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Evaluating the Economic Incentives of Biomass Removal on Site Preparation for Different Harvesting Systems in Australia

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Abstract: *Research Highlights:* This study evaluated the impacts of biomass recovery on site preparation costs while proposing a mathematical model and framework to catalogue the benefits depending on harvesting system. *Background and Objectives:* Biomass as a viable product depends on the requisite costs of production compared to the price paid by relative markets. The removal of biomass directly impacts site preparation costs, and the operational and economic ramifications of this should inform the feasibility of biomass harvesting and market viability. The relative incentives for biomass removal depend on the quantity, presentation, and location of the residues and are thus a result of the commercial sawlog harvesting system. This incentive also largely depends on the required work to prepare a site for replanting. *Materials and Methods*: This study developed a mathematical model to connect the concepts of site preparation, harvesting, and biomass costs and revenues to determine the maximum net revenue. This work also developed a framework for understanding and calculating the key model inputs related to site preparation and the relative economic site preparation incentive for biomass harvesting. The framework was then illustrated by using industry data from plantations in Queensland, Australia. *Results and Conclusions:* The analysis identified a potential reduction in site preparation costs due to biomass harvesting of USD 75–450 ha^{-1}, with a greater incentive when using cut-to-length harvesting systems compared with whole-tree harvesting due to the greater volume of residues after cut-to-length harvesting. For example, a removal of 20 t ha^{-1} of recoverable biomass after cut-to-length harvesting may equate to an economic incentive of USD 22 t^{-1}. Depending on the biomass market, this incentive may represent a significant percentage (or even exceed) the biomass market price. The combination of biomass market price plus site preparation economic incentive may make biomass an attractive market opportunity, even in challenging biomarkets.

Keywords: biomass harvesting; forest residues; site preparation costs; economics; mathematical model

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1. Introduction

Forest harvest residues are increasingly seen as potentially viable products for energy production or a critical feedstock for emerging bio-chemical products. Biomass as a viable feedstock or product depends on the requisite costs of production compared to the price paid by relative markets (e.g., biofuels, pellets, torrefied wood). In this context, biomass is material that is generated during traditional stump-to-truck forest harvesting operations (tree felling, field or landing processing, forwarding, or skidding) and typically includes tops, unmerchantable species, undersized trees, crooked pieces, broken pieces, branches, and leaves. Biomass is generally considered to be a low-value product with a high cost of production, as one must handle a generally dirty and bulky material in suboptimal conditions resultant from the traditional harvesting operation [1]. The economic viability of biomass products often depends on the nuances of the production process and markets where thin margins are common [2–4].

From an Australian perspective, emerging biomass markets include using harvest residues for pellet production supporting existing and emergent export markets in Asia (with the potential of hundreds of thousands of tonnes per year exported) as well as the local consumption of residues for boiler fuel for on-site power and heat generation or feedstock for niche local markets (e.g., landscaping and pet bedding). The utilization of biomass in Australia is largely market-driven with a lack of government subsidy for bioenergy production. Australia has recently met its 2020 20% renewable energy target (largely via solar and wind) but has no specific goals for domestic bioenergy usage, which is well below the Organization for Economic Cooperation and Development (OECD) average (Australia bioenergy production is 0.9% of total output vs. the 2.4% OCED average) [5,6]. This regional context highlights the importance of outright financial viability to enable biomass utilization in Australia.

The amount and composition of slash remaining after harvest depends on a number of factors including the harvest system, species, products, markets, and tree handling. Each of these factors then impact the ultimate site preparation operations required to restore the site to a condition where it can then be re-planted for next generation growth and harvest. Forest residue profiles have implications for environmental sustainability [7] but are also related to reduced operational costs due to greater efficiency of traditional roundwood harvest and reduced site preparation costs [8]. Logically, the presence (or absence) of woody material on site dictates the subsequent operations required for replanting. Overall, very little research has been done to quantitatively evaluate the economic impact biomass harvest may have on subsequent site preparations, even though this may very well be the key to enabling the viability of the biomass markets. The associated variable costs of these site preparation operations then provide an incentive (or disincentive) for biomass harvesting depending on the site and requirements for site preparation, and should be connected with the broader suite of operational costs (harvesting and biomass extraction) and product revenues to evaluate market viability.

