.58	0.988
insurance	The possible need for insurance	0-5	915	3.46	0.883
privacy	Having other people on my land	0-5	919	3.62	1.05
change	The land changing in a way that I can no longer use it as I want	0-5	919	3.89	0.976
profit	How profitable it will be	0-5	917	3.61	0.792
questions	Lack of information	0-5	912	3.36	0.872
lossBiodiversityConcern	Loss of biodiversity	0-5	916	3.71	1.00
lossSoilConcern	Risk lower soil and water quality	0-5	917	3.64	1.06

* 0 = no, 1 = yes

† 1= strongly disagree, 2= disagree, 3= uncertain, 4= agree, 5= strongly agree

Sampling weights are applied.

IV. Empirical Methods

We estimate the relationships between acreage offered and the variables explained in table (1) by estimating an indirect utility function, or the probability that a forest owner will accept the offer to harvest timber residue at randomly varying levels of payment per acre, $price\_slash$.

A. Probit Model

Let the observed decision of every forest owner $n[n = 1 \ldots, N]$ be represented by $y \in \{0,1\}$, where 1 signifies that n accepts the offer to harvest timber slash, and 0 means that n declines the offer. The probability that a forest owner accepts the offer is also the probability that the forest owner's utility from forested land (from equation (1)) is greater with acceptance than it is without acceptance and vice versa, as in equations (3-4).

(3) $$\Pr[\mathrm{y} = 1] = Pr[U(\bar{A}) > U(0)]$$

(4) $$\Pr[\mathrm{y} = 0] = Pr[U(\bar{A}) \leq U(0)]$$

For the timber residue question, the forest owner either commits all their forested acres to timber residue harvest, or none (see equation (5)).

(5) $$y = \begin{cases} 1, & A = \bar{A} \\ 0, & A = 0 \end{cases}$$

(6) $$\Pr[y = 1] = \Phi(D)$$

$$= \Phi\big(\alpha + \beta_p p + \boldsymbol{\beta_m m} + \boldsymbol{\beta_d dem} + \boldsymbol{\beta_f\, for} + \boldsymbol{\beta_a activities}$$

$$+\ \boldsymbol{\beta_k knowledge} + \boldsymbol{\beta_b\, belief} + \boldsymbol{\beta_c\, concerns}\ + \varepsilon\big) = \Phi(\boldsymbol{X_n}'\boldsymbol{\beta})$$

Equation (6) is an empirical version of the reduced form timber residue supply model in equation (2). The explanatory variables for the model are captured by price *p,* and the vectors ***m, dem, for, use, knowledge, belief***, and ***concerns*** which are described in table (1).

Under the assumption that ε from equation (6) is approximately normal, we use the cumulative distribution function of the standard normal distribution, $\Phi(\boldsymbol{X_n}'\boldsymbol{\beta})$, to map equation (6) to a probability function in equation (7) (Wooldridge, 2009).

(7) $$\Pr\,(y_n = 1|\boldsymbol{X_n}) = \Phi(\boldsymbol{X_n}'\boldsymbol{\beta}) = \int_{-\infty}^{X_n{}'\beta} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2}\boldsymbol{X_n}'\boldsymbol{\beta}^2\right) d\varepsilon$$

The standard normal distribution is applied to the binary choice faced by the forest owner in our sample. An owner that accepts is represented by equation (8). A rejection of the harvest offer is $1 - \Phi(\boldsymbol{X_n}'\boldsymbol{\beta})$. The density function, conditional on the forest owner's characteristics and their respective coefficients is then defined by equation (8).

(8) $$\mathrm{f}(y_n|\boldsymbol{X_n};\boldsymbol{\beta}) = \Phi(\boldsymbol{X_n'\beta})^{y_n}[\mathbf{1} - \Phi(\boldsymbol{X_n'\beta})^{\mathbf{1}-y_n}]$$

From the conditional density function, we derive the likelihood function, equation (9). The likelihood function may be transformed into a log function, $\mathrm{L}(\boldsymbol{\beta}\,)$, which is then maximized via iterative numerical computation in order to estimate the vector of coefficients $\boldsymbol{\beta}$.

(9) $$L(\boldsymbol{\beta}) = \prod_{n=1}^{N} \mathrm{f}(y_n | \boldsymbol{X_n}; \boldsymbol{\beta})$$

Since the dataset was of complex survey type, likelihood-ratio tests were inappropriate (Binder, 1983). We used the Wald Test to carry out exclusion restrictions for the most collinear variables that were not strongly grounded in theoretical relevance. Because of these tests, we dropped a forest management plan variable and two types of zoning dummy variables.

B. Imputation

Model variables such as household income, education, and age had many missing answers on the survey, which limited the sample size of the final model. To fill in these gaps, improve efficiency, and reduce the potential for statistical bias in the model, we imputed missing data for these variables using a multivariate, multiple imputation method. This imputation procedure, championed by Rubin (1987), involves the creation of multiple datasets with values imputed by a Bayesian posterior predictive distribution, an analysis of each separate dataset with the chosen model, and a pooling step that combines this analysis into a single result.

C. Factor Analysis

Intuitively and empirically, 5-point Likert belief and concern variables were correlated with one another. To reduce the number of variables and detect latent structural relationships between variables, we conducted a factor analysis. After analyzing the number of factors that returned eigenvalues over 1 (Kaiser, 1960) and the Scree plots (Cattell, 1966), we reduced the 11 belief variables and nine concern variables to a total of three factor variables. After a factor-based axis rotation (Harman, 1960), we analyzed the loadings for the retained factors, which appear in table

(3). The first factor was characterized by high loadings in two beliefs pertaining to pro-bioenergy energy concepts such as a belief that the use of bioenergy feedstocks in place of fossil fuel will help mitigate climate change. The second factor carried two high loadings, both in concepts pertaining to a loss of environmental amenities such as biodiversity and soil quality. The third factor also carries two high loadings and seems to represent concerns over disamenities, such as noise and smell. Cronbach's alpha for each grouping of items with the highest loadings in each of the three factors (bold in table (3)) is above .70 and below .82, falling within the recommended range for variables with high correlation in underlying latent factors (Tavakol & Dennick, 2011).

In addition, a probit model with the three factors in place of the 20 original explanatory variables was jointly significantly different from zero via a Wald Test for both the harvest and the stand improvement scenarios. We tested squared transformations for all continuous variables to test for quadratic behavior. No squared transformations were significantly different from zero via Wald test in either scenario.

D. Endogeneity

Second stage sampling of land owners was based upon participation in a forest program such as Michigan's Qualified Forest and Commercial Forest programs and Wisconsin's Managed Forest Law. These forest owners typically only comprise about 6% of the population of non-industrial private forest owners nationwide (Butler, 2010). Michigan and Wisconsin are no exception. However, these types of owners were expected to be more commercially oriented and were therefore over-sampled in this study (see more detail on this in section (III)). To maintain precise estimates, the econometric model is weighted by the inverse probability of selection (table 6 in the Appendix). We also report unweighted results in the Appendix (tables (8-9)).

In addition, the participation of a forest owner in forest programs is intuitively related to the decision to participate in other logging events such as a timber harvest. We confirmed the presence of endogeneity associated with forest program participation via the Rivers and Vuong (1988) test, which is also recommended by Wooldridge (2002). Due to the results of this diagnostic test, we decided to drop the forest program variable. As a robustness check, we conducted an instrumental variable (IV) regression alongside the base probit econometric specification (results are discussed in section (V)).

Since the endogenous variable itself was binary, two-stage least squares (2SLS) regression was inappropriate and could provide inconsistent estimates. Instead, we used a maximum likelihood (MLE) bivariate probit (BP) regression (Heckman, 1978) as recommended by Wooldridge (2002). For each of our BP models, we used bootstrapped confidence intervals as recommended by Chiburis et al. (2012). For our instrumental variable (IV), we chose a variable that indicated whether a forest owner had a conservation easement. To prove instrumental relevance for the conservation easement variable, we followed test recommendations from Wooldridge (2015). The conservation easement variable's coefficient was statistically different from zero at more than 99% confidence when regressed on forest program participation (the endogenous variable) while including all other independent variables from the chosen model. At the same time, the presence of a conservation easement did not have a coefficient that was statistically different from zero when included in the chosen model (only 30% confidence). Therefore, the conservation easement variable is correlated with the forest program endogenous variable but is not correlated with the harvest decision variable, making it a reasonable proxy for the endogenous variable to maintain unbiased and consistent estimates in the two-stage least squares model (Wooldridge, 2015). Additionally, the Hausman test for endogeneity confirmed that the forest program was endogenous (Knapp & Seakes, 1998) with 97% confidence.

Table 3: Factor analysis from belief and concern variables

Component	Pro-Bioenergy Loading	Conservationist Factor Loading	Anti-rent Factor Loading
Developing renewable energy (e.g., wind, solar, bioenergy, hydro-electrical) is important to our nation's future.	0.5809	0.0772	-0.0978
Bioenergy should be prioritized over other forms of renewable energy such as wind or solar power.	0.0535	-0.1018	-0.0106
Burning bioenergy feedstocks to generate electricity instead of burning coal is worth the extra cost.	**0.6624**	0.0204	-0.0391
Substituting bioenergy feedstocks for fossil fuels will help mitigate climate change.	**0.7083**	-0.018	0.0446
Growing bioenergy feedstocks on cropland will increase competition with food needs.	-0.0285	0.1192	0.0033
Increased bioenergy feedstock production will result in significant forest loss.	-0.0248	0.2923	0.2059
Government should allow regular harvesting of public forest land and CRP land for bioenergy purposes.	0.1115	-0.3026	-0.1527
Biodiversity should be maintained when land use is changed.	0.3829	0.2289	-0.0634
Liquid biofuels are a promising alternative energy technology that will be successful in the future.	0.2839	-0.088	-0.0484
The use of fossil fuels can be harmful to human health and the environment.	**0.6037**	0.1792	-0.0167
The world will run out of fossil fuels (e.g., oil, natural gas) in the next 50 to 120 years.	0.5657	0.0962	0.1066
The potential smell	-0.0006	0.1852	**0.7439**
Noise from harvesting, planting, or other activities	-0.0042	0.2622	**0.7501**
The possible need for insurance	-0.0325	0.2573	0.2993
Having other people on my land	-0.0152	0.4027	0.3016
The land changing in a way that I can no longer use it as I want	-0.0228	0.53	0.2047
How profitable it will be	-0.0592	0.0846	0.0487
A lack of information about the potential feedstocks	0.0272	0.2268	0.2557
The loss of biodiversity on my land (e.g., insects, birds, mammals, plants, etc)	0.1203	**0.7699**	0.183
The risk of lower soil and water quality	0.0651	**0.7427**	0.2214
Cronbach's alpha	**0.7004**	**0.8171**	**0.8185**

Results are from the factor analysis of the "next timber harvest" scenario, which are nearly identical to the "stand improvement" scenario loadings. Bold type signifies "heavy" loadings (x>0.60).

E. Hypotheses

To test which drivers are the most important behind the forest owners' decision to harvest timber residue, we developed several hypotheses. The variables included in equation (6) are grounded in theoretical expectations stemming from equation (1). These expectations can be formulated as testable hypotheses. Rejection of the null hypothesis in each of the following expectations supports the theoretical explanation.

We expect that because the forest owner gains utility from marketed goods and services, the higher the offered payment for timber residues, the more the landowner will earn and the more likely the landowner will be to accept the offer to harvest timber residues. To state the first hypothesis in formal, null form:

- H1: Price offered for timber residue has no effect on the decision to sell timber residues.

Single species tracts lend themselves well to harvesting slash due to the intensive stand improvements or timber harvests that take place in these tracts. In one harvesting method common to single species, single age tracts, large amounts of residue are cut and piled at a central location. Thus, we expect that the more acres of single species forest that a forest owner possesses, the more likely that forest owner will be to harvest timber residue. Stating the second null hypothesis formally, we have:

- H2: The area of acres of single species trees that a forest owner possesses has no effect on the decision to sell timber residue.

