

Submitted Article

Why Biomass Residue Is Not as Plentiful as It Looks: Case Study on Economic Supply of Logging Residues

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Abstract *Biomass inventories and techno-economic supply studies tend to overestimate economic supply of crop and timber residues, because they ignore human decisions on whether to permit residue removal. By combining information about biophysical availability, production and delivery costs, and the willingness of different types of decision maker to permit removal of logging residues, we develop a realistic prediction of economic supply that becomes very price inelastic. Because managers of only 52% of Michigan and Wisconsin forestland studied would allow the removal of logging residues, we conclude that most forecasts overestimate residue biomass supply by 50 to 100%.*

Key words: Bioenergy supply, biofuel, cost of production, landowner willingness to accept, timber residues.

JEL codes: Q41, Q23, Q16.

In the pursuit of environmentally sustainable, economically viable sources of energy biomass, crop and timber residues offer great promise. Bioenergy accounts for nearly half of U.S. renewable energy consumption (Energy Information Administration 2020); the latest assessment of U.S. biomass availability calculates that crop and logging residues represent 36% of the unexploited potential supply at a price of \$60 per dry ton (U.S. Department of Energy 2016).

Residues offer three key advantages. First, their harvest has scant effect on the supply of primary food, feed, and fiber products. As byproducts of existing production, residues fail to trigger the price increases that accompany

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redirection of primary products from their markets (Searchinger et al. 2008; Taheripour, Cui, and Tyner 2018). Second, when removed at sustainable levels, residue harvest does not undermine key ecological processes like soil organic matter cycling (Petrolia 2008a). Third, residues are cheap. Byproducts need only cover the added costs of harvest, minor processing, storage, and transportation to support profitability. In supply analyses of energy biomass, whether for cellulosic biofuel or for bioelectricity, residues from crops and timber are available at lower prices than dedicated bioenergy crops (Egben-dewe-Mondzozo et al. 2011; Egben-dewe-Mondzozo et al. 2015; Khanna et al. 2011).

Despite their low costs of production, residues are underused as bioenergy feedstocks relative to their physical availability. This may seem puzzling. Research in prominent journals has identified large quantities of potentially available residue biomass (Becker et al. 2009), as have more industry-oriented studies of biomass inventories (U.S. Department of Energy 2016; GC, Miller, and Potter-Witter 2017). Yet huge quantities of crop and logging residues are left on the ground. Why? The economic supply of residues is limited by factors beyond conventional production costs—notably by limited landowner willingness to sell residues (GC and Mehmood 2012; Markowski-Lindsay et al. 2012; Aguilar, Cai, and D’Amato 2014a; Dulys-Nusbaum, Klammer, and Swinton 2019).

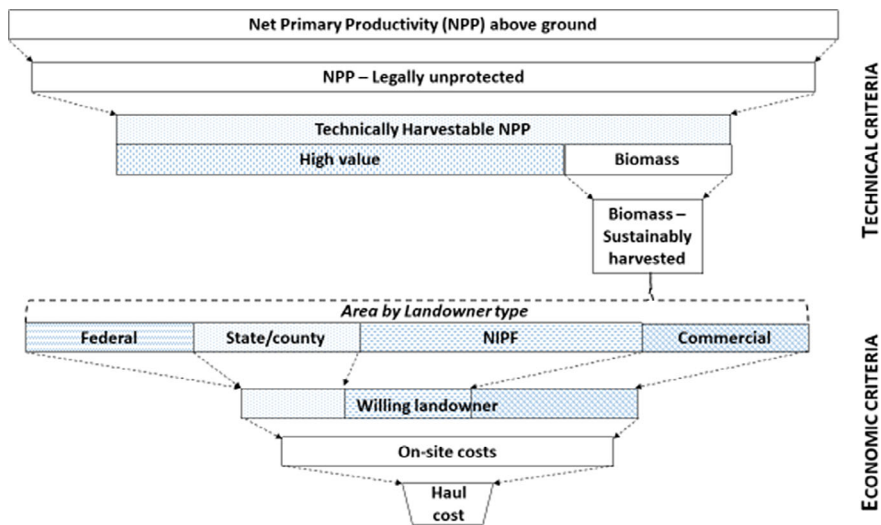
This article highlights the importance of landowner willingness to allow residue removal among the factors that shape the economic supply of energy biomass. Using a two-stage model of economic supply, we first examine whether (and at what cost) landowners would make logging residues available for removal. Second, we calculate the cost of collection, processing, and delivery of those residues to a demand point. We illustrate the approach for the case of logging residues delivered to an industrial bioenergy facility in Michigan’s heavily forested Upper Peninsula (UP). In so doing, we address two research questions:

1. How important is the landowner’s willingness to supply logging residues to the total economic supply of these residues?
2. What are the consequences for the shape of the residue supply schedule and the price elasticity of supply?

How Biomass Residue Reaches Energy Users: A Tale of Two Literatures

The potential supply of residues as bioenergy feedstocks can be imagined as a funnel (Figure 1). Starting with the broad tier of total biophysical availability (net primary productivity), the funnel narrows to legally and technically recoverable biomass. That portion is partitioned between high-value products (like grain or sawlogs) and residues (like stover and straw or tree branches and tops). From there the supply narrows to what is sustainably removable, particularly in light of soil carbon needs. This technically available supply is the endpoint for most inventories of energy biomass on the land. But it is the starting point for the economic supply of crop and logging residues. The next funnel is the landowner’s willingness to allow removal of residues, which depends on the type of landowner. The proportions of consenting landowners illustrated in Figure 1 correspond to the results described later in this paper. The final factors narrowing the economic supply of biomass residues are the costs of on-site preparation and hauling to the demand site

Figure 1 Hierarchy of biomass residue supply availability [Color figure can be viewed at wileyonlinelibrary.com]



(Springer et al. 2017). How this supply funnel works is chronicled in two distinct literatures, a techno-economic one focused on cost of production and a behavioral one focused on landowner willingness to participate.

A large body of techno-economic analyses has predicted how much energy biomass is technically and economically available. That literature starts with the trilogy of U.S. Department of Energy “billion ton” reports (Perlack et al. 2005; U.S. Department of Energy 2011; U.S. Department of Energy 2016), and includes many regional analyses (Petrolia 2006; Becker et al. 2009; Eidman et al. 2009; Abbas et al. 2011; Jones et al. 2013; Jenkins and Sutherland 2014; Yemshanov et al. 2014; Springer et al. 2017).

These techno-economic supply analyses follow a three-step process. They begin by developing an inventory of technically available biomass from forest biomass inventories. “Technically available” is a filter that excludes trees on steeply sloped lands and biomass that conventional equipment would be unable to remove. The term often extends to “sustainably available” in the sense of requiring that a certain share of biomass be left in place to maintain soil organic matter and associated ecosystem services (typically 30%–50%). In these studies, “economically available” is the subset of technically available biomass that passes two filters based on costs. The first is preprocessing costs at the forest site, for collecting tops and branches at forest landing sites and for chipping into residues. These tend to be uniform, at least for each type of forest stand. Transport from forest site to demand point is the second cost category. These costs vary by distance.