This topic is most important to forest or plantation managers whose objective is to ensure the highest value is sustainably recovered from the forest resource as is typically the business model in Australia. When maximizing overall value, the financial considerations (revenue and cost of production) of traditional sawlog products and biomass products must both be considered along with related altered operational costs (site preparation) in addition to other tangential considerations (ease of access, risk profiles, etc.), which also may impact business costs. This broader value recovery discussion is also of importance to harvesting contractors (those that execute the forest management and harvesting plans) that they may better understand the incentives for implementing altered harvesting systems and recovery options from both practical and commercial perspectives. At the very least, harvesting contractors should understand the true value of biomass recovery operations in order to negotiate appropriate compensation for this work, as ideally value would be shared and incentivized throughout the supply chain. In this paper, we focused on the operational costs of production associated with biomass harvesting from a forest managers perspective.

1.1. Harvesting Systems and Biomass Availablity

Harvesting systems have been found to be the most important factor when determining harvest residue volumes [9,10] and associated clean up requirements. Traditionally, there are two different harvest methods, cut-to-length (CTL) and whole tree (WT) operations utilized in forest harvesting operations. In Queensland, Australia, southern pine plantations (*Pinus elliottii* × *Pinus caribaea* var. *hondurensis*) are the dominant source wood supply supporting domestic sawlog and pulp markets—operationally, this is the difference between using a feller-buncher and skidding material for whole-tree central processing (WT) along roadside for long logs or in-field harvesting/processing followed by forwarding short logs to roadside for extraction (CTL). With CTL operations, slash material is spread out along corridors over the planting area, while with WT harvesting operations there is a lower slash level through the general plantation area (GPA) and accumulated piles along the roadside. This remaining residue profile then dictates the site-preparation operations required to then plant for the next generation harvest.

1.2. Site Preparation

Site preparation plays a vital role in the establishment of plantations and is highly influenced by the harvesting system and constrained by cost of technology, sustaining nutrients and biodiversity while creating additional cost–benefit and improved growth of new trees [11–15]. The removal of forest biomass after clear-cut is well investigated from a nutrient and fertilization point of view to sustain productivity [7,16], although biomass nutrition sustainability implications are outside the scope of this work. From a cost perspective, there are only a few research studies on the economic incentive for a forest grower to remove biomass for bioproducts [8,17,18].

Gan and Smith [17] indicated that site preparation costs could potentially be reduced by USD 250 ha^{-1} (all dollars are in USD) by removing logging residues for bioenergy production in East Texas, USA, using landscape scale approximations in a region dominated by whole-tree harvesting systems in pine clear-cut plantations with roadside pile removal likely being the mechanism for the incentive. Wrobel-Tobiszewska et al. [18] suggested that the reduction in site preparation costs could be correlated to the site's harvested biomass quantity. They estimated site preparations savings may vary from USD 75 ha^{-1} (10–14 t ha^{-1} of biomass harvested) up to USD 300 ha^{-1} (≥30 t ha^{-1} of biomass harvested), with no incentive below 10 t ha^{-1} of biomass harvested, although they did not indicate the associated operational mechanisms. The work of Wrobel-Tobiszewska et al. [18] was a regional study completed in Tasmania, Australia, with aggregate assumptions pertaining to local pine and eucalyptus plantations in a region dominated with the use of CTL harvesting systems where biomass removal mitigates the need for stacking, windrowing, or burning site preparation procedures. Another Australian study in *Pinus radiata* plantations with CTL systems estimated savings of up to USD 375 ha^{-1} from avoiding the need to stack and windrow logging residues [19]. This study also suggested that harvesting residues of larger diameter (>200 mm) with a high volume of unmerchantable material (e.g., non-commercial native regrowth) correlated to a higher site preparation cost than smaller diameter residues (<80 mm). Other studies also indicate that the presence of coarse debris (recoverable from a biomass harvest perspective) is likely more relevant than total residue volumes when predicting site preparation costs [20]. Furthermore Kizha and Han [21] suggested that recovering logging residues can result in a site preparation cost savings potentially equal to the cost of piling and burning scattered restudies (USD 1000–1200 ha^{-1}), although they did not account for other potentially required operations for replanting. Harrill [22] noted that site preparation savings of USD 100 ha^{-1} may be applicable in integrated biomass harvesting in northern California under whole-tree harvesting operations from the removal of logging slash piles. For North Carolina, Megalos et al. [23] cited savings of USD 65–150 ha^{-1}, presumably related to pine plantations using WT harvesting techniques and slash pile removal. Other published work on site preparation practices to reduce cost of operations indicate that site preparation savings may be on the order of USD 4–8 t^{-1} (USD 11–20 t^{-1} in 2020 dollars), although these figures date back to the United States Forest Service in the 1980s and were not related to the removal of biomass using current harvesting technology [8,24].