We also expect that the higher the value a forest owner places on the environmental amenities on her or his land that can be harmed by the harvest of timber residues, the less likely she or he is to offer up forested land for timber residue harvest. These amenities can be expressed through the "conservationist" factor that is positively loaded on concerns about loss of biodiversity and land use change. We state the third null hypothesis as:

- H3: Value placed on environmental amenities associated with the harvest of timber residue has no effect on the decision to harvest.

We expect the "pro-bioenergy" attitude factor to have a positive effect because the more an individual values bioenergy, the more utility they gain from providing timber residue by way of their integrity (*i(b)* in equation (1)). In the dataset, this translates to higher Likert scores in the base variables with high loadings correspond to a more favorable view of bioenergy with respect to the variables that have a high loading in this factor. We state the fourth null hypothesis as:

- H4: Bioenergy knowledge and attitudes have no effect on the decision to sell timber residue.

We expect that disamenities associated with harvesting timber residues will increase with timber residue harvest, lowering the likelihood that a forest owner will harvest timber residues from her or his land. Disamenities can be expressed through the "anti-rent" factor that captures concern variables such as noise, smell, and privacy. We state the fifth null hypothesis as:

- H5: Concern over disamenities associated with the harvest of timber residue has no effect on the decision to harvest.

V. Results and Discussion

Frequency percentages of landowner willingness to sell timber residues at four different prices per acre is presented in table (4). "Yes," is monotonically increasing for all price levels. Overall willingness to sell is high at over 50% both at next harvest and at next stand improvement. The difference for the undifferentiated, non-specific "no" is less marked between $60 and $90 in "next timber harvest" and from $30 to $60 in "stand improvement." Some changes go against expectation, such as "no, maybe with higher payment" from $30 to $60 and "no, never," from $60 to $90 for both scenarios. In general, the descriptive statistics remain consistent with our hypothesis H1 that price has a positive effect on the probability of accepting an offer to harvest timber residues.

Table 4: Forest owners willing to sell timber residues at four price levels

	At next timber harvest					**At next stand improvement**				
	Price ($/acre)					**Price ($/acre)**				
Response (%)	**15**	**30**	**60**	**90**	**Overall**	**15**	**30**	**60**	**90**	**Overall**
Yes	45	47	58	63	53	39	42	56	64	51
No, no plans	19	19	15	12	16	19	18	17	10	16
No	3	4	3	3	3	3	4	4	2	3
No, maybe with higher payment	16	14	16	8	13	21	15	17	8	15
No, never	16	17	8	14	14	17	21	6	16	15
N =	**938**					**899**				

The weighted results from the probit analysis appear in table (5) (additional variables are reported in table (7) in the Appendix). Unweighted results for comparison (as recommended by Solon et al. (2015)) also appear in tables (8-9) in the Appendix.

All probit results are presented as marginal effects at the mean, or the marginal change in the probability of acceptance given a change in the explanatory variable at its mean. Presenting coefficient estimates at their marginal effects at the mean of the data improves the ease of interpreting probit results generally as well as providing basic comparisons between different variables. Other marginal changes computed between specific values reported in this results section are computed separately.

Comparing coefficients between weighted and unweighted models is a frame of reference regarding the functional form of the model (Solon et al., 2015). If the coefficients drastically differ, the model specification is unreliable. Weighted estimates (tables (5,7)) tend to have coefficients slightly larger in magnitude than coefficients in the unweighted regression (tables (8-9)), but all coefficients express the same direction, and statistical significance is largely shared between the same coefficients. In addition, the bivariate IV probit results in table (10) display results that are generally on par with the weighted findings in table (5). Together, these are a signal that our chosen functional form is generally robust (Lee & Solon, 2011; Solon et al., 2015).

Additionally, we report the elasticities of select variables graphically in figure (2). Elasticities, like the marginal effects in tables (5, 7-10), are reported at the mean. The elasticity is the change in the natural log of the probability of acceptance as a function of the change in the natural log of a given explanatory variable. In other words, the elasticity is the percentage change in the probability of acceptance for a percentage change in each explanatory variable. Reporting elasticities is helpful in viewing the sensitivity of pertinent variables that have very different measurement units.

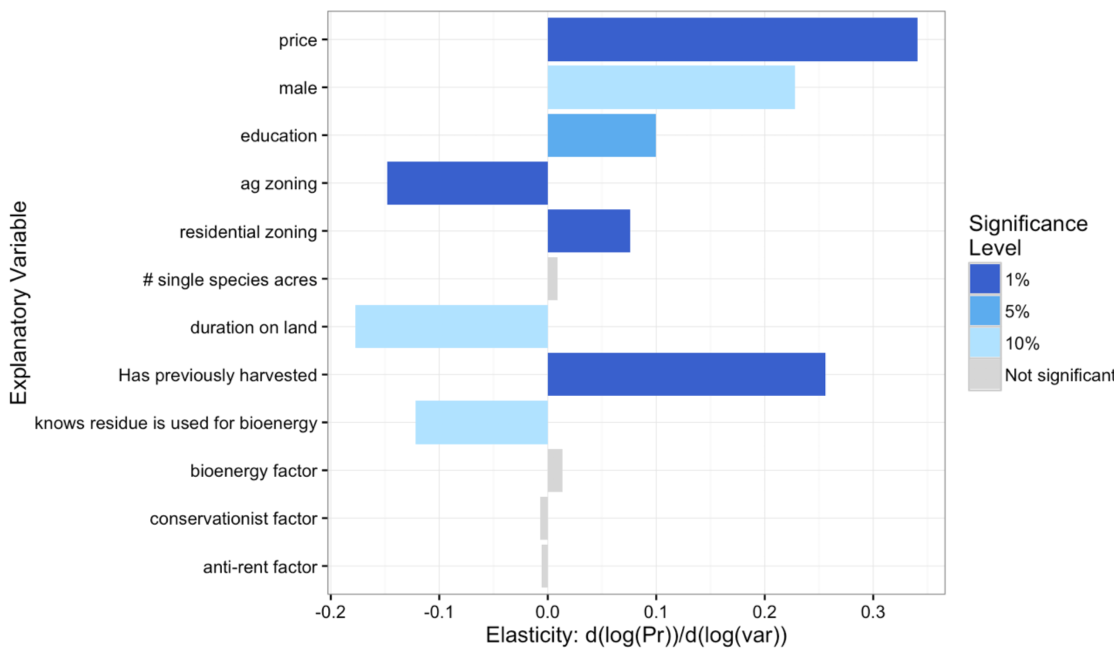
Table 5: Willingness to supply timber residues under two different scenarios, weighted

	At Next Timber Harvest			At Next Stand Improvement		
Variable	**Marginal Probability**	**Std. Dev.**	**p-value+**	**Marginal Probability**	**Std. Dev.**	**p-value+**
Income						
Price offered	0.0039***	0.0012	0.0010	0.0052***	0.0012	0.0000
Income	-9.55×10^{-7}	6.31×10^{-7}	0.1310	-1.61×10^{-7}	6.37×10^{-9}	0.8010
Demographics						
Age	0.0036	0.0036	0.3160	0.0027	0.0035	0.4350
Male	0.1660*	0.0880	0.0610	0.1496*	0.0877	0.0940
Farmer	0.1174	0.0798	0.1540	0.0328	0.0899	0.7160
Education	0.1436**	0.0711	0.0430	0.1554**	0.0718	0.0310
Ag zoning	-0.2347***	0.0766	0.0030	-0.1430*	0.0777	0.0690
Residential zoning	0.2505***	0.0786	0.0060	0.1986**	0.0883	0.0360
Duration on land	-0.0043*	0.0025	0.0900	-0.0029	0.0025	0.2470
Is resident of land	-0.0527	0.0800	0.5140	-0.0438	0.0808	0.5890
Forest Characteristics						
# of mixed forest acres	-0.0003	0.0002	0.1030	-0.0006*	0.0003	0.0590
# of single-species acres	0.0006	0.0006	0.3070	0.0007***	0.0003	0.0100
# of acres of other forest	0.0009	0.0021	0.6610	0.0008	0.0009	0.4110
Has mixed forest over 10 years old	0.0781	0.1049	0.4540	0.1263	0.1012	0.2180
Has single-species forest over 10 years old	0.0739	0.0718	0.3070	-0.0715	0.0708	0.3140
Use						
Has previously harvested timber	0.2521***	0.0698	0.0000	0.1709**	0.0734	0.0220
Uses forest for personal use	0.1083	0.1051	0.3010	0.1497	0.1002	0.1450
Knowledge						
Landowner has heard of bioenergy	-0.0412	0.1095	0.7100	-0.1470	0.1112	0.2070
Knows slash can be feedstock	-0.1373*	0.0725	0.0610	-0.1816**	0.0741	0.0160
Has seen a pile of slash	0.0464	0.0750	0.5360	-0.0536	0.0743	0.4720
Factors						
Pro-bioenergy	0.0606	0.0384	0.1160	0.0468	0.0374	0.2110
Conservationist	-0.0352	0.0431	0.4150	-0.0330	0.0445	0.4590
Anti-rent	-0.0292	0.0394	0.4590	-0.0995**	0.0409	0.0150
n=	**751**			**754**		

+ p-values reported are from the original probit regression coefficients; α Robust standard errors
* Significant at the 10% level, ** Significant at the 5% level, *** Significant at the 1% level
Marginal probabilities are reported at the mean value of the respective explanatory variable.

Based on the highly significant coefficients on the price variables in both scenarios, we reject the first null hypothesis that price offered has no effect on the decision to allow the harvest of timber residues (H1). Price carried a positive coefficient under both scenarios, with a larger effect in the "stand improvement" scenario. It is also clear from figure (2) that price is the most elastic, significant, positive influence on the probability to harvest. At the mean price of about $50 per acre, a $30 increase in price would make a forest owner 11.7% more likely to harvest timber residues at the next timber harvest and 15.6% more likely at the next stand improvement.

Figure 2: Elasticities of statistically significant coefficients in the "next timber harvest" scenario



Based on the highly significant coefficient on number of single species acres in the "stand improvement" scenario in table (5), we reject H2, the null hypothesis that the possession of single species acres does not affect the likelihood that a forest owner will allow the harvest of timber residues. This relationship is also consistent with our hypothesis.

We fail to reject the hypothesis H3 that value placed on environmental amenities has no effect on the probability of accepting harvest of timber residue. The “conservationist” factor, which is positively associated with environmental amenity attitudes, carried a negative coefficient in both scenarios but was not significantly different from zero.

We fail to reject H4, the hypothesis that bio-energy knowledge and attitudes do not affect willingness to harvest timber residues. The “pro-bioenergy” factor carried positive coefficients in both scenarios, but was not significantly different from zero with at least 90% confidence for either scenario.

The results from our weighted probit analysis in table (5) lead us to reject null hypothesis H5 that concerns over disamenities associated with the harvest of timber residue will not affect the willingness to harvest said residue. The coefficient on the “anti-rent” factor, which carried high loadings for smell and noise concerns, had a negative, significant effect in the “stand improvement” scenario in the weighted regression with over 95% confidence. The coefficient in the “next harvest” scenario was also negative, but its effect was insignificant.

Variables other than price, environmental amenities, and disamenities are also relevant in the timber residue discussion. Having at least a college education made a forest owner 14.3% more likely at time of timber harvest and 15.5% more likely at time of stand improvement to accept the price offer, both with confidence levels of at least 95%. This finding is consistent with both Gruchy et al. (2012) and Aguilar et al. (2014), who report positive, significant coefficients associated with the prediction of accepting an offer to pay for timber residue.

Other demographic characteristics worth noting include land ownership duration and previous harvesting behavior. Forest owners who had resided on her or his land for longer periods were less apt to harvest residue in the "next harvest" scenario. Every additional ten years of land duration lowered the probability to accept harvest of timber residue by 4.3% in the "next harvest scenario. Forest owners with a history of harvesting timber were over 25.2% more likely to accept the offer at next timber harvest and 17% more likely to accept at the next stand improvement. This could imply that the presence of commercial behavior raises the likelihood of harvest as found by Aguilar et al. (2014) and is consistent with our rejection of H2 (single species acres).