Much research on the economic availability of residues as energy biomass has focused on crop residue supply potential. One set of studies has projected availability on the land (“at the farm gate”), assuming that landowners aim to maximize profit (Egbendewe-Mondzozo et al. 2015; Khanna et al. 2011; Sessmero 2014). But biomass at the farm gate is not yet available at the biorefinery or power plant. Biomass availability at the point of demand is the focus of a separate set of techno-economic studies that calculate transportation costs within a tractable shipping distance. Using different cost assumptions, both Perlack and associates at the Department of Energy (Perlack and

Turhollow 2003; Perlack et al. 2005; U.S. Department of Energy 2016) and university economists (Petrolia 2008b; Brechbill, Tyner, and Ileleji 2011) have estimated the accounting costs to supply corn stover to a demand point like a power plant or biorefinery.

A separate body of survey research has analyzed the expressed willingness of landowners to supply technically available crop residues, analyzing what factors contribute to their willingness to harvest or to permit the harvest of crop residues (Altman and Sanders 2012; Bergtold et al. 2014; Altman et al. 2015; Mooney, Barham, and Lian 2015; Skevas et al. 2016). These works show that landowners are largely willing to allow sustainable levels of crop residue removal (*e.g.* corn stover and wheat straw), at least where they do not face strong local demand for livestock feed and bedding uses (Mooney, Barham, and Lian 2015).

Although timber residues as a bioenergy feedstock have received less academic attention than crop residues, they have seen more industrial use in forested parts of the nation. Timber residues take two forms: mill residues (like sawdust and wood trimmings) and logging residues (tree tops and branches). Mill residues are produced in quantity at saw mills and paper pulping plants. They are readily available, tend to be free of dirt, and they are often chipped and used for power. Not only have many small-scale electric plants relied on wood chips for fuel (Leefers 2011), but some commercial paper companies like Domtar have made major investments in cofired power generation¹ that can utilize timber residues. Logging residues also have the potential to be used for power, but to date they are generally left in the forest, especially where selective timber harvest is practiced. From this point forward, this paper will focus on logging residues whose dispersion across space and landowners creates a more complex supply problem than that of mill residues.

Like crop residues, logging residues are spatially dispersed byproducts of harvest operations. But logging residues differ from crop residues in two ways that affect landowner willingness to allow residue removal. First, mixed forests differ from monoculture crops in the range of ecosystem services they provide. The capacity of forests to support hunting, fishing, hiking, and a host of biodiversity-mediated ecosystem services means that timber harvest and the added disturbance from removing residues poses opportunity costs to landowners who value those services. These costs are distinct from the direct costs of crop residue removal. Second, some timber harvests are selective cuts rather than clear cuts that remove all trees. When timber harvests are selective (as for hardwood sawlogs), residue removal can damage the remaining stand. This added cost is absent for the clear cut harvest of an annual crop or single-age, planted forest.

Who owns forestland and why they hold it both strongly influence owner willingness to harvest timber and to harvest the accompanying logging residues. US forestland has four major types of owners: private commercial (industrial), nonindustrial private forest (NIPF), public federal, and public state and county forests.

Most academic studies of the economic availability of logging residues focus on NIPF landowners. Although appreciation of natural amenities affects the willingness of NIPF owners to harvest timber, several studies

¹Wisconsin Statewide Wood Energy Team. "Large-size Commercial and Industrial Wood Energy Case Studies." <https://fyi.extension.wisc.edu/energy/wisconsin-state-wood-energy-team/case-studies/large-size-commercial-and-industrial-wood-energy-case-studies/>. (Accessed 6/2/20.)

report widespread willingness to harvest residues once owners have decided to harvest mixed forests across the northern tier of Minnesota, Wisconsin, Michigan, and Massachusetts (Markowski-Lindsay et al. 2012; Aguilar, Cai, and D'Amato 2014a; Dulys-Nusbaum, Klammer, and Swinton 2019) and in Missouri (Aguilar, Daniel, and Cai 2014b). Many NIPF owners are reluctant to allow logging residues to be removed from their properties, even when offered market-rate biomass payments. Studies in Minnesota, Wisconsin, Michigan, and Missouri found 30%–41% of NIPF owners likely to permit residue removal at time of timber harvest if paid roughly an extra \$25/acre (Aguilar, Cai, and D'Amato 2014a; Aguilar, Daniel, and Cai 2014b). Studies offering NIPF owners payment rates for residue removal at time of timber harvest up to \$100/acre have found higher probable willingness to supply residues of 33%–63% in Michigan and Wisconsin (Dulys-Nusbaum, Klammer, and Swinton 2019), but only 7%–10% in Massachusetts (Markowski-Lindsay et al. 2012). Doubling the pulpwood price was found to raise willingness to allow removal of small diameter trees and logging residues among NIPF owners in Arkansas, Florida, and Virginia from a range of 16%–29% to a range of 58%–74% (GC and Mehmood 2012).

Compared to NIPF owners, the decisions of commercial forest landowners have received scant attention in published academic research. The extant evidence focuses on expected profitability as the key decision driver. In a study of sawlog and pulpwood production in the southeastern United States, Newman and Wear (1993) found commercial and NIPF forestland owners both to be strongly influenced by input and output prices, with NIPF owners placing greater value on the amenities of standing forest. In a recent study in northern Michigan and Wisconsin, the current authors compared commercial and NIPF landowner willingness to harvest logging residues at time of timber harvest (Dulys-Nusbaum, Klammer, and Swinton 2019). We found both private owner types (but not public and NGO foresters) to be strongly influenced by biomass price. Commercial forestland owners were highly willing to harvest residues if costs were fully covered, compared to one- to two-thirds of NIPF owners.

The equally sparse literature on how managers of public forests make biomass removal decisions highlights regulatory paralysis in federal forests. Although the forests of the U.S. Forest Service (USFS) and the Bureau of Land Management operate under a multiple-use mandate that includes timber harvest, rates of tree removal have been low in recent decades (Oswalt et al. 2018). Low and uneven rates of timber harvest from federally managed forests result from a convergence of inadequate staffing, time-consuming environmental impact assessments, public auctions, and endangered species protections (Becker et al. 2011). Infrequent timber harvests have contributed to elevated fire risk, causing the already small literature on energy biomass from federal forests to mostly focus on how removal of dead wood and logging residues can be a cost-effective alternative to “fuel treatments” that remove biomass to mitigate risk of wildfires (Evans and Finkral 2009; Abbas et al. 2011).