None of these studies have attempted to compare different in situ biomass quantities to a range of relative site preparation costs whilst comparing harvesting systems and translating these data into the context of economic incentives for biomass extraction. Furthermore, no study has explored the economic incentives of biomass recovery on site preparation in Queensland, Australia. This paper is the first to our knowledge that connects the topics of harvesting systems, logging residues, and site preparations to help establish the specific net economic value of recovering forest biomass stemming from its impact on silviculture and site preparation. This paper proposes a mathematical model for evaluating the relative operational incentives for biomass removal in the context of the supply system costs. This paper also proposes an operational framework to develop the incentive for biomass removal from a site preparation perspective while providing a regional example to illustrate the economic implications of biomass removal with respect to site preparation on biomass quantity and harvesting system setting. This work is novel in evaluating these important aspects of biomass economics, helping to enable viable biomass supply chains internationally. Structurally, the model is first presented, and then the site preparation costing framework is operationalized using an Australian regional example in pine plantations.

2. Materials and Methods

2.1. Mathematical Model

Mixed-integer programming (MIP) optimization models are common in forestry to develop optimal solutions for biomass supply chains, including considerations for logistics, products, time periods, revenues, and other key variables [25–29]. The proposed general mathematical model seeks to maximize the net revenues from harvesting logs plus harvesting biomass less the cost of site preparation activities (with or without biomass collection) for 2 saw log harvesting systems (Equation (1)). Decision variables are harvesting method, biomass collection, and site preparation. The objective is to maximize net revenues (Equation (1)) subject to harvesting system conditions (Equations (2)–(4)):

$$Max \sum A_i T_i (R_i - HC_i) I_i + \sum A_i TB_i (RB_i - HCB_i) IB_i - \sum A_i (SPBG_i + SPBR_i) IB_i - \sum SP_i A_i IC_i \quad (1)$$

$$\sum I_i = 1 \quad (2)$$

$$IB_i + IC_i = I_i \;\; i = 1, 2 \quad (3)$$

$$I_i, IB_i, IC_i = \{0, 1\} \quad (4)$$

Using the following notation and key parameters as presented in Table 1:

Table 1. Optimization model nomenclature.

Notation	
i	Harvesting method (1 = WT, 2 = CTL)
A_i	Area (ha)
T_i	Tonnage of product (logs) delivered (t ha^{-1})
TB_i	Tonnage of biomass product extracted (t ha^{-1})
R_i	Revenue for logs (USD t^{-1})
RB_i	Revenue for biomass (USD t^{-1})
HC_i	Harvest cost (USD t^{-1})
HCB_i	Harvest cost of biomass (USD t^{-1})
$SPBG_i$	Site preparation costs with biomass collection for general plantation area (USD ha^{-1})
$SPBR_i$	Site preparation costs with biomass collection for roadside consolidated area (USD ha^{-1})
SP_i	Site preparation cost without collection of biomass (USD ha^{-1})
I_i, IB_i, IC_i	Binary variables (can only choose one harvest method)