We ran the instrumental variable bivariate probit regression discussed in section (IV) (D) with our chosen model as a robustness check. The results of the instrumental variable bivariate probit regression (see table 10 in the Appendix) are on par with the weighted results in table (5), which a few exceptions. The coefficient estimate on mixed forest acres in the unweighted regression in table (8) was negative and statistically different from zero at over 99% confidence (as compared with 90% in table (5)). The coefficient on old mixed forest was statistically significant at 10% and carried a positive coefficient. The lack of major disparities between the models' results implies robustness.

The general congruence between variables across the timber harvest and stand improvement scenarios communicate that these two situations tend to have overlapping answers. The stand improvement model, however, tends to have marginal probabilities with a larger magnitude. It is possible that forest owners that are not expecting commercial value from a necessary, typically non-commercial chore are more likely to grasp at an opportunity to create value from it.

VI. Summary and Conclusion

Willingness to supply timber residues is generally high on private forest lands in the Northern Tier. Over 50% of non-industrial private forest owners surveyed were willing to supply timber residues at some price level. At $90 per acre, willingness was over 60% for both scenarios. When controlling for demographic, forest, and other characteristics, our results show that several factors contribute to the willingness to supply timber residue.

The price effect was significant in both situations and notable in magnitude. College-educated forest owners that had harvested timber in the past were more willing to harvest. Land owners with concerns over noise, smell, and other disamenities associated with harvest were less likely to harvest. Forest owners with larger single species acreage tracts were more prone to harvest timber residues.

While economic drivers such as price remain important, they are hardly the only factor in the equation. The large magnitude and high significance on the coefficient that represents whether a forest owner has previously harvested timber implies that commercially-leaning private forest owners are more likely to derive added value from their land when given the opportunity. This is combined with the fact that a forester with a tree species makeup heavier in single species acres is more apt to allow harvest of timber residue in at least one scenario. These findings support Aguilar et al.'s (2014) and Butler's (2008) findings that landowners with larger timber revenues were more willing to sell residues and that timber residue markets are bound to the commercial wood market.

Based on the findings of this study, most owners of non-industrial private forest lands in areas of northern Michigan and Wisconsin are favorably disposed to supply timber residues for energy biomass. As byproducts, such residues would have a negligible effect on timber product prices and none on food prices, while preserving several environmental advantages. The price offered for timber residue, the number of single species acres, and aversion to disamenities are the main drivers behind the provision of timber residues, along with factors such as education, previous harvesting behavior, and duration on land. The implication of previous studies that forest owners with a commercial predilection are more likely to supply timber residues has merit. Based on our results, the most effective way to increase timber residue supply beyond the already high levels of support is to target educated, non-conservationist owners with a history of harvesting timber, rather than simply offering a higher price for timber residues in isolation.

APPENDIX

Table 6: Survey weights (inverse sampling probabilities) by county and stratum

	Forest Program*		No Forest Program	
	10-100 acres	**100+ acres**	**10-100 acres**	**100+ acres**
<u>Michigan</u>				
Alger County	1.83	1.00	2.54	1.17
Alpena County	1.00	1.00	20.3	8.88
Antrim County	1.04	1.00	6.40	1.22
Clare County	1.00	1.00	11.1	3.51
Emmet County	1.23	1.00	6.79	2.26
Gladwin County	1.00	1.00	14.5	4.15
Grand Traverse County	1.00	1.00	12.7	2.79
Iosco County	1.00	1.00	7.27	4.24
Marquette County	23.4	6.00	2.29	1.38
Mason County	1.04	1.00	11.0	3.97
Schoolcraft County	4.63	2.42	2.63	1.08
Wexford County	4.21	1.00	11.08	2.18
<u>Wisconsin</u>				
Bayfield County	7.19	2.88	52.1	11.9
Florence County	5.17	1.85	25.8	1.00
Lincoln County	5.58	1.85	7.38	2.19
Polk County	6.90	2.50	60.7	16.3
Portage County	11.0	2.13	70.7	16.1
Shawano County	5.38	1.00	52.4	8.70

*Forest programs include the Michigan Qualified Forest Program, the Michigan Commercial Forest Program, and the Wisconsin Forest Law Programs.

Table 7: Willingness to supply timber residues, county dummies, weighted

	At Next Timber Harvest			At Next Stand Improvement		
Variable	**Marginal Probability**	**Std. Dev.** $^{\alpha}$	**p-value**$^{+}$	**Marginal Probability**	**Std. Dev.** $^{\alpha}$	**p-value**$^{+}$
County Dummies						
Alger	-0.2479	0.1499	0.1200	-0.2352	0.1499	0.1540
Alpena	-0.4633**	0.1306	0.0260	-0.3712*	0.1504	0.0770
Antrim	-0.1822	0.2062	0.3870	-0.1763	0.2193	0.4450
Bayfield	-0.1985	0.1573	0.2150	-0.1647	0.1667	0.3360
Clare	-0.5606***	0.0446	0.0000	-0.5017***	0.0478	0.0000
Emmet	-0.3509**	0.1387	0.0340	-0.2705	0.1548	0.1270
Gladwin	-0.1482	0.1936	0.4470	-0.0545	0.2012	0.7870
Grand Traverse	-0.2070	0.2014	0.3210	-0.2322	0.1810	0.2450
Iosco	-0.0003	0.2415	0.9990	-0.0860	0.2379	0.7200
Lincoln	-0.2746*	0.1396	0.0670	-0.2015	0.1490	0.2010
Marquette	-0.2367	0.1814	0.2130	-0.2387	0.1752	0.2130
Mason	-0.2413	0.1765	0.1980	-0.3298**	0.1374	0.0570
Polk	-0.4722***	0.1115	0.0010	-0.4372***	0.1179	0.0040
Portage	-0.2606*	0.1511	0.0980	-0.2928*	0.1440	0.0660
Schoolcraft	-0.2704*	0.1489	0.0940	-0.2408	0.1533	0.1560
Shawano	-0.2502	0.1510	0.1100	-0.3150**	0.1421	0.0480
Wexford	-0.4740***	0.1082	0.0070	-0.4291**	0.1028	0.0130
Florence	-0.2066	0.1575	0.1990	-0.1505	0.1670	0.3790
n=		**751**			**754**	

$^{+}$ p-values reported are from the original probit regression coefficients; $^{\alpha}$ Delta-method standard errors
* Significant at the 10% level, ** Significant at the 5% level, *** Significant at the 1% level
Marginal probabilities are reported at the mean value of the respective explanatory variable.
Weights are the inverse of sampling probabilities.

Table 8: Willingness to supply timber residues under two different scenarios, unweighted

	At Next Timber Harvest			At Next Stand Improvement		
Variable	**Marginal Probability**	**Std. Dev.** α	**p-value**+	**Marginal Probability**	**Std. Dev.** α	**p-value**+
Income						
Price offered	0.0027***	0.0007	0.0000	0.0052***	0.0012	0.0000
Income	2.00×10^{-7}	3.73×10^{-7}	0.5920	-1.61×10^{-7}	6.37×10^{-7}	0.2860
Demographics						
Age	0.0013	0.0021	0.5340	0.0027	0.0035	0.3700
Male	0.0475	0.0593	0.4200	0.1496	0.0877	0.9170
Farmer	-0.0175	0.0532	0.7420	0.0328	0.0899	0.1990
Education	0.1103**	0.0445	0.0130	0.1554***	0.0718	0.0000
Ag zoning	-0.1208**	0.0475	0.0110	-0.1430	0.0777	0.8530
Residential zoning	0.0295	0.0586	0.6170	0.1986	0.0883	0.3650
Duration on land	-0.0043***	0.0014	0.0010	-0.0029**	0.0025	0.0210
Is resident of land	-0.0519	0.0450	0.2510	-0.0438	0.0808	0.5800
Forest Characteristics						
# of mixed forest acres	-0.0001*	0.0001	0.0610	-0.0006**	0.0003	0.0260
# of single-species acres	0.0004	0.0005	0.3930	0.0007	0.0003	0.2770
# of acres of other forest	0.0006	0.0010	0.5480	0.0008	0.0009	0.4500
Has mixed forest over 10 years old	0.1333*	0.0716	0.0620	0.1263*	0.1012	0.0720
Has single-species forest over 10 years old	0.0401	0.0409	0.3280	-0.0715	0.0708	0.7700
Use						
Has previously harvested timber	0.1770**	0.0463	0.0000	0.1709***	0.0734	0.0020
Uses forest for personal use	0.0829	0.0574	0.1460	0.1497	0.1002	0.1240
Knowledge						
Landowner has heard of bioenergy	-0.0208	0.0810	0.7980	-0.1470	0.1112	0.3310
Knows slash can be feedstock	-0.0567	0.0434	0.1940	-0.1816*	0.0741	0.0580
Has seen a pile of slash	0.0522	0.0483	0.2770	-0.0536	0.0743	0.8480
Factors						
Pro-bioenergy	0.0461**	0.0226	0.0410	0.0468	0.0374	0.4880
Conservationist	-0.0672***	0.0247	0.0060	-0.0330***	0.0445	0.0080
Anti-rent	-0.0451*	0.0251	0.0720	-0.0995**	0.0409	0.0250
n=		**751**			**754**	

+ p-values reported are from the original probit regression coefficients; α Delta-method standard errors
* Significant at the 10% level, ** Significant at the 5% level, *** Significant at the 1% level
Marginal probabilities are reported at the mean value of the respective explanatory variable.

Table 9: Willingness to supply timber residues, county dummies, unweighted

	At Next Timber Harvest			At Next Stand Improvement		
Variable	**Marginal Probability**	**Std. Dev.** $^{\alpha}$	**p-value**$^{+}$	**Marginal Probability**	**Std. Dev.** $^{\alpha}$	**p-value**$^{+}$
County Dummies						
Alger	-0.0492	0.1171	0.6710	-0.2352	0.1499	0.5130
Alpena	-0.3672***	0.1115	0.0070	-0.3712	0.1504	0.0320
Antrim	-0.0482	0.1416	0.7310	-0.1763	0.2193	0.2220
Bayfield	-0.0180	0.1061	0.8650	-0.1647	0.1667	0.4920
Clare	-0.3603**	0.1216	0.0140	-0.5017**	0.0478	0.0240
Emmet	-0.2343*	0.1207	0.0630	-0.2705	0.1548	0.2830
Gladwin	-0.1352	0.1629	0.4060	-0.0545	0.2012	0.7490
Grand Traverse	-0.2844*	0.1562	0.0960	-0.2322*	0.1810	0.0980
Iosco	0.0813	0.1618	0.6290	-0.0860	0.2379	0.9000
Lincoln	-0.1453	0.1024	0.1560	-0.2015	0.1490	0.1790
Marquette	-0.0928	0.1209	0.4390	-0.2387	0.1752	0.5280
Mason	-0.0495	0.1278	0.6960	-0.3298	0.1374	0.4440
Polk	-0.2139**	0.0968	0.0310	-0.4372***	0.1179	0.0100
Portage	-0.2106**	0.1003	0.0400	-0.2928	0.1440	0.0150
Schoolcraft	-0.2065	0.1239	0.1040	-0.2408	0.1533	0.0870
Shawano	-0.1985*	0.1007	0.0530	-0.3150***	0.1421	0.0050
Wexford	-0.2575**	0.1223	0.0480	-0.4291**	0.1028	0.0260
Florence	-0.1830*	0.0974	0.0630	-0.1505*	0.1670	0.0770
n=	**751**			**754**		

$^{+}$ p-values reported are from the original probit regression coefficients; $^{\alpha}$ Robust standard errors
* Significant at the 10% level, ** Significant at the 5% level, *** Significant at the 1% level
Marginal probabilities are reported at the mean value of the respective explanatory variable.