The element missing from the literature on the economic supply of logging residues is incorporation of landowner willingness to make residues available. Two distinct literatures exist. One attempts to account for the techno-economic supply of biomass *assuming that all landowners are willing* (Becker et al. 2009; U.S. Department of Energy 2016). The other examines the willingness of landowners to allow residues to be removed (GC and Mehmood 2012; Markowski-Lindsay et al. 2012; Aguilar, Cai, and D'Amato 2014a; Aguilar,

Daniel, and Cai 2014b; Dulys-Nusbaum, Klammer, and Swinton 2019). Until now, no study has incorporated into the techno-economic accounting of biomass supply the cost of inducing landowner consent to allow biomass removal. Yet both components are necessary to a complete analysis of the economic cost to supply timber residues. Drawing on recent research into forestland managers' willingness to supply logging residues (Dulys-Nusbaum, Klammer, and Swinton 2019), the authors aim to fill this gap.

In what follows, we combine analyses of landowner willingness to supply logging residues with detailed costs to develop the economic supply schedule for logging residues from forestlands surrounding a hypothetical biorefinery or power plant located at Escanaba, Michigan, USA (the location of a paper mill that has historically burned woodchips). The illustration reveals that nearly half the logging residues that are biophysically, technically, and sustainably available would not be supplied economically even in a heavily forested region at biomass prices more than double the energy equivalent cost of natural gas.

Model of Economic Supply

The supply of logging residues for bioenergy depends upon decisions by two key actors, the forestland manager and the logger. The forestland manager decides whether (and under what conditions) to permit the logger to remove residues at time of timber harvest or tree thinning. The logger decides whether to collect and chip those residues and deliver them to an energy user. Economic supply of logging residues occurs only when both the land manager is willing to allow residue removal and the logger can fully cover costs in removing and selling the residues. We treat these two decisions as separable, because in the hardwood forests of the Upper Midwest, forestland managers generally contract out the timber harvest operation to a logger, and the option to remove residues is a potential contract provision.

Once the manager or owner of the forestland makes the decision to harvest timber, a subsequent choice is whether to allow the logger to remove logging residues (the tops and branches of harvested trees along with trees culled at thinning) or to leave the residues where they lie. That choice involves weighing the benefits against costs. How those choices are weighed depends upon the manager's objectives, which can vary substantially across landowner types (Dulys-Nusbaum, Klammer, and Swinton 2019). The chief benefit is revenue from a "stumpage fee," or the premium paid by the logger. As for costs, forestland managers tend to weight them quite differently, according to their managerial objectives. Potential damage to remaining trees in a multi-age stand matters strongly to commercial timberland managers (Klammer 2017). The disamenities of noisy harvest equipment and a disturbed forest floor matter to some NIPF owners (Dulys-Nusbaum 2017). The risk of lowering key ecological attributes (The Nature Conservancy 2010) matters to a conservation organization like The Nature Conservancy, while compliance with the National Environmental Policy Act and the Endangered Species Act matter highly to the USFS (Klammer 2017).

For loggers, once the landowner has agreed to allow logging residue removal in exchange for a stumpage fee, the key question is whether and at what price they can sell the residues at a profit (Klammer 2017). Practically speaking, residues for bioenergy purposes must be delivered to the demand site (such as a power plant, biorefinery, or power-demanding industrial

facility). The logger's decision to supply residues therefore hinges on receiving a sale price per ton that covers all costs. These include the costs of gathering tree tops and branches in the forest (c_g), chipping them (c_{ch}), and transporting the chips to the demand point ($c_t T$, where T is the road transport distance), as well as covering the stumpage fee (on a per-ton basis, this is the payment per acre (p_s) divided by the yield of removable residue per acre (Y)). Finally, the logger must achieve an adequate rate of return (r) to cover other fixed costs and to compensate business risk.

Equation (1) indicates that the profit-maximizing logger will offer economic supply quantity Q_{ES} of chipped logging residues, which is the sum of site-specific, economic supplies of logging residues (q_{ij}^{ES}) across all forest sites, i , and forestland manager types, j , where managers are willing to make residues available and the price paid (p_{BE}) covers all logger costs. Equation (2) specifies that quantities available from forestland managers (q_{ij}^{FM}) depend upon the biophysically available quantity (Q_{ij}^0) at each forest site i , owned by manager type, j , and the stumpage fee offered (p_s). Equation (3) specifies the breakeven price constraint that defines the quantities q_{ij}^{ES} in Equation (1) that achieve break-even prices at each site.

$$Q_{ES} = \sum_j \sum_i q_{ij}^{ES} \left(p_{BE}, c_g, c_{ch}, c_t, p_s, T_i, Y_i \left(q_{ij}^{FM} \right) \right) \quad (1)$$

Subject to:

$$q_{ij}^{FM} = q_{ij}^{FM} \left(p_s, FMType_j(z), Q_{ij}^0 \right) \quad (2)$$

$$p_{BE} \geq \left(c_g + c_{ch} + c_t T_i + \frac{p_s}{Y_i} \right) (1 + r) \quad (3)$$

Data and Empirical Methods

In two analytical steps, we use mixed empirical methods to predict the economic supply of logging residues for a bioenergy demand point located at Escanaba, Michigan. The first step implements Equation (2), predicting the forestland manager's willingness to make logging residues available for removal at timber harvest. Those predictions depend heavily upon the landowner type and their associated management objectives.

Data on the willingness of different types of manager to make logging residues available at harvest comes from two sources. First is county-level quantitative predictions from an econometric model based on a 2015 statistically representative survey of 750 NIPF owners in northern Michigan and Wisconsin (response rate 34.6%) (Dulys-Nusbaum, Klammer, and Swinton 2019). Second, to determine willingness of large-scale commercial and public forests to permit residue removal, we draw upon qualitative, personal interviews in 2016 with managers of six of the seven commercial forestland tracts exceeding 25,000 acres in Michigan's UP along with three public forest managers responsible for the state and federal forests in the region (Dulys-Nusbaum, Klammer, and Swinton 2019). For these interviews, the largest commercial forest holdings were identified from land enrolled in the Commercial Forest

Figure 2 Map of the 8 Michigan and 3 Wisconsin counties with centroids within 100 miles of the Escanaba, Michigan, energy biomass facility



Program with the Michigan Department of Natural Resources (MDNR), while public forests were identified from MDNR and USFS web sites (Klammer 2017). Although the sample size is unsuited to statistical analysis, these managers make decisions about the great majority of forestland of these ownership types in Michigan’s UP.

On forestland where managers are willing to permit residue removal, the second step implements Equations (1) and (3) to calculate the site-specific quantity (q_{ij}^{ES}) where wood chip prices (p_{BE}) cover all costs for a representative logger to gather, chip, and transport the residues from forests within a 100-mile radius of Escanaba, Michigan (see map, Figure 2). Logger cost data are drawn from personal interviews with two UP loggers (Klammer 2017) and verified using the USFS public timber harvest cost calculator (U.S. Forest Service 2017). The data are again qualitative, because we could identify very few loggers in the region who chip and haul logging residues, so we triangulate evidence by using different data sources (Yin 2014). The “sites” here are counties, where county-level USFS data on timber stand inventories and state data on forestland ownership types establishes the biophysical quantities available (Q_{ij}^0) in each county i under each ownership type j , and actual road

hauling distances (T_i) were calculated from county centroids to Escanaba, Michigan. We assumed evenly distributed logging residues across each county.

Data and Empirical Methods for Economic Supply Estimation

In order to build up the economic supply of logging residues in Equation (1), we first predict the potential supply where forestland managers will permit residue removal, implementing Equation (2). These site-specific potential quantities (q_{EMi}) depend upon the stumpage fee (p_s), the type of forestland manager, and the biophysical timber availability. Based on key informant interviews (Klammer 2017) and the existing literature on cellulosic bioenergy feedstock demand (Eidman et al. 2009; Brechbill, Tyner, and Ileleji 2011; U.S. Department of Energy 2016), we assume that transportation costs obviate the relevance of counties farther afield than the eleven Michigan and Wisconsin counties within a 100-mile radius of the Escanaba delivery site. Based on the evidence that logging residue supply is available largely from private owners (Dulys-Nusbaum, Klammer, and Swinton 2019), we initially assume that logging residues come from large-scale commercial and NIPF forests (an assumption to be relaxed later, when we consider potential availability from county and state forests). We use different approaches to predict supply from each type of forestland manager.

The large-scale commercial forestlands are all managed under Timber Investment Management Organizations (TIMOs) or Real Estate Investment Trusts (REITs). The six managers we interviewed were responsible for 77% of the 1,748,000 acres of commercial forestland holdings over 25,000 acres in area that represented the population of large-scale forestland enrolled in the Commercial Forest Program in Michigan's UP (further details in (Klammer 2017). The managers were unanimous in affirming their willingness to make logging residues available at stumpage fees in the range of \$2–\$5 per green US ton. Hence, we assume that logging residues are available from all commercial forestlands for a stumpage fee of \$4 per green ton (the upper tercile of this range), a value used in a previous study in the region (Becker et al. 2009).

We calculated the annual, county-level, total biophysical supply of logging residues from commercial forestlands as the product of all sustainable, removable forest logging residue (from the USFS Forest Inventory EVALIDator website²) times the share of commercial forest land in each forest region.³ Consistent with the norms for technical feasibility and sustainable soil productivity followed by the U.S. Environmental Protection Agency, U.S. Department of Energy, and National Renewable Energy Research Laboratory (Springer et al. 2017), we assume that only 50% of total logging residues are removed, as part of a fifteen-year selective harvest cycle for these multiage, maple-dominant hardwood forests. For full details on the projections, see the approach used for NIPF owners in Dulys-Nusbaum (2017), pp. 43–54 and 69–70. Given that gathering and chipping costs are incurred with green residues at time of harvest, we converted the USFS annual logging residue

²U.S. Department of Agriculture (USDA), Forest Service, Northern Research Station; Forest Inventory EVALIDator web-application Version 1.6.03. (11 July 2016d). Retrieved July 24, 2016 from <https://apps.fs.usda.gov/Evalidator/evalidator.jsp>

³S.A. Pugh, Forester, U.S. Forest Service, Houghton, MI. Phone interview with E. Dulys-Nusbaum August 23, 2016.

Table 1 Private and Public Forestland Ownership within 100 miles of Escanaba, Michigan, Compared to the States of Michigan and Wisconsin, 2016

Owner type	Case study	Wisconsin	Michigan	United States
Private	61%	65%	62%	58%
Public: State & county	21%	22%	23%	31%
Public: National	18%	10%	15%	11%
Total:	100%	97%	100%	100%

Sources: Michigan (Pugh 2018); Wisconsin (Perry et al. 2008), USA (Oswalt et al. 2018).

inventory values from oven-dry, short tons (ODT) to average green tons by multiplying by two (ratio of green weight to ODT weight). For a fifteen-year - cycle between timber harvests or stand thinnings, we multiplied annual residue accumulation by fifteen to approximate the full amount of residues biophysically available for removal from the site. The resulting values for county-average logging residue yield on NIPF land ranged from 1.3 to 2.5 green tons per acre at time of selective harvest.

NIPF owners were heterogeneous in their attitudes toward allowing logging residue removal, with only 33%–63% willing to do so. To predict the probability that NIPF owners would make logging residues available at time of harvest, we tailored the probit econometric model of Dulys-Nusbaum, Klammer, and Swinton (2019) to traits of NIPF owners in the relevant counties.

Model predictions were adjusted for each of eleven Michigan and Wisconsin counties within 100 miles of Escanaba at payment rates of \$15 and \$30 per acre (corresponding to \$6–\$12 per green ton and \$12–\$23 per green ton, according to timber yield levels) (Dulys-Nusbaum 2017)⁴. County-level mean NIPF willingness to supply logging residues was predicted from the probit model in Dulys-Nusbaum, Klammer, and Swinton (2019) holding all variables at the mean values stated in Table 1, except for *Price Offered* (\$15 or \$30 per acre) and *Age*, *Education*, and *Income*. These last three were made county-specific by taking county census averages and calibrating them to the survey data, which showed that NIPF owners are older, better educated, and higher earning than the population as a whole (Dulys-Nusbaum 2017). As we did for the commercial forests, we calculated county-level total biophysical supply of logging residues from NIPF lands by multiplying the county-level predicted probability that NIPF owners made logging residues available times the share of NIPF land in each forest region using the USFS Forest Inventory EVALIDator website.

The forest-level availability of logging residues from NIPF owners is calculated as the probability of supply at \$15/acre (from the first step, ranging from 0.33 to 0.35, depending on county) times the county-average technical availability of logging residue biomass from NIPF lands. This resulted in NIPF stumpage fee estimates of \$6–\$12 per green ton (median of \$7/gr ton). This process was repeated for the marginal gain in timber supply by incrementing the landowner payment from \$15 to \$30 per acre (resulting in small, additional residue quantities available at \$12–\$23 per green ton).

⁴We also calculated predicted acreage supply at \$60 and \$90 per acre, but the marginal increase in quantity was under 2% of the NIPF supply at \$15/acre. Supply schedule with NIPF quantity at these rates is available from the authors, but was omitted from this paper as trivially small.

Given the quantities of logging residues that forestland managers would allow to be removed, we next calculated the quantity from each county available at prices that would fully cover the costs of a representative logger (implementing Equation (3)). This process essentially reverse-engineered a standard economic supply function by assuming that the share of willing forestland owners (of each type, j) in each county would make available all residues at the break-even price that covers all costs for that owner type. The relevant costs were determined as follows.

The cost of gathering (c_g) tree tops and branches depends on timber harvesting technology used. Under the traditional whole-tree harvest method, gathering costs for residues are low, because cut trees are dragged to a landing site where tops and branches are removed. Costs of gathering residues are higher under the newer cut-to-length method, where trees are cut to eight-foot lengths where they stand, so tops and branches must be gathered and transported to a landing in a separate step. We were able to identify a single professional logger in Michigan's UP whose business extended to the collection and hauling of chipped logging residues. Per that key informant, in 2016, 90% of the timber harvests in Michigan's UP used the cut-to-length method, with the rest using the whole-tree method, resulting in an expected value of c_g equal to \$7.20 per green ton (Klammer 2017) (p. 60).