Table 10: Willingness to supply timber residues under two different scenarios, weighted bivariate probit IV regression

	At Next Timber Harvest			At Next Stand Improvement		
Variable	**Marginal Probability**	**Std. Dev.** $^{\alpha}$	**p-value**$^{+}$	**Marginal Probability**	**Std. Dev.** $^{\alpha}$	**p-value**$^{+}$
Income						
Price offered	0.0024**	0.0010	0.0130	0.0042***	0.0010	0.0000
Income	-5.59×10^{-7}	3.54×10^{-7}	0.1140	-3.19×10^{-7}	3.29×10^{-7}	0.3320
Demographics						
Age	0.0042	0.0029	0.1480	-0.0018	0.0027	0.4980
Male	0.0351	0.0761	0.6440	0.1209*	0.0685	0.0780
Farmer	0.3860***	0.0472	0.0000	0.2498***	0.0663	0.0000
Education	0.0876*	0.0491	0.0740	0.1975***	0.0509	0.0000
Ag zoning	-0.2760***	0.0723	0.0000	-0.0735	0.0734	0.3160
Residential zoning	0.3937***	0.0457	0.0000	0.3965***	0.0769	0.0000
Duration on land	-0.0101***	0.0022	0.0000	-0.0026	0.0019	0.1750
Is resident of land	-0.3501***	0.0507	0.0000	-0.3413***	0.0575	0.0000
Forest Characteristics						
# of mixed forest acres	-0.0003***	0.0001	0.0060	-0.0004*	0.0002	0.0600
# of single-species acres	0.0028***	0.0010	0.0050	0.0025***	0.0008	0.0010
# of acres of other forest	0.0056***	0.0021	0.0090	0.0028	0.0027	0.2970
Has mixed forest over 10 years old	0.1094	0.0974	0.2610	0.0964	0.0841	0.2520
Has single-species forest over 10 years old	0.0667	0.0571	0.2430	-0.1668***	0.0547	0.0020
Use						
Has previously harvested timber	0.3716***	0.0620	0.0000	0.2407***	0.0619	0.0000
Uses forest for personal use	0.0573	0.0677	0.3970	0.1351**	0.0591	0.0220
Knowledge						
Landowner has heard of bioenergy	0.1442	0.1118	0.1970	-0.0564	0.1127	0.6170
Knows slash can be feedstock	-0.2617***	0.0673	0.0000	-0.2409***	0.0653	0.0000
Has seen a pile of slash	0.1000	0.0622	0.1080	-0.1653**	0.0654	0.0110
Factors						
Pro-bioenergy	0.0819***	0.0274	0.0030	0.0445*	0.0259	0.0860
Conservationist	-0.0199	0.0291	0.4940	-0.0165	0.0286	0.5630
Anti-rent	-0.0561**	0.0258	0.0300	-0.1264***	0.0280	0.0000
n=		**751**			**754**	

$^{+}$ p-values reported are from the original probit regression coefficients; $^{\alpha}$ Delta-method standard errors
* Significant at the 10% level, ** Significant at the 5% level, *** Significant at the 1% level
Marginal probabilities are reported at the mean value of the respective explanatory variable.

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Chapter 2: How Much Timber Residue can be Supplied Economically from Non-Industrial Private Lands in the Northern Tier of the Great Lakes?

I. Introduction

The Northern Tier of the Great Lakes has a massive, largely untapped bioenergy resource. The region is active with commercial timber production activity, yet harvesters leave behind timber residue, a useful and abundant byproduct of logging events. Timber residue is a part of the "wood and wood residues" part of the Department of Energy's (2011) definition of biomass. Timber residue is also known as "timber slash," "logging residue," and "tree and branch biomass" (TBB). It only includes aboveground tree tops, limbs, branches, and residue biomass (stumps, boles, and any biomass below ground are not included). In the North Central region of the United States, which includes the Northern Tier of the Great Lakes, harvesters use only 20.6% of timber residue and leave the remaining 79.4% on-site (Smith et al., 2004). When utilized for bioenergy, timber residue contributes to the Renewable Portfolio Standards, reduces greenhouse gas emissions (Zhang et al., 2015), and displaces the use of coal. Even though current fuel prices remain low, future price instability and changing markets could render timber residue a valuable piece of an affordable, less carbon-intensive energy economy in the Northern Tier.

Private lands serve as one of the largest sources of forested lands in the Northern Tier of the Great Lakes, thus one of the largest sources of timber residue. According to the National Forest Service's Forest Inventory Analysis, Wisconsin and Michigan have about 11.9 million and 12.6 million acres of private forested land, respectively. This is over half of all forests: in Michigan, private forests comprise 62% of the total forested land; private forests are 70% in Wisconsin (USDA, 2016c). Of the private forested lands, the vast majority of these are under the ownership of non-industrial private forest owners (NIPFs) (MI DNR, 2010; USDA, 2004). Quantifying the availability of timber residues within the holdings of NIPFs sheds light on a sizable proportion of market potential.

The potential growth of bioenergy in the United States hinges on the availability of bioenergy feedstocks such as timber residue. Accurate timber residue supply projections are crucial to inform bio-refinery entrepreneurs, investors, policy-makers, and bioenergy researchers where to focus their efforts to maximize growth (Langholtz & Jacobson, 2013). Shipments of forest residue over a 50-mile radius are generally recognized to be uneconomical (USDA, 2004), therefore the strategic siting of bio-refineries and power plants with wood-burning capabilities should be informed by an accurate understanding of where biomass supply exists. Supply estimates with a more location-specific framework provide a benchmark for existing supply estimates that guide federal policies such as the Energy Independence and Security Act of 2007 (US Congress, 2007). Timber residue projections provide geographical points of focus in which to conduct future microeconomic studies. The National Biorefinery Siting Model found that the majority of woody biomass will come from the North Central and the Southeastern United States (NRC, 2011), yet the majority of studies projecting supply center on the Southeast. County-level estimates of timber residue supply in the Northern Tier of the Great Lakes could measure the marginal cost of delivery to a conversion facility such as Petrolia (2006) conducted in Minnesota.

How do we measure timber residue availability? There are two broad type classes within timber residue supply. Biophysical supply pertains to the actual, physically present and/or extractable timber residue. Biophysical constraints include soil type, site productivity, tree size, and tree age. Socio-economic supply refers to the amount of residue that private individuals and firms are willing to provide based on market or demographic factors such as owners' knowledge about bioenergy, harvest behavior, possession of single species tracts, and forest program membership as well as price offered for timber residue (as seen in Chapter 1). Some models also include geographical constraints within socio-economic models in order to account for travel costs.

An abundant literature is devoted to understanding NIPF behavior, but these studies are rarely used to inform supply estimates. Previous studies that aim to measure timber residue supply focus on only either biophysical supply (Goerndt et al., 2012; Tyndall et al., 2011; Becker et al., 2009; DOE, 2011; Aguilar et al., 2013; GC et al., 2017) or socio-economic (Langholtz & Jacobson, 2013; Galik et al., 2009; Becker et al., 2013) methods of quantification, but rarely both. Of the studies that combine these two aspects (Becker et al., 2010), none exists in the Northern Tier of the Great Lakes, a region with a strong commercial timber industry.

The goal of this study is to adjust county-level USDA Forest Service data for timber residue supply to account for non-industrial forest owner behavior. Adjusting for behavior reduces estimates in a way that reflects the true nature of private land: land is used at the will of the landowner. Satellite-level estimates or estimates that use only the timber resource base ignore this fact: we cannot use resources from private timberland unless the owner of the private timberland consents. This adjusted projection at the county level can serve entrepreneurs, investors, policymakers, and future researchers hone in on the most crucial counties for timber residue supply.

II. Conceptual Model

We assume that all private forest owners n $[n = 1 \dots, N]$ in the Northern Tier are seeking to maximize their utility with respect to the use of their forested land. Define the optimal quantity of acres, *A**, as in equation (10) (from Chapter 1, equation (2)). The utility function U is assumed to be differentiable and increasing concavely with respect to A as in Chapter 1, equation (1). The reduced form supply function for timber residue land, A (equation (2)), is also assumed to be differentiable and increasing concavely in price (p), environmental amenities (a), the number of single species acres owned (s), and knowledge of/attitudes toward bioenergy (b). The function A is decreasing in disamenities (d). These arguments, in turn, are affected by choice variable *A**, the number of acres that a landowner makes available for the harvest of timber residues.

(10)
$$A^* = A(p, a, b, d, \boldsymbol{ft} | \bar{A}, m, X_n) = \begin{cases} \bar{A}, & U(\bar{A}) > U(0) \\ 0, & U(\bar{A}) \leq U(0) \end{cases}$$

We found in Chapter 1 that the variables that drive the supply of timber residues in the Northern Tier are price, the number of single species acres owned, and disamenities. Supply is also conditional on variables such as income (m), age (j), and education (e), and characteristics captured by the vector $\boldsymbol{Z}$ in equation (10). The vector $\boldsymbol{Z}$ is comprised of all variables other than price, single species acres, disamenities, income, age, and education that we listed in Chapter 1, tables (5,7).

Define the individual acreage supply for timber residues, q_n, in the Northern Tier as in equation (11). I define timber residue supply as an aggregated representation of all individual private forest owners' optimal acreage values in the Northern Tier from equation (10). I assume supply is differentiable and increasing concavely in price.

(11) $$q_n(p|\overline{A_n}, m, j, e, \boldsymbol{Z\beta}) = A_n(p, s_n, d|\overline{A_n}, m, j, e, \boldsymbol{Z_n})$$

I describe the aggregate supply of all private forest owners n $[n = 1 \ldots, N]$ in the Northern Tier by Q_a in equation (12).

(12) $$Q_a = \sum_{n=1}^{N} q_n(p|\overline{A_n}, m, j, e, \boldsymbol{Z\beta})$$

By varying price, p, Q_a provides the number of acres available for timber residue harvest in the Northern Tier of the Great Lakes. I assume that other variables in equation (12) are representative of the population in the Northern Tier when held at their respective means.

III. Empirical Methodology

A. Model

Let the observed decision of every forest owner n $[n = 1 \dots, N]$ be represented by $y \in \{0,1\}$, where 1 signifies that n accepts offer to harvest timber slash, and 0 means that n declines the offer. The probability that any given individual n has greater utility from accepting the timber residue harvest than their utility from not accepting the harvest is equivalent to the probability that they accept the offer. This is also the probability that the number of acres individual n offers is equal to their number of available acres, $\bar{A}$, as seen in equation (13).

$$\text{(13)} \qquad \Pr\,(accept)_{\mathrm{n}} = \Pr[\mathrm{y} = 1]_n = Pr[A = \bar{A}]_{\boldsymbol{n}} = Pr[U(\bar{A}) > U(0)]_{\boldsymbol{n}}$$

We then map the function D from Chapter 1, equation (6) onto the cumulative distribution function of the standard normal distribution, $\Phi(\cdot)$. Using this link function, we define the density function, derive the likelihood function, and maximize the log likelihood to obtain marginal coefficients on the explanatory variables on the probability of acceptance in equation (13). The probability of acceptance represented by $q_n(p)$ in equation (14) serves as the proportion of total acreage for available for timber residue extraction.

$$\text{(14)} \qquad q_n(p|\overline{A_n}, m, j, e, \boldsymbol{Z\beta}) = \Pr(accept)_n * \overline{A_n} = \ \Phi(D) * \overline{A_n}$$

Equation (15) describes the function I used, *D,* in detail. This is the same function *D* from Chapter 1, equation (6).

$$(15)\quad \Phi(\mathrm{D}) = \Phi\big(\beta_0 + \beta_1 price_j + \beta_2 income + \beta_3 forestIncome + \beta_4 recIncome + \beta_6 age + \beta_7 male + \beta_9 farmer + \beta_{10} education + \beta_{11} agZone + \beta_{12} resZone + \beta_{13} duration + \beta_{14} resident + \beta_{15} mixed + \beta_{16} single + \beta_{17} other + \beta_{18} oldMix + \beta_{19} oldSingle + \beta_{20} prevHarv + \beta_{21} personal + \beta_{22} forestProg + \beta_{23} bioenergy + \beta_{24} slashEthanol + \beta_{25} seenSlash + \beta_{26} proBioenergy + \beta_{27} conservationist + \beta_{28} antiRent + \varepsilon\big)$$

B. Prediction of County Willingness to Harvest

Utilizing the weighted model developed from 2170 non-industrial, private forest owners in Michigan and Wisconsin in Chapter 1, equation (6), I predict the timber residue supply in acres that considers price-influenced non-industrial forest owner behavior. This chapter focuses on a problem of a predictive nature and, as such, it is important to have a model that is representative of the sample frame. I used a version of equation (15) that weighted each respondent by the inverse probability of their selection at each level of stratification (Solon et al., 2015).