The cost of chipping (c_{ch}) tree tops and branches in 2016 was calculated using machinery data from the U.S. Forest Service (U.S. Forest Service 2017) and the key informant logger in the region. Using both data sources for labor, operating, and ownership costs of a 540 hp chipper operating at 30 tons/hour with 90% utilization, the long-run average cost to chip logging residues came out at \$6 per green ton (Klammer 2017)(pp. 47–50, 61). The sum of the on-site gathering and chipping costs, \$15.20 per green ton with return on investment included, is slightly below the \$17.80 per green ton value calculated for selective harvest in Ozark oak forests of Missouri in 2012 (Saunders et al. 2012). Both of these estimates surpass the \$8 per green ton (\$15–\$17 per dry ton) value for upland hardwood forest in the North Central Region in the most recent DOE billion ton report (U.S. Department of Energy 2016), which assumed an integrated logging and residue harvest operation.

The cost of hauling chips to the Escanaba, Michigan, bioenergy demand destination, ($c_t T_i$), hinges upon the road distance from forest site to Escanaba (T_i) and truck operating costs (c_t), including whether or not the truck returns empty (has no backhaul) to retrieve the next load. These costs were calculated using the Forest Residues Transportation Model (FoRTS, v.5) (Rummer 2005). Operating cost calculations assumed a standard chip van (120 cubic yard capacity with a 33 ton base payload) over actual chip hauling distances on typical UP roads from private forests within 100 miles of Escanaba (91% US/State Highway, 8% two-lane paved, and 1% unimproved forest roads) with gasoline at \$2.60/gallon. Those transportation costs averaged \$0.13 per green ton-mile (\$0.26 per dry ton-mile) assuming empty backhaul⁵ (Klammer 2017) (p. 65). This cost per mile is bracketed by recent costs of \$0.12 and \$0.14 per green ton-mile in North Carolina (Wood-Energy 2019) and about half of the \$0.26 per green ton-mile value in the latest DOE billion ton report (assuming thirty-five mile-per-hour travel) (U.S. Department of Energy 2016)

⁵FoRTS v.5 calculates hauling costs assuming no backhaul, per personal communication from Jason D. Thompson, Staff Engineer, U.S. Forest Service, Southern Research Station, Auburn, AL (email to Scott Swinton, June 6, 2018).

(p. 230). Road distances within 100 miles of the City of Escanaba were calculated from the geographic centroid of each county, using Google Maps.

The final cost element was the assumed return on investment. This was set at 15%, the level that a key informant logger reported he would need in order to make the logging residue business competitive with his other logging activities (Klammer 2017) (p. 22). The U.S. Department of Energy uses 15% for overhead costs associated with logging residue costs (U.S. Department of Energy 2016), an equivalent calculation.

Results of Economic Supply Estimation

Assembling the county-level costs per delivered oven-dry short ton of logging residues and treating them as equivalent to break-even prices generates two major sets of economic supply results. Table 2 presents those from large-scale commercial forests. Table 3 presents those from NIPF owners assuming stumpage payments of \$15 per acre, which would attract 33–35% of NIPF owners to allow logging residue supply. Table 4 presents additional supply from NIPF owners if stumpage payments were to rise to \$30 per acre, roughly 2% added NIPF supply per county.

In general, the breakeven price per ton at which NIPF owners are willing to supply logging residue is higher than for commercial owners of forestland. As shown in the economic supply of logging residues from private forests in Figure 3, the lowest cost supply enters at a price just above \$50 per ODT. These materials come entirely from nearby commercial forests in Delta, Menominee, and Dickinson counties. Even at the highest price for residues from within 100 road miles of the Escanaba mill (over \$100 per ODT), NIPF supply represents only 31% of the cumulative total from private forests (55 K ODT out of 179 K ODT). Commercial quantities are higher, partly because all commercial forests are treated as able to supply residues at a stumpage fee of \$4 per green ton, and partly because some important counties have more commercial forestland than NIPF land (*e.g.*, Iron and Marquette counties in Michigan).

The economic interpretation of the supply curves in Figure 3 centers on the cost thresholds that cause the graph to have its stepwise progression. The graph becomes discontinuous below \$50 per ODT, because there are important threshold costs that must be covered before any supply can be delivered. Even if hauling costs are zero, the minimum cost per green ton is \$40 per ODT, simply to cover costs at the forest site (commercial stumpage fee, gathering, and chipping). Over the price range of \$50–\$59 per ODT, wood chips from commercial sites within 30 miles rapidly become available. The own price, arc elasticity of logging residue supply from private sources (dashed line) in this price range is 8.1, meaning that a 10% rise in price induces an 81% jump in quantity supplied. Over the range of \$59–\$69, commercial residues farther afield become available, along with residues from NIPF forests earning \$15/acre stumpage fees. Over this price range, the arc elasticity of residue supply remains virtually unchanged, at 8.3.

Beyond \$69 per ODT, however, the logging residue supply from commercial and low-cost NIPF lands is exhausted, so additional quantities fall dramatically in spite of rising prices. Over the price interval of \$70–\$79 per ODT, additional residue is supplied from more distant NIPF lands getting \$15/ac stumpage fees plus small amounts from nearer NIPF lands where stumpage fees have stepped up to \$30/ac. Over this price range, the arc price elasticity of supply from private forestland plummets to 0.9, meaning that a

Table 2 Supply Quantity and Prices for Logging Residues from Commercial Forests Delivered to Escanaba, Michigan, USA

County	Private forest	Probability to supply @ \$15/ac	Harvestable residues	Dist. to Escanaba	Hauling to dest. @ \$0.13/mi	Collect +			Total cost	Supply Price @15% ROI	Supply Price	Quantity county
						Stumpage	Chip	\$/gr ton				
Units:	acres	(0,1)	gr ton/ac/yr	miles	\$/gr ton	\$/gr ton	\$/gr ton	\$/gr ton	\$/gr ton	\$/gr ton	\$/dry ton	dry tons
Alger, MI	104,376	1.00	0.16	59	7.67	4.00	13.20	24.87	28.60	57.20	8,399	
Delta, MI	123,015	1.00	0.13	36	4.68	4.00	13.20	21.88	25.16	50.32	7,761	
Dickinson, MI	112,491	1.00	0.15	47	6.11	4.00	13.20	23.31	26.81	53.61	8,442	
Florence, WI	57,068	1.00	0.17	67	8.71	4.00	13.20	25.91	29.80	59.59	4,720	
Forest, WI	76,975	1.00	0.15	97	12.61	4.00	13.20	29.81	34.28	68.56	5,725	
Iron, MI	377,032	1.00	0.11	92	11.96	4.00	13.20	29.16	33.53	67.07	20,817	
Marquette, WI	151,525	1.00	0.16	71	9.23	4.00	13.20	26.43	30.39	60.79	12,225	
Marquette, MI	518,302	1.00	0.13	78	10.14	4.00	13.20	27.34	31.44	62.88	34,729	
Menominee, MI	228,082	1.00	0.09	39	5.07	4.00	13.20	22.27	25.61	51.22	9,863	
Oconto, WI	65,186	1.00	0.15	88	11.44	4.00	13.20	28.64	32.94	65.87	5,021	
Schoolcraft, MI	85,944	1.00	0.14	67	8.71	4.00	13.20	25.91	29.80	59.59	6,149	

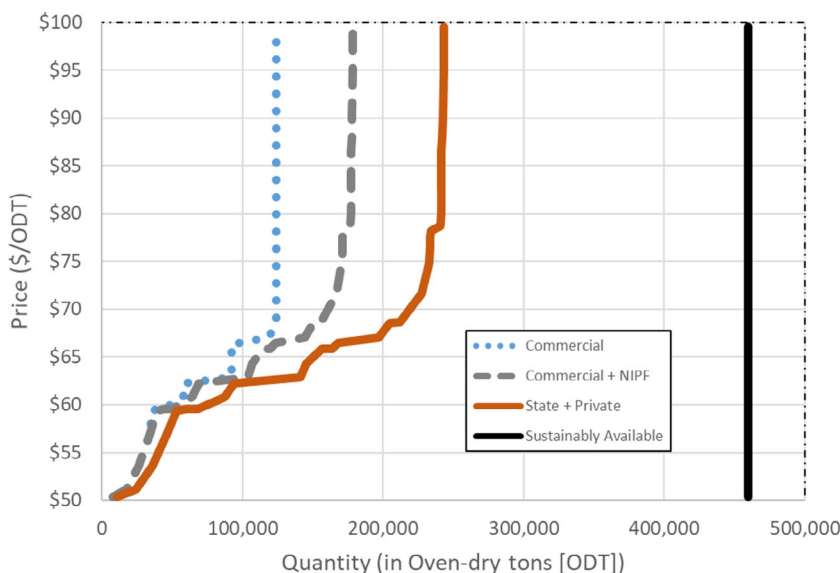
Table 3 Supply Quantity and Prices for Logging Residues from NIPF Forests Delivered to Escanaba, Michigan, at \$15/acre Stumpage Payment

County	Private forest	Probability to supply @ \$15/ac	Harvestable residues	Dist. to Escanaba	Hauling to dest. @ \$0.13/mi	Collect			Total cost	Supply Price @15% ROI	Supply Price	Quantity county
						Stumpage	Chip	+				
Units:	acres	(0,1)	gr ton/ac/yr	miles	\$/gr ton	\$/gr ton	\$/gr ton	\$/gr ton	\$/gr ton	\$/gr ton	\$/dry ton	dry tons
Alger, MI	177,722	0.34	0.16	59	7.67	6.21	13.20	13.20	27.08	31.15	62.29	4,907
Delta, MI	209,458	0.34	0.13	36	4.68	7.92	13.20	13.20	25.80	29.68	59.35	4,510
Dickinson, MI	76,569	0.34	0.15	47	6.11	6.66	13.20	13.20	25.97	29.87	59.74	1,966
Florence, WI	111,275	0.34	0.17	67	8.71	6.05	13.20	13.20	27.96	32.15	64.30	3,109
Forest, WI	150,091	0.34	0.15	97	12.61	6.72	13.20	13.20	32.53	37.41	74.82	3,782
Iron, MI	256,636	0.35	0.11	92	11.96	9.06	13.20	13.20	34.22	39.35	78.70	4,973
Marquette, WI	295,452	0.34	0.16	71	9.23	6.20	13.20	13.20	28.63	32.92	65.84	8,103
Marquette, MI	352,794	0.33	0.13	78	10.14	7.46	13.20	13.20	30.80	35.42	70.84	7,911
Menominee, MI	388,357	0.34	0.09	39	5.07	11.56	13.20	13.20	29.83	34.31	68.61	5,730
Oconto, WI	127,104	0.34	0.15	88	11.44	6.49	13.20	13.20	31.13	35.80	71.60	3,290
Schoolcraft, MI	146,337	0.34	0.14	67	8.71	6.99	13.20	13.20	28.90	33.23	66.47	3,533

Table 4 Added Supply Quantity and Prices for Logging Residues from NIPF Forests Delivered to Escanaba, Michigan, at \$30/acre Stumpage Payment

County	Private forest	Added prob. to supply @ \$30/ac	Harvestable residues	Dist. to Escanaba	Hauling to dest. @ \$0.13/mi	Collect +				Supply Price	Added Quantity
						Stumpage	Chip	Total Cost	Supply Price @15% ROI		
Units:	acres	(0,1)	gr ton/ac/yr	miles	\$/gr ton	\$/gr ton	\$/gr ton	\$/gr ton	\$/gr ton	\$/dry ton	dry tons
Alger, MI	177,722	0.02	0.16	59	7.67	12.43	13.20	33.30	38.29	76.58	273
Delta, MI	209,458	0.02	0.13	36	4.68	15.85	13.20	33.73	38.79	77.58	252
Dickinson, MI	76,569	0.02	0.15	47	6.11	13.33	13.20	32.64	37.53	75.06	110
Florence, WI	111,275	0.02	0.17	67	8.71	12.09	13.20	34.00	39.10	78.20	175
Forest, WI	150,091	0.02	0.15	97	12.61	13.44	13.20	39.25	45.14	90.29	212
Iron, MI	256,636	0.02	0.11	92	11.96	18.11	13.20	43.27	49.76	99.52	273
Marquette, WI	295,452	0.02	0.16	71	9.23	12.39	13.20	34.82	40.05	80.10	454
Marquette, MI	352,794	0.02	0.13	78	10.14	14.92	13.20	38.26	44.00	88.01	448
Menominee, MI	388,357	0.02	0.09	39	5.07	23.12	13.20	41.39	47.60	95.21	320
Oconto, WI	127,104	0.02	0.15	88	11.44	12.98	13.20	37.62	43.27	86.53	186
Schoolcraft, MI	146,337	0.02	0.14	67	8.71	13.98	13.20	35.89	41.27	82.54	199

Figure 3 Annual supply of timber residues to Escanaba, Michigan, from privately owned Commercial Forests only (dotted line), Commercial plus NIPF Forests (dashed line), Public state/county plus all private forests (solid curve), and Technically & Sustainably Available (vertical line) [Color figure can be viewed at wileyonlinelibrary.com]



10% price rise elicits only a 9% boost in quantity supplied. Above \$79 per ODT, the supply from private forests becomes highly inelastic. The price elasticity of 0.05 implies that a 10% price increase has the negligible effect of nudging up supply by only 0.5%. This occurs because the only available sources for increased supply come from NIPF owners who are either more distant or demand higher payment. Among this group, doubling the per-acre payment from \$15 to \$30 per acre raises the probability of NIPF supply by only 2% on average, resulting in just 2,000 ODT of increased quantity supplied.