To extrapolate the number of acres available for timber residue harvest in the entire 76-county sample frame in the Northern Tier of the Great Lakes, $Q_c{}'$ (equation (18)), I use county-level averages for demographic variables plus a "premium" that adjusts each average to better reflect the sample population of non-industrial private forest owners. Forest owners, by nature, have capital in the form of land. The forest owners in our sample owned at least 10 acres, some owning substantially more. Landowners such as these tend to be older, more wealthy, and educated than the average representation of the US Census. Therefore, the premiums are always positive. In order to calculate this premium (pm) for each county c, we averaged the difference of the non-missing variables (k) (education, age, or income) for each individual n from the survey with the corresponding US Census variables (h) for the individual's county over each county's population N_c in the sample (see equation (16)). These premiums can be found in table (16) in the appendix.

These premiums were necessary because the census population did not accurately represent the population of interest.

(16)
$$pm_c = \frac{\sum_{n=1}^{N_c}(k_n - h_c)}{N_c}$$

For the counties that were not included in the survey sample, I added the average premium across all sampled counties to each county's US Census value for each of the respective variables. These variables include median income and education level from the US Census American FactFinder (US Census, 2016) in place of sample-level averages for every sample frame county, c, plus their respective premium pm_c. This allows a better reflection of the variation of the true population of the Northern Tier (equation (17)). The probit results used to calculated $q_c(p)$ are found in table (11). These results exclude county fixed effects due to extrapolating over the entire region. Only three variables change across counties in equation (17); the rest are held at the sample means from the weighted survey regression in table (5).

(17)
$$\begin{aligned} q_c(p) = \Pr(accept)_c = \\ = \Phi\big(&\beta_0 + \beta_1 price_j + \beta_2 \overline{income_c} + \beta_3 forestIncome + \beta_4 recIncome \\ &+ \beta_6 \overline{age_c} + \beta_7 male + \beta_9 farmer + \beta_{10} \overline{education_c} + \beta_{11} agZone \\ &+ \beta_{12} resZone + \beta_{13} duration + \beta_{14} resident + \beta_{15} mixed + \beta_{16} single \\ &+ \beta_{17} other + \beta_{18} oldMix + \beta_{19} oldSingle + \beta_{20} prevHarv + \beta_{21} personal \\ &+ \beta_{22} forestProg + \beta_{23} bioenergy + \beta_{24} slashEthanol + \beta_{25} seenSlash \\ &+ \beta_{26} proBioenergy + \beta_{27} conservationist + \beta_{28} antiRent + \varepsilon\big) \end{aligned}$$

Table 11: Weighted probit results without county fixed effects

	At Next Timber Harvest		
Variable	**Marginal Probability**	**Std. Dev.** α	**p-value**+
Income			
Price offered	0.0088***	0.0030	0.0030
Income	$-1.98\text{x}10^{-6}$	$1.57\ \text{x}10^{-6}$	0.2080
Demographics			
Age	0.0074	0.0095	0.4410
Male	0.2734	0.2232	0.2210
Farmer	0.1542	0.2088	0.4600
Education	0.3444*	0.1831	0.0600
Ag zoning	-0.4287**	0.1982	0.0310
Residential zoning	0.6904**	0.2873	0.0160
Duration on land	-0.0114*	0.0065	0.0810
Is resident of land	-0.1747	0.2009	0.3850
Forest Characteristics			
# of mixed forest acres	-0.0004	0.0004	0.2950
# of single-species acres	0.0025	0.0027	0.3480
# of acres of other forest	0.0041	0.0111	0.7110
Has mixed forest over 10 years old	0.1795	0.2625	0.4940
Has single-species forest over 10 years old	0.2194	0.1829	0.2300
Use			
Has previously harvested timber	0.6435***	0.1812	0.0000
Uses forest for personal use	0.2916	0.2458	0.2350
Knowledge			
Landowner has heard of bioenergy	-0.1027	0.2791	0.7130
Knows slash can be feedstock	-0.3309*	0.1878	0.0780
Has seen a pile of slash	0.1630	0.1876	0.3850
Factors			
Pro-bioenergy	0.1163	0.0953	0.2220
Conservationist	-0.0846	0.1067	0.4280
Anti-rent	-0.0767	0.1026	0.4550
Constant	-1.1671	0.7223	0.1060
n=	**757**		

α Robust standard errors

* Significant at the 10% level, ** Significant at the 5% level, *** Significant at the 1% level

These are raw probit coefficients, not marginal probabilities.

C. Acreage Adjustment by Willingness to Harvest

To obtain the quantity of acres adjusted to account for forest owner economic behavior in the Northern Tier, I multiply the probability of acceptance per county by the total number of privately owned acres in each given county, Q_c as in equation (18). Private acreage data are available at the county level from US Forest Inventory & Analysis National Program's (FIA) Forest Inventory Data Online System (FIDO) (USDA, 2016c) in Michigan and Wisconsin. Since the private acreage data from the FIA does not differentiate between industrial and non-industrial, I multiply the number of privately-owned acres by the proportion non-industrial private acres to industrial private acres, NI_r for each county's US Forest Service region, *r*.[2] These regional proportions are detailed in table (17) in the appendix, as well as which counties belong to which US Forest Service region. This study uses the most current data available, based on the year 2015. These techniques vary by forest type group (t) and composition (single species stands are likely to be similar in harvesting technique as well). Let equation (18) represent the adjusted acreage, $Q_c{}'$, or the total number of non-industrial private acres available for timber residue extraction per county in the 76-county sample frame.

(18) $$Q_c{}' = q_c(p) * Q_c * NI_r$$

I estimate the biophysical ceiling comparison of maximum available residue by way of equation (18) and converting the acreage to ODT as in the following section.

[2] Due to privacy law, the USDA does not provide private acreage data that are disaggregated by industrial vs. non-industrial at the county-level; region-level disaggregation was the finest level attainable by law. I obtained region-specific data by special request via Scott Pugh, Forested with the US Forest Service (Phone interview and request for specific acreage data from the FIA, August 23, 2016). Only state-level data at this level of granularity are publicly available online.

D. Conversion and Units

There is high variation in harvesting practices amongst non-industrial private forest owners in the Great Lakes Region (GC et al., 2017). Therefore, I report the amount of available timber residue at an annual rate based on growth to normalize these differences and to provide an actual supply projection independent of harvest timing and intensity. Actual annual timber residue supply will vary depending these factors, but an annual rate based on growth gives a maximum physical availability for the market. I measure biomass supply in oven-dry short tons (ODT) of annual growth, or the weight of biomass that extractable in each year with 0% moisture content.

To convert acreage into ODT biomass estimates, I use data generated by the FIA's EVALIDator (USDA, 2016d) which disaggregates forest type groups, private lands, and regions. This allows the conversion of acreage to ODT based on heterogeneity that exists in real forest type variation throughout the sample frame. The FIA's EVALIDator reports data on forestland and timberland. Since privately owned forest eligible for harvest is better represented by timberland, which is land that can produce 20 cubic feet of wood per acre per year, I used timberland values for conversion. All data are pulled for both Michigan and Wisconsin. I calculate annual growth in cubic feet to ODT of timber residue, or tree and branch biomass (TBB)[3] per acre per year, O_t, for each forest type (t) group by way of a series of conversions. Table (11) specifically describes the components that make up the conversion to ODT from timber residue acreage. Equation (19) calculates O_t from weight (w_t), volume (v_t), and growth (g_t) measures provided by the FIA (USDA, 2016d).

[3] TBB is an appropriate proxy for timber residue.

Table 12: Components of equation (19)

Symbol	Description	Unit
O_t	Average annual net growth of live trees at least 5 inches in diameter by forest type group per acre	Oven-dry short tons (ODT)
g_t	Average annual net growth of live trees at least 5 inches in diameter per acre	ft^3
w_t	Total dry weight of all live trees at least 1 inch in diameter per acre	ODT
v_t	Net volume of live trees at least 5 inches in diameter per acre	ft^3
b_t	Proportion of the total dry weight of tops and limbs (timber residue) at least 5 inches in diameter per acre to the total dry weight of all live trees at least 1 inch in diameter per acre	ODT

(19)

$$O_t = g_t * \left(\frac{w_t}{v_t}\right) * b_t$$

Let equation (19) represent the conversion from timber residue acreage to ODT. The results of this conversion provide the ceiling (biophysical) biomass supply by giving annual growth per acre of various forest types in Michigan and Wisconsin (table (13)). If 100% of the amount of TBB in table (13) were harvested per year for each acre in the sample frame, the forests would experience no net loss in trees. This is the concept of sustainable timber harvest, and is the standard operating procedure in the Lake States. The rule of the thumb for sustainable harvest is that, "…the rate of harvest of forest production shall not exceed levels which can be permanently sustained," (MI DNR, 2016). This study reflects this standard.

Table 13: Annual tree and branch biomass (TBB) growth by forest type group for Michigan and Wisconsin

FIA Forest Type Group	TBB growth/acre/year (ODT)
White / red / jack pine group	0.19
Spruce / fir group	0.08
Other eastern softwoods group	0.15
Fir / spruce / mountain hemlock group	0.19
Exotic softwoods group	0.19
Oak / pine group	0.20
Oak / hickory group	0.20
Oak / gum / cypress group	0.39
Elm / ash / cottonwood group	0.11
Maple / beech / birch group	0.18
Aspen / birch group	0.15
Exotic hardwoods group	-0.08

Define the potential economic supply of biomass from timber residues, Q_b, as in equation (20). The variable Q_b is a function of the total acreage per county (Q_c) per forest type group (t).

(20)

$$Q_b = \sum_{c=1}^{N_c} \sum_{t=1}^{N_t} O_t * Q_{c_t}{}'$$

E. Extraction Adjustment

The amount of timber residue extracted is not equal to the total available amount per year. A certain proportion, e, is left in the process due to equipment, wildlife guidelines, or other reasons. Rates of extraction vary in the literature from about 50% (Domke et al., 2012; DOE, 2011) to 65% (Butler et al., 2010). For the purposes of this study, I will use the most common extraction scenario, 50%. Equation (21) reflects the adjustment to Q_b imposed by the rate of extraction, e.

(21) $$Q_b{}' = (1 - e)Q_b$$

IV. Results

The county-level results for the economic behavior-adjusted supply projections are found in tables (14-15). Projections are disaggregated by price offered per acre of timber residue. They are displayed in ODT rather than millions ODT to highlight differences more easily.