Even at a delivered price of \$100 per dry ton of wood chip biomass—more than double the cost per BTU of alternative energy sources like natural gas—fully 65% of NIPF owners remain unwilling to supply logging residues. Because NIPF owners manage 55% of privately owned forestland in the region (2.29 m of the 4.19 m acres of private forestland), their reluctance to supply logging residues means that the economic supply from private lands at the highest price is only 64% of the total biophysical availability of 276,000 dry tons on private forestland in counties within 100 miles of Escanaba.

What about public lands? Publicly owned forests represent a large share of potential available energy biomass. They accounted for 44% of U.S. forestland in 2012 (U.S. Department of Energy 2016) and 38% of the 2016 forestland in our case study zone within 100 miles of Escanaba, Michigan. Public forestland in those eleven counties totals 2.62 m acres, including 1.46 m acres of state and county forests plus 1.17 m acres of national forests (the Nicolet portion of the Chequamegon-Nicolet National Forest of Wisconsin and the West side of the Hiawatha National Forest in Michigan).

Our qualitative interviews with timber harvest managers in state and national forests offer only enough information to form conjectures. But the picture that emerges is of an even lower rate of willingness to allow collection

of logging residues than in the private sector. The timber managers interviewed at the USFS indicate that the likelihood of logging residue supply from national forests (NF) is negligible at any foreseeable price. They cited as major impediments scant staff time for processing Environmental Impact Assessments and managing the competitive bidding procedures associated with timber sales as well as caution in complying with the Endangered Species Act (Klammer 2017; Dulys-Nusbaum, Klammer, and Swinton 2019). These impediments to logging residue supply from federal lands are echoed in the published literature (Becker et al. 2011) and are evident from the list of mandated procedures for timber harvest on federal lands (Riddle 2019). Hence, the potential supply of 82,000 ODT of logging residues from the Nicolet NF in Wisconsin and west side of the Hiawatha NF in Michigan are unavailable in a practical sense.

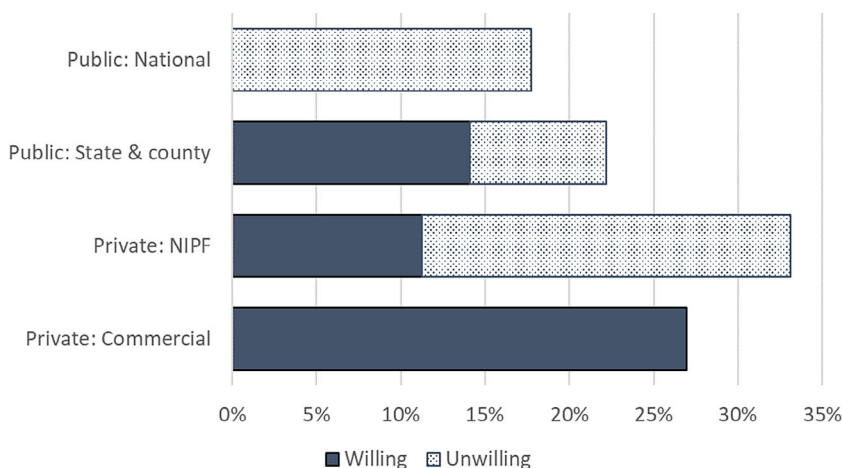
Roughly 102,000 ODT could potentially become available from state and county public forests within 100 miles of Escanaba⁶, but state foresters were unwilling to specify prices that would be required. Assuming that logging residues were supplied from the same share (64%) and in the same proportions as from all private forests, the combined supply curve would look like the solid curve in Figure 3, with total economic availability rising by 65,000 to 243,000 ODT at a price of \$100/ODT. This quantity represents 52% of the technically and sustainably available quantity in the counties within a 100-mile radius of the demand point. (We omit the very small percentage of land managed by nongovernmental organizations; if the largest such forestland owner in Michigan, The Nature Conservancy, is indicative, logging residue supply would be nil or close to it from this owner group (Klammer 2017)).

Since the total economic availability of logging residues begins from the share of land that owners would make available for residue removal, the degree that past studies have overestimated economic availability can be gauged by the proportion of forestland whose owners would not allow residue removal at a high price. Figure 4 shows the proportions of technically and sustainably available logging residues that are available from private sector sources at a stumpage fee of up to \$30 per dry ton at the forest site and indicative values for public sector forestland managers.

While the qualitative methods underpinning part of our research preclude formal confidence intervals around these estimates of landowner willingness to allow the harvest of logging residues, even generous assumptions about landowner willingness only extend participation from the current 52% to 65%. On commercial lands, the 100% landowner willingness that we assume is already an upper bound. On NIPF lands, the coefficient of variation around the effect of stumpage price on the marginal probability of landowner willingness to supply residues was 0.31 (Dulys-Nusbaum, Klammer, and Swinton 2019), implying that the 95% confidence interval around the mean probability of 34% participation ranges from 13% to 55%. On federal lands, our interviews and the extant literature indicate that under current environmental regulations and with current Forest Service budget and staffing levels, removal of logging residues is very unlikely (Becker et al. 2011;

⁶Based on 0.07 ODT/ac annual mean timber residue yield and 2018 state and county forest areas reported for Wisconsin by Wisconsin County Forests Association: Forest Acres (accessed 4/11/19): <https://www.wisconsincountyforests.com/forest-resources/forest-acres/> and for Michigan by Brian Maki, GIS Support Unit Manager, Resource Assessment Section, Forest Resources Division, Michigan DNR. Email to Scott Swinton (4/16/2019).

Figure 4 Share of technically and sustainably available logging residue that each type of timberland owner is willing to remove (black bars) for the 460,000 oven-dry tons annually collectable within 100 miles of Escanaba, Michigan [Color figure can be viewed at wileyonlinelibrary.com]



Klammer 2017). Nonetheless, 0% availability is clearly a lower bound. Given that the forester in charge of timber sales at the Hiawatha National Forest in 2016 reported harvesting 37% of the timber allowable under its forest plan (with no authorized removal of logging residues) (Klammer 2017), an upper bound might be residue removal on half of that 37%, or 19% of federal forest land. Following our approach of treating state and county forests as typical of private lands, we would push the upper bound from 64% to 75%.

The overall upper bound on willingness to permit removal of logging residues in the case study area rises to 65% of forestland from our base case of 52%. The upper bound estimate continues to assume availability of all commercial forestland (27%), a rise on NIPF land (33% of total area) to 18% from 11%, a rise on federal forestland (18% of total area) to 3% from zero, and a rise on state and county forestland (22% of total area) to 17% from 14%.

Discussion

Our results are consistent with the literature in both the price range for providing residues and the shape of the resulting supply curve. However, our findings depart from the literature in that they show dramatically lower quantities available for economic supply. Factoring in landowner willingness to permit residue removal accounts for the difference.