Table 14: Timber residue availability in Wisconsin section of the Northern Tier

	Timber Residue Available (ODT)			
WI County	**$15/acre**	**$30/acre**	**$60/acre**	**$90/acre**
Adams	7122	7519	8336	9173
Ashland	3839	4054	4497	4952
Bayfield	7823	8258	9149	10062
Burnett	5582	5891	6526	7178
Clark	4900	5181	5759	6355
Door	3476	3668	4060	4462
Douglas	7340	7754	8606	9482
Florence	3109	3284	3644	4013
Forest	3782	3995	4431	4880
Iron	4042	4264	4719	5185
Juneau	5173	5466	6067	6686
Langlade	4391	4638	5143	5663
Lincoln	5635	5952	6605	7276
Marathon	9381	9913	11006	12131
Marinette	8103	8558	9490	10448
Marquette	3404	3596	3993	4400
Menominee	4509	4761	5279	5811
Oconto	3290	3475	3857	4250
Oneida	7259	7661	8486	9331
Polk	5928	6264	6952	7660
Portage	4483	4733	5247	5774
Price	9028	9531	10562	11621
Rusk	6893	7279	8070	8883
Sawyer	8209	8663	9596	10553
Shawano	4511	4768	5294	5836
Taylor	5689	6011	6673	7354
Vilas	4878	5146	5694	6255
Washburn	5947	6277	6955	7649
Waupaca	4726	4993	5542	6107
Wood	4420	4669	5182	5708
Total	**166,873**	**176,222**	**195,422**	**215,138**

Table 15: Timber residue availability in the Michigan section of the Northern Tier

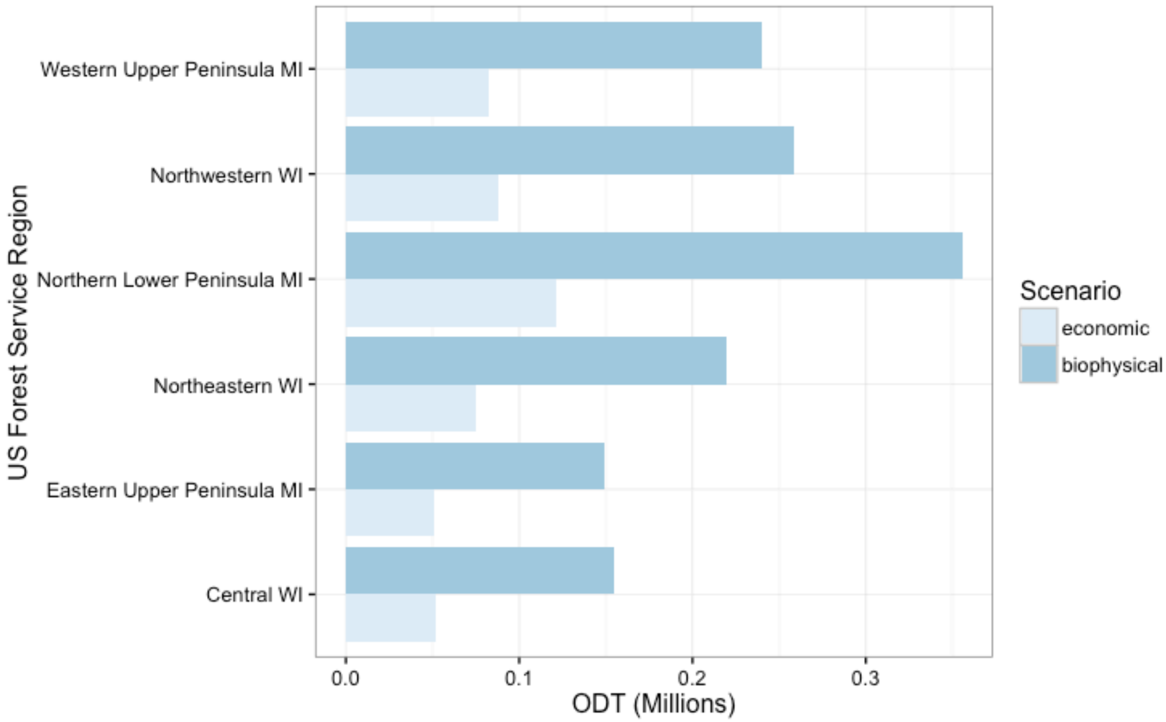
	Timber Residue Available (ODT)			
MI County	**$15/acre**	**$30/acre**	**$60/acre**	**$90/acre**
Alcona	3782	3989	4415	4851
Alger	4907	5181	5742	6317
Alpena	4867	5141	5702	6279
Antrim	3316	3502	3882	4273
Arenac	1877	1982	2198	2420
Baraga	4168	4403	4887	5385
Benzie	1677	1770	1961	2157
Charlevoix	2503	2642	2928	3221
Cheboygan	3781	3992	4424	4867
Chippewa	4961	5242	5819	6413
Clare	3908	4126	4574	5035
Crawford	2539	2681	2972	3270
Delta	4510	4762	5279	5811
Dickinson	1966	2076	2301	2532
Emmet	3266	3444	3809	4183
Gladwin	3608	3813	4233	4665
Gogebic	3420	3610	4000	4399
Grand Traverse	3418	3608	3996	4394
Houghton	4475	4728	5249	5785
Iosco	2089	2204	2440	2681
Iron	4973	5246	5805	6378
Kalkaska	2881	3043	3377	3720
Keweenaw	2143	2260	2501	2747
Lake	4862	5131	5685	6252
Leelanau	2256	2380	2632	2891
Luce	4645	4905	5441	5992
Mackinac	3715	3920	4342	4775
Manistee	3952	4172	4623	5085
Marquette	7911	8359	9280	10227
Mason	3074	3247	3601	3965
Mecosta	2225	2351	2612	2880
Menominee	5730	6050	6708	7383
Midland	1863	1967	2182	2403
Missaukee	3156	3334	3701	4078
Montmorency	4108	4336	4802	5279
Newaygo	7145	7550	8382	9238
Oceana	3692	3901	4329	4769
Ogemaw	1902	2008	2226	2450
Ontonagon	4163	4392	4860	5339

Table 15 (con't)

	Timber Residue Available (ODT)			
MI County	**\$15/acre**	**\$30/acre**	**\$60/acre**	**\$90/acre**
Osceola	4555	4812	5341	5886
Oscoda	3539	3736	4140	4554
Otsego	4782	5051	5603	6171
Presque Isle	4102	4329	4794	5270
Roscommon	1773	1871	2071	2276
Schoolcraft	3533	3732	4141	4561
Wexford	3118	3291	3645	4009
Total	**168,837**	**178,269**	**197,636**	**217,514**

Before the economic behavioral adjustment from this analysis, I calculate that Michigan's section of the Northern Tier has a biophysical ceiling of 0.494 million ODT of timber residue available annually from non-industrial private forest owners at \$15/acre, whereas Wisconsin's section has 0.491 million ODT from the same group. This still considers the 50% extraction rate as well as the downward adjustment to eliminate industrial forest acreage. However, non-industrial private forest owners' willingness to harvest adjusts this biophysical estimate significantly. Figure (3) highlights this difference by region.

Figure 3: Biophysical ceiling vs. economic projection by region



The economic scenario for this graph is when the price offered per acre if $15.

The regions of the Northern Tier with the most potential timber residue supply are the Northern Lower Peninsula and Northwestern Wisconsin (figure (3)). As found in Chapter 1, price offered per acre is one of the drivers for NIPFs' willingness to provide timber residue. It should be noted that all other factors are held constant when examining the relationship between price and timber residue supply. Figure (4) shows the difference in supply projection per the price offered in graphical form. Price elasticities are similar, implying a similarity between forest residue markets in the two states.

Figure (5) highlights the forest type differences between the Michigan and Wisconsin sections of the Northern Tier by acreage, whereas figure (6) displays the information from table (12) for easy comparison to figure (3). The forest type group makeup is similar across Michigan and Wisconsin. Wisconsin's overall supply is slightly larger than Michigan's, which is likely due to the higher number of acres in the white/red/jack pine and the oak/hickory forest type groups, which both have ODT/acre/year growth rates that are higher than average (see figures (5-6)).

Figure 4: Timber residue supply in the Northern Tier

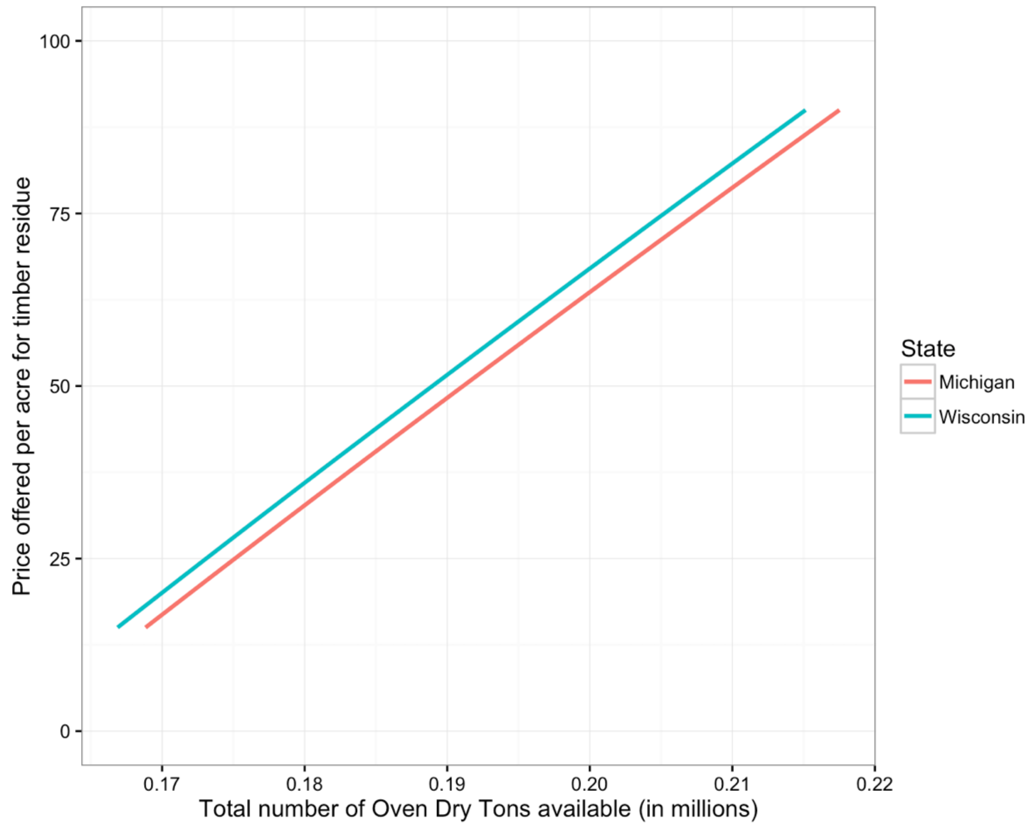


Figure (7) highlights differences by county in both states of the Northern Tier using a consistent scale. Marathon County, Wisconsin has the largest supply of timber residue at 9,400 ODT/year at $15/acre. Michigan's leading county, Marquette County (not to be confused with Marquette County, Wisconsin) could supply 7,900 ODT/year at an offer of $15/acre. These counties comprise over 5% of the total available timber residue in the Northern Tier at $15/acre.

Figure 5: Distribution of forest type groups by state

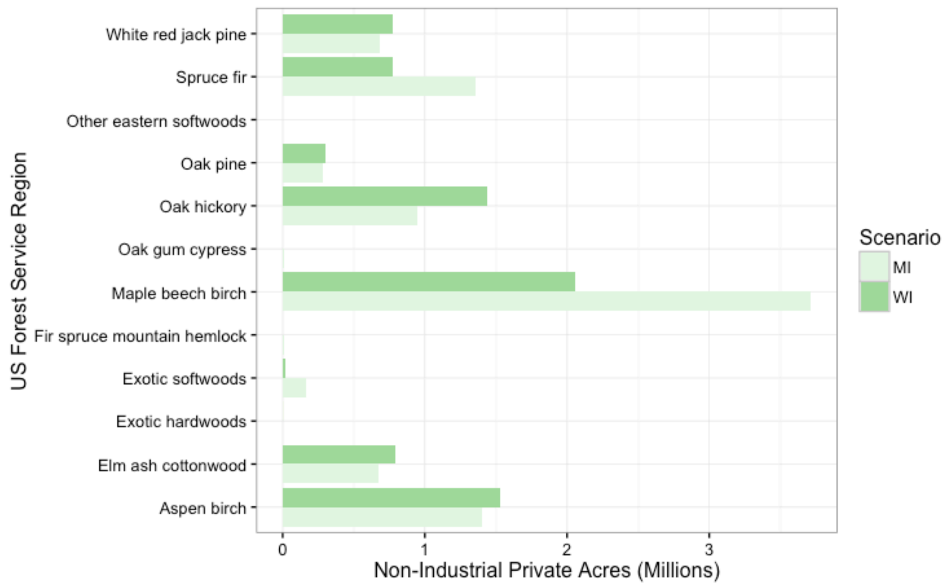
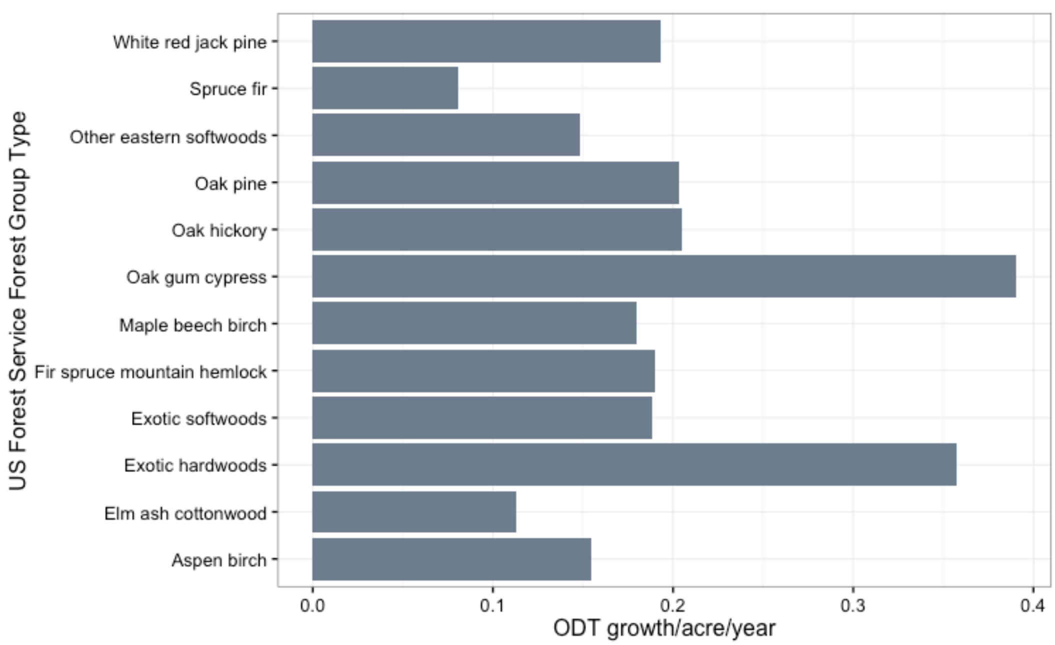


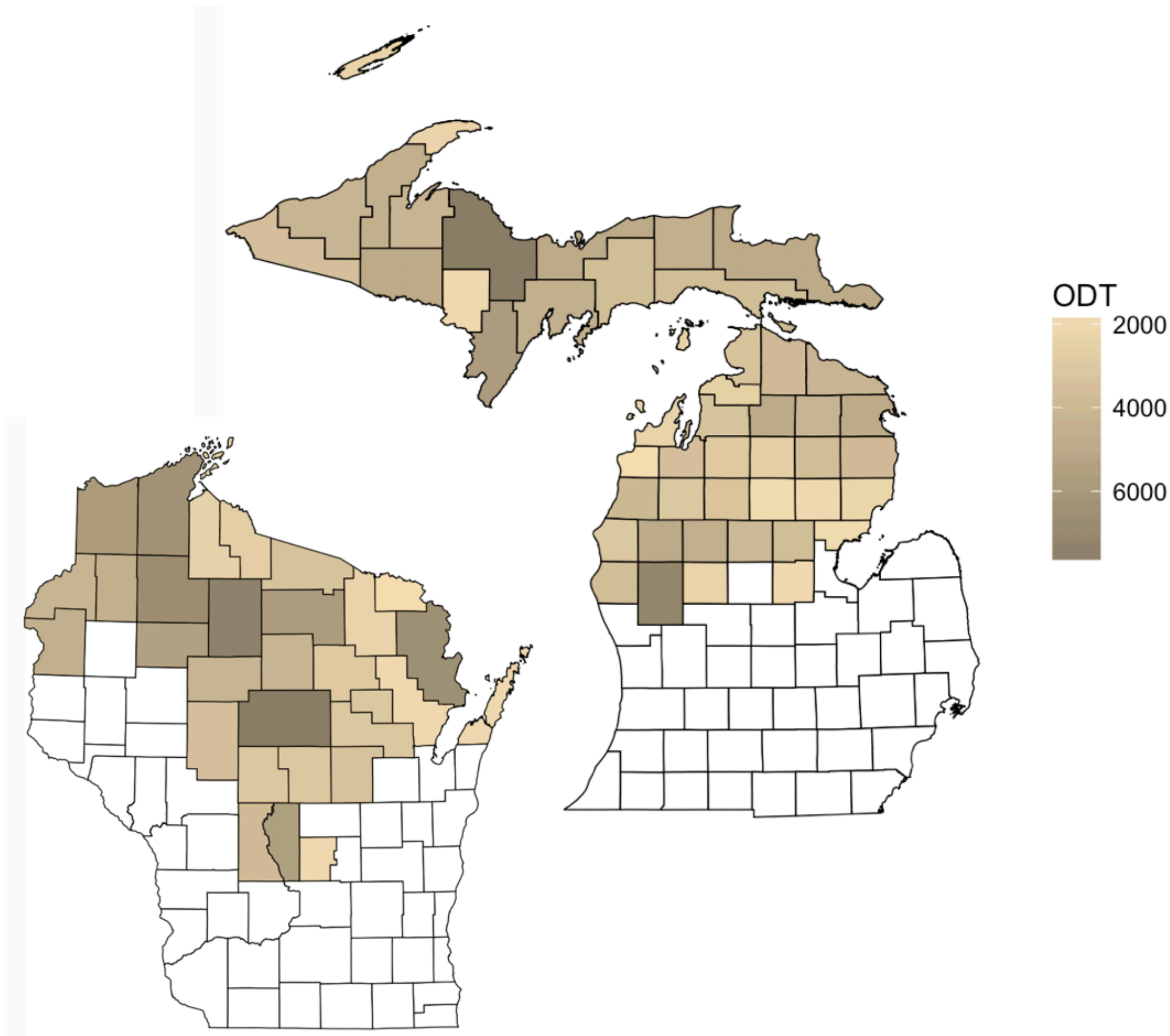
Figure 6: Annual ODT growth for forest type groups



The distribution of timber residue supply does not have outliers in the Northern Tier. Michigan's counties in the Northern Tier have timber residue supplies as high as 7,900 in

Marquette to as low as 1,700 ODT/year in Benzie at $15/acre. Wisconsin, similarly, has an upper limit of 9,400 in Marathon to Florence Counties at 3,100 ODT/year at $15/acre.

Figure 7: Timber residue supply in Michigan and Wisconsin at $15/acre



V. Conclusion and Discussion

A significant stock of energy biomass is available from timber residues. The potential energy uses for this stock are electricity generation (typically co-fired with coal) or as a liquid transportation fuel (after conversion to cellulosic ethanol). The latter is an end-use that relies heavily on technological advances.

A. Co-Firing

Burning biomass with coal has benefits. Compared with coal alone, it reduces NO_x and SO_x particulates and sometimes improves boiler efficiency (Demirbaş, 2003). Moreover, burning biomass in existing infrastructure can generate electricity while keeping the cost of transport for biomass low by using the material locally.

Timber residue may be burned with coal in a coal-fired power plant that has been retrofitted for co-firing. The type of boiler and the desired level of biomass mix burned affect the cost of the retrofit. Cyclone-type boilers are generally more flexible to accommodate biomass due to the particle size of the coal. Pulverized coal boilers are also compatible, but the most appropriate retrofit comes at a higher cost. Retrofits that utilize existing fuel feeding systems are going to be the lowest cost, but can limit the maximum biomass burn mixture. Installation of a separate biomass feed system prevents the biomass from limiting the coal's efficiency in its own fuel feeding system and allows the biomass mix to increase (Hughes, 1998).

Biomass can be burned as 0% to 20% of the fuel mix, depending on the retrofit. The level of biomass and the investment costs depend on the fuel feeding system (De & Assadi, 2009). Large cyclone boilers support a 2.5% biomass mixture, whereas small pulverized coal boilers can take a 15% mixture (Hughes, 1998).

Storage of biomass is a major limiting factor, however. Moisture content of the piled biomass affects the heating value of the material. Rainfall, humidity, small particle size, and compaction all degrade the heating value of the biomass. Stem chips are less sensitive to these changes than whole tree chips (Lin & Pan, 2015). Additionally, biomass with alkaline materials is damaging to coal boilers. The mixture of the alkali with the sulfur from the coal creates a "fouling" material in the boilers (De & Assadi, 2009; Demirbaş, 2003).

Assuming a 10% wood moisture content in a hardwood-softwood mix, a 100-megawatt power plant would require about 12,900 ODT annually to generate 5% of the power alongside coal. A 10% biomass burn would require approximately 26,700 ODT, and 15% would require 41,300. An ambitious plant burning 20% biomass would need 56,900 ODT per year. If a power plant burned 100% biomass, the 100-megawatt plant would need 342,300 ODT annually (White et al., 2013).

The Wisconsin Renewable Portfolio Standard (RPS), passed in 2006, pledged that 10% of energy produced in Wisconsin would come from renewable energy sources (Wisconsin State Legislature, 2006). As of 2012, Wisconsin was approaching the goal with 7.1% of energy coming from renewables, with 1.4% of which coming from wood and wood waste materials such as timber residue. This amount of electricity from biomass translates to 878 thousand megawatt hours (EIA, 2016). This is just over the equivalent of one 100-megawatt capacity power plant running at 100% capacity every hour of a full year.

In Michigan, the Clean, Renewable and Efficient Energy Act of 2008 established a renewable electricity generation target of 10% by 2015. As of 2012, Michigan was producing 2.7% electricity from renewables with 1.5% from wood and wood waste biomass. The amount from wood was the equivalent of 1,670 thousand megawatt-hours (EIA, 2016). Two 100-megawatt power plants running 100% of the year could produce this amount of electricity if purely fueled by biomass.

No one county in the Northern Tier could supply a minimum of 5% of electricity for a 100-megawatt power plant in the respective county from solely timber residues. Bounding the estimates within counties serves as a proxy for the widely-accepted 50-mile distance radius limitation (Simpkins et al., 2006) and highlights the unlikelihood that timber residues could supply a significant source alone within one county. Supplying 5% or more to a power plant of solely timber residue would be difficult given transportation costs at greater distances. However, timber residue could be a valuable supplementary material in power plants across the Northern Tier, at the same time contributing to state Renewable Portfolio Standards at lower incidences.

B. Bio-refinery Needs

Alternatively, timber residue could provide feedstock for a bio-refinery producing cellulosic ethanol. If a bio-refinery converts one ODT to 70 gallons of ethanol (NRC, 2011), table (15) shows the maximum attainable number of gallons of ethanol from each of the top performing counties in the Northern Tier, ignoring geographic limitations. The 10 counties with the largest timber residue availability in the Northern Tier combine to have a potential of nearly 5.12 million gallons of ethanol per annum from NIPF sources at $15/acre. If all the timber residue from NIPFs in the Northern Tier were converted to ethanol on an annual basis at 70 gallons/ODT (NRC, 2011), the supply would provide 23.5 million gallons of ethanol per year at $15/acre. At $90/acre, the Northern Tier would provide about 30.3 million gallons.

Technology is a limiting factor for building bio-refineries fed principally by timber residues and woody biomass. Optimal production for a bio-refinery that takes only lignocellulosic materials requires between 4.7-7.8 million dry tons of biomass per year. This differs substantially from corn grain ethanol plants, which only require 1.2 million dry tons of corn material (Wright & Brown, 2007). Timber residue can serve as a valuable supplemental feedstock, but is not likely to fuel an entire facility.