We find that the roadside costs of logging residues range from about \$39 per dry, short ton in large-scale commercial forests to \$44–\$57 per dry ton for nonindustrial private forest (NIPF) owners. The variable cost of hauling wood chips to a demand point means that the break-even price for delivering to a bioenergy demand point near the northern Wisconsin-Michigan border (at Escanaba, MI) ranges from \$50–\$100 per dry short ton (\$25–\$50 per green ton). This price range is consistent with earlier estimates for hardwood logging residues delivered to a Minnesota biorefinery site at delivered prices ranging from \$38–\$90 per dry ton (Petrolia 2006) and \$53–\$115 per dry ton (Eidman et al. 2009) and from the Lakes States of Minnesota, Wisconsin, and Michigan (Becker et al. 2009) that calculated roadside prices of \$40 per dry, short ton and delivered prices beginning around \$56 per dry ton. These

values also overlap heavily with intervals for breakeven costs of delivered, chipped logging residues to a Montana bioenergy facility at \$31–\$79 per dry ton and a Missouri site, ranging from \$46 per short dry ton (\$23 per green ton) at roadside to a maximum of \$72 per dry ton delivered (Saunders et al. 2012).

These results further indicate that logging residues have the potential to be supplied at prices similar to those for crop residues like corn stover. The original U.S. Department of Energy “Billion Ton Report” estimated that substantial quantities of corn stover could be supplied at delivered prices of \$43–\$52 per dry ton over a transport distance of 22 to 62 miles (Perlack and Turhollow 2003; Perlack et al. 2005); the latest version estimates the same range as \$30–\$60 per dry ton (U.S. Department of Energy 2016). Brechbill, Tyner, and Ileleji (2011) estimated a higher cost during a period of higher fuel prices, putting the cost of supply in Indiana at \$63–\$75 over a distance of 40 miles, a range bracketed by a \$53–\$93 corn stover delivered price range for delivery to a Minnesota facility with no distance limit (Petrolia 2008b). However, all of these studies omitted the economic cost of persuading landowners to elect to remove and sell stover. Bergtold et al. (2014) queried Kansas farmers about their willingness to harvest and contract to sell corn stover, finding a price range of \$51–\$74 per dry ton at the farm gate, which does not account for transportation costs to a demand point.

The current study’s supply schedule for residues takes nearly a stepwise form: No supply is available below a threshold delivery price of \$50 per dry ton, and above \$80 per dry ton, rising prices elicit virtually no added quantity. This stepwise pattern of no supply, highly priced elastic supply, and then highly priced inelastic supply echoes earlier findings in the region, using both techno-economic (Becker et al. 2009) and econometric (Du and Runge 2014) approaches. Similar patterns have been reported for techno-economic studies of the supply of forest residues in Montana (Jones et al. 2013) and for the 48 contiguous U.S. states (U.S. Department of Energy 2016) (pp. 89, 349). In each instance, the lower bound is the minimum price to cover costs at the lowest-cost site, while the upper bound is where the technically available supply that landowners will permit is exhausted. (Worth noting but beyond our scope of logging residues, is that pulpwood becomes a competing source of energy biomass in neighboring Minnesota and Wisconsin at prices in the \$70–90 range per ODT (Petrolia 2006; Du and Runge 2014).

The important difference between this study of economic supply and its predecessors is that this one explicitly factors in the unwillingness of some landowners to allow residue removal. Past inventory and availability studies have largely assumed that logging residues are available from all forestland that is not legally protected as wildland (Perlack et al. 2005; Jones et al. 2013; Yemshanov et al. 2014; GC, Miller, and Potter-Witter 2017; Springer et al. 2017), perhaps with restrictions on federal lands (Becker et al. 2009; U. S. Department of Energy 2016). At least one study explicitly notes that actual supply is likely to be less due to nonparticipation by some landowners (especially NIPF) (Becker et al. 2009), whereas two studies arbitrarily assumed a 75% level of landowner participation (Petrolia 2006; Eidman et al. 2009). By eliciting landowner willingness to allow the removal of logging residues in exchange for payment, we are able to reach empirically grounded estimates of the potential economic supply of logging residues. These begin from a best estimate that logging residues are available from just 52% of forestland at prices exceeding a breakeven threshold that accounts for normal profit.

The substantial literature on willingness of landowners to allow removal of crop and logging residues reveals strong support for this finding, though that literature does not incorporate landowner willingness into estimated economic supply of deliverable biomass. In general, that literature shows that willingness can be quite limited, especially when residue removal poses opportunity costs. For crop residues, like corn stover, those opportunity costs tend to come from competing enterprises. Mooney, Barham, and Lian (2015) found that at a price of \$100 per dry ton, only 40% of Wisconsin dairy farms and 10% of crop farms would make corn stover available for removal, with farmers valuing stover either as silage and/or as a source of soil organic matter. For logging residues, availability fell in a similar range. Aguilar, Cai, and D'Amato (2014) found that given a decision to harvest timber, an offer of \$8–\$56 per acre would induce only 35%–40% of Lake States NIPF owners to allow removal of logging residues. A similar study in Missouri found that an extra \$25 per acre induced removal from only 30%–41% of NIPF landowners (Aguilar, Daniel, and Cai 2014b). In Massachusetts, payments up to \$100 per acre induced NIPF owners to allow residue removal on only 7%–10% of their forestland (Markowski-Lindsay et al. 2012). These landowners seem to find the opportunity cost of allowing logging residue removal to exceed the payment levels offered. On the other hand, in drier areas of the United States where logging residues represent a fire hazard, landowners may be more willing to allow removal of residues (Jones et al. 2013).

The willingness of public forest managers to supply logging residues seems to be more restrictive yet. Concerns about regulatory compliance and litigation risk drastically constrain the availability of logging residues from National Forests (Becker et al. 2011), a limitation magnified by the time demands for timber sales planning by foresters who may be called to fight forest fires at short notice (Klammer 2017). For organizations that hold forestland for conservation purposes, the opportunity cost of disrupting ecological processes tends to outstrip by far the appeal of revenue from logging residues (Dulys-Nusbaum, Klammer, and Swinton 2019). Hence, the availability of logging residues from these two landowner types is effectively nil. Only among state and county public forests is there potential willingness to permit logging residue removal (Dulys-Nusbaum, Klammer, and Swinton 2019), a level likely to be no greater than private sector levels.

In conclusion, biomass inventories often show abundant supplies of potential bioenergy feedstocks (Becker et al. 2009; Gelfand et al. 2013; GC, Miller, and Potter-Witter 2017) that appear to be available at low marginal costs for on-site production plus delivery to a demand site. However, we find that managers of only 52% of forestland are willing to allow the removal of logging residues in northern Michigan and Wisconsin. This finding implies that overlooking landowner willingness results in overestimates of available logging residues close to double the true economic supply. Overestimates in the “Billion on Report” (U.S. Department of Energy 2016) are smaller, because it excludes supplies from federal forests. Nonetheless, assuming 100% willingness to participate from private forests where we found 64% maximum participation still results in overestimating the economically available supply by half. A similar degree of overestimate may apply to techno-economic estimates of crop residue supply that assume all farmers are willing to participate.

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