Table 16: Potential ethanol production from the top five Northern Tier counties in Michigan and Wisconsin

	$15/acre	**$30/acre**	**$60/acre**	**$90/acre**
Michigan				
Marquette	0.5538	0.5851	0.6496	0.7159
Newaygo	0.5001	0.5285	0.5867	0.6467
Menominee	0.4011	0.4235	0.4696	0.5168
Iron	0.3481	0.3672	0.4064	0.4465
Chippewa	0.3473	0.3669	0.4073	0.4489
Wisconsin				
Marathon	0.6567	0.6939	0.7704	0.8492
Price	0.6320	0.6672	0.7394	0.8134
Sawyer	0.5746	0.6064	0.6717	0.7387
Marinette	0.5672	0.5990	0.6643	0.7314
Bayfield	0.5476	0.5780	0.6404	0.7044

The most likely home for timber residue biomass is a multi-functional bio-refinery that is fed by a variety of sources outside of the lignocellulosic vein. A bio-refinery that takes multiple material types of materials such as hybrid poplar, corn stover, and timber residue needs about 730,000 ODT per year to operate optimally (Huang et al., 2009).

C. Comparison to Billion Ton Report

The US Department of Energy's (2011) Billion Ton Update provides forest and woody biomass estimates for the whole of the United States. The Billion Ton Report (BTR) bases timber residue supply estimates upon existing timber product output (DOE, 2011). This study, on the other hand, estimates timber residue supply by way of the potential output from acreage with the consideration of the agency of private forest owners. The two complement each other by providing estimates of timber residue at various price levels, but the overall aim of each differs. BTR principally aims at estimating timber residue supply potential. By adding in the forest owner behavior component, this study aims to quantify timber residue availability.

Assumptions underlying this study and the BTR have a few differences. BTR assumes a minimum 30% of retention of logging residues on-site (lower than our 50% to accommodate other parts of the US). The BTR makes timber residue supply estimates from both stand improvements and timber harvest events. The BTR assumes the use of whole-tree logging systems, which gather timbered trees for cutting logs, thereby collecting residues at the landing area. The alternative is cut-to-length systems, which cut whole trees into logs in place, thereby leaving residues in the forest and making them costly to collect. Like the BTR, the present study also does not differentiate timber harvest collection systems (such as cut-to-length or feller-and-buncher). Both this study and the BTR assume that tops and limbs can be removed from trees that are 1-5 inches in diameter of uneven ages (DOE, 2011).

The BTR's economic assumptions also differ from this study. Per their dataset, they calculate a "distance to road" variable that allows the sorting out of timberlands that would be too marginally expensive to include. An exact distance variable is not used in this study, though we assume a 50-mile radius, whereas county boundaries serve as a reasonable proxy. Additionally, the BTR includes all public and private lands that are harvested, making various assumptions by type. They only use the undifferentiated private class, which is lumped together by FIA to protect corporate privacy (DOE, 2011). This study breaks that class apart by regional proportions specific to the Northern Tier provided by the FIA (S. Pugh, Phone interview, August 23, 2016).

When only accounting for the Northern Tier (the BTR data is at the county-level), the BTR reports that the combined timber residue from all private and public lands amount to 0.74 million ODT are available per year in the Michigan section of the Northern Tier and that 0.93 million ODT are available in the Wisconsin section. The price of $80/ODT converts to about $16/acre for the forest type groups in the Northern Tier, making them comparable to my $15/acre estimates. My estimates place Michigan and Wisconsin sections of the Northern Tier both having 0.17 million ODT available at $15/acre, respectively among NIPFs. The supply disparity between these estimates is largely due to this study only including non-industrial private acreage, whereas the BTR includes the entire state and all sources public and private.

If I include all private lands in my estimates and assume that private landowners behave similarly to NIPFs, I predict Michigan's timber residue supply to be 0.25 million ODT/year and Wisconsin's to be 0.27 million ODT/year at $15/acre. The inclusion of public lands in Michigan and Wisconsin would narrow that gap still further, but it is likely that this study's estimates are more conservative than BTR's due to the socioeconomic willingness to harvest component that the BTR lacks. The BTR's supply curve estimates are built on regional price and market data rather than survey data, as in this study.

D. Biophysical Estimates

Estimates from biophysical ceiling studies range from 0.22 to 1.2 million ODT for Michigan and 0.25 to 1.7 million ODT for Wisconsin (Kukrety et al., 2015; Becker et al., 2009). Calculations from government estimates are similar; if harvesters extracted all timber residues from the total actual annual removals for Michigan and Wisconsin in 2015, this would total 1.0 million ODT and 0.95 million ODT, respectively (USDA, 2016d). The values from this study are not directly comparable to these estimates due to this study's focus being on a sub-region of two states at large, but they fall into the appropriate range. I calculate both Michigan and Wisconsin's biophysical estimates to be 0.49 million ODT each, totaling about 1 million ODT for the Northern Tier.

Historically, estimates of timber residue supply are overly optimistic (DOE, 2011; Becker et al., 2009): landowner behavior could cause a large gap between potentially and economically available residue. Accounting for forest owner behavior (as represented by NIPFs) and choice with respect to their private lands in this study reduced biophysical estimates an amount ranging from 45-60%, depending on the price offered and the area. Overall, the forest owner behavior reduced timber residue supply at $15/acre for Michigan and Wisconsin by 46% and 58% at $90/acre. This adjustment is from the biophysical ceiling is smaller than the approximately 66% reduction found in a similar study that considered socio-economic adjustments in the Great Lakes Region (Butler et al., 2010).

E. Limitations

Though this study applies multiple adjustments to provide a more accurate estimate, its accuracy is limited by the available data. The myriad variables associated with tree growth, harvest timing, tree mortality, species economy, and private acreage that affect estimates and are subject to assumptions, albeit reasonable ones. Moreover, the positioning of bio-refineries and co-fire-capable power plants determine the biomass supply market due to high variable costs. Timber residue markets are also closely tied to pulpwood markets, confounding their economic availability in a simple study. Lastly, forecasts are subject to change due to unknown future events, such as fires or market changes. Even though this study provides estimates for timber residue availability in Michigan and Wisconsin that are as accurate as the available data allow, the calculations are to be taken with these limitations in mind.

In focusing on the potential availability of timber residues, this study assumes that demand would be available. In fact, the capacity for co-firing biomass with coal is limited by many factors that are not addressed in this study. The storage of biomass is a major concern with respect to co-firing timber residue alongside coal in a facility. Moreover, the makeup of the wood local to an area can be damaging to boilers and curtail the possibility of a co-firing retrofit being low-cost or possible at all.

Choice of appropriate technology on the part of the harvester has a large impact on extraction, and, in turn, timber residue supply. This affects the rate of extraction, e, from equation (20). Whole tree harvesting tends to create piles of tops and limbs that are lower cost to extract (a larger e). By contrast, cut-to-length harvesting requires forwarders to collect timber residue from stump sites at a significant cost due to the nature of the equipment (smaller e) (Peterson, 2005). The gradual expansion of cut-to-length technology in the Northern Tier is decreasing the availability of low-cost residue. However, the measurement of the use of this technology in the Great Lakes Region aside from broad generalizations is outside of the scope of this study.

Distance is a major factor in the availability of timber residues (Becker et al., 2009; Becker et al., 2010). Typically, marginal costs due to transportation of tree and branch biomass to processing facilities exceed marginal benefit above about 50 miles (Simpkins et al., 2006). County-level estimates provide a proxy for distance in the case of this study.

The pulpwood and timber residue markets are linked, so price spillover effects are possible if energy demand rises sufficiently for biomass feedstock to compete for pulpwood (Du & Runge, 2014).

F. Concluding Remarks

The amount of timber residue utilized and economically attainable is far lower than biophysical ceiling estimates, but the possibility remains for this supply to become commercially available under the right economic circumstances. Those economic circumstances would likely include high fossil fuel prices, subsidies for renewable biomass materials, low pulpwood prices, more bioenergy-capable facilities spread throughout the Northern Tier to minimize transport distance, and the use of equipment that minimizes the cost of timber residue harvest and collection.

A market for timber residue as electricity or a liquid fuel will only become viable if petroleum fuel increases in price substantially, political pressure for renewable energy increases, and the technology for cellulosic biofuel and power plant retrofitting improves. The fact that timber residues are a low-cost, less environmentally intensive product of existing industry creates a possible future for a market given these circumstances. If this future arrives, the Northern Tier of the Great Lakes are poised with an abundant supply of this byproduct that could offset greenhouse gases and offset baseload coal power.

APPENDIX

Table 17: Premiums added to census data of sample counties

	Income			Education			Age		
	Pop.	**Census**	**Pm**	**Pop.**	**Census**	**Pm**	**Pop.**	**Census**	**Pm**
Michigan									
Alger County	91406	39211	52195	55.36%	17.10%	38.26%	63	48	14
Alpena County	105729	38353	67376	48.57%	16.10%	32.47%	66	47	19
Antrim County	119196	46480	72716	61.90%	24.90%	37.00%	65	49	16
Clare County	76630	33264	43366	44.44%	10.50%	33.94%	62	46	16
Emmet County	80405	51113	29292	54.17%	33.30%	20.87%	70	44	26
Gladwin County	86111	37725	48386	36.84%	12.50%	24.34%	61	49	13
Grand Traverse County	84659	52487	32172	53.13%	30.80%	22.33%	65	42	23
Iosco County	76316	36928	39388	51.72%	14.50%	37.22%	67	52	15
Marquette County	109559	45066	64493	54.55%	28.80%	25.75%	60	39	20
Mason County	90000	42156	47844	51.22%	20.10%	31.12%	61	46	15
Schoolcraft County	100962	35955	65007	50.00%	13.90%	36.10%	62	50	13
Wexford County	88306	40368	47938	53.85%	16.70%	37.15%	65	42	23
Wisconsin									
Bayfield County	87868	45158	42710	59.26%	28.30%	30.96%	62	50	11
Florence County	97547	49703	47844	50.00%	15.40%	34.60%	62	50	12
Lincoln County	93833	49189	44644	45.83%	15.20%	30.63%	62	46	16
Polk County	90028	49679	40349	41.12%	19.20%	21.92%	62	44	18
Portage County	87321	50837	36484	52.27%	28.30%	23.97%	62	36	26
Shawano County	87331	46903	40428	38.37%	15.10%	23.27%	60	44	16

Imputed values for counties remaining in the sample frame were their respective US Census variable plus the average premium for all counties in the above table.

Table 18: Percentage of non-industrial private forest acres relative to all private acres by region

State	Proportion Non-Industrial	Counties from Sample Frame
Michigan		
Eastern Upper Peninsula	63.0%	Alger, Chippewa, Delta, Luce, Mackinac, Menominee, Schoolcraft
Northern Lower Peninsula	85.2%	Alcona, Alpena, Antrim, Arenac, Benzie, Charlevoix, Cheboygan, Clare, Crawford, Emmet, Gladwin, Grand Traverse, Iosco, Kalkaska, Lake, Leelanau, Manistee, Mason, Mecosta, Midland, Missaukee, Montmorency, Newaygo, Oceana, Ogemaw, Osceola, Oscoda, Otsego, Presque Isle, Roscommon, Wexford
Western Upper Peninsula	40.5%	Baraga, Dickinson, Gogebic, Houghton, Iron, Keweenaw, Marquette, Ontonagon
Wisconsin		
Central	90.3%	Adams, Clark, Door, Juneau, Marathon, Marquette, Portage, Waupaca, Wood
Northeastern	66.1%	Florence, Forest, Langlade, Lincoln, Marinette, Menominee, Oconto, Oneida, Shawano, Vilas
Northwestern	79.7%	Ashland, Bayfield, Burnett, Douglas, Iron, Polk, Price, Rusk, Sawyer, Taylor, Washburn

I obtained the proportions via special data request (S. Pugh, Phone interview and request for specific acreage data from the FIA, August 23, 2016). A map of Wisconsin that shows where FIA border lie is found in "Wisconsin's Forests, 2009" (USDA, 2009). For Michigan, a similar map is found in "Michigan's Forests, 2009" (USDA, 2012).

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