The general model can recognize fundamental differences between CTL systems that produce shorter log lengths (5–8 m) and WT systems that permit the flexibility to capture longer log lengths (10–18 m), potentially affecting both value and volume recovery [30]. The model also highlights the relationship between biomass collection and site preparation activities, with the potential for lower site preparation costs associated with the removal of biomass from the landscape. As such, one of most important elements of the mathematical model is the allowance for different site preparation costs and the subsequent identification of the estimate with biomass collection (SPB) and without biomass collection (SP) variables that quantify the site preparation incentive for collecting residual biomass (Equations (5) and (6)). Data input for log and biomass revenues, harvesting, and biomass collection costs are generally better documented as they are either known to the forest manager (established market pricing), easily approximated with operational considerations (harvesting and recovery costs), or estimated via market surveys and emerging market analysis (biomass revenue). In the remainder of this paper, we concentrate on the site preparation variables and framework proposed to develop this model.

$$SPB = SPBG + SPBR \tag{5}$$

$$SPincentive = SP - SPB \tag{6}$$

While the general model includes allowances for multiple harvesting systems and associated value and product streams in a management area (enabled by using integer variables in the formulation), many management plans only operate with a pre-defined single harvesting system (CTL or WT) exclusive of broader system value optimization. In this case, a simplified version of the general model can be used to calculate net revenues for a single harvest area with a single harvesting system type with or without biomass harvesting. The general formulation translates to the following deterministic equations (with and without biomass harvesting), with the higher net revenue option being the preferred financial and operational option (Equations (7) and (8)):

Net revenue with no biomass harvest (*NR_NBH*):

$$NR\_NBH = A * T(R - HC) - A * (SP) \tag{7}$$

New revenue with biomass harvest (*NR_BH*):

$$NR\_BH = A * T(R - HC) + A * TB * (RB - HCB) - A * SPincentive \tag{8}$$

Furthermore, given the simplification of assuming a single harvest area and system, the break-even biomass market price (*RB*) can be calculated by setting Equations (7) and (8) equal to each other and solving for the biomass market price point (on the basis of site preparation, biomass tonnage, and biomass harvesting costs) to initiate viable biomass harvesting operations (Equation (9)). In this simplification, area (*A*), product revenue (*R*), product tonnage (*T*), and harvesting cost (*HC*) cancel out of the formulation and the binary variables are not necessary.

Break-even biomass pricing:

$$RB = \frac{SP - SPincentive}{TB} + HCB \tag{9}$$

2.2. Site Preparation Framework

In order to populate the key site preparation variables to evaluate the model, we developed a cost matrix framework to evaluate the relative impact of biomass removal on site preparations for future harvest under both CTL and WT harvesting operations in Queensland, Australia. To achieve this, a matrix of site preparation best practices and costs characteristic for the region was developed to evaluate the economic ramifications of the associated remaining biomass. The framework is partitioned into different categories to recognize a range of slash levels corresponding with treatments for the general plantation area (GPA) as well as additional consolidated material treatment zones characteristic for the harvesting system (e.g., roadside for WT systems) and associated costs of treatment (Table 2). Each area would relate to specific treatments (e.g., equipment, rates, and average operating times) to develop a range of treatment costs (high and low). The framework would be replicated for each representative harvesting system. Qualitative and quantitative left slash levels related to the broader volumes in-field are connected to the frequencies of occurrence (percentage of planting area for a certain slash level) to develop a composite incentive for biomass harvesting from a regional site preparation perspective to inform best practices. Ideally, long-term implications of site preparation (including remounding for drainage and other cultivation requirements) and an allowance for area no longer plantable (forgone future income) would also be accounted for within the costing with the present value of the loss (or gain) noted. Additionally, when burning, one can also use this model to account for the negative impacts of burning (carbon emissions, etc.) by associating a correlated market value on the impact or conversely account for the financial risk of not burning, although these metrics are outside the scope of this work. Operationally, it is logical to view these costs and impacts on a USD ha^{-1} of planted area basis.

Table 2. Framework for determining site preparation costs compared with slash level accounting for the general plantation area (GPA), roadside, and long-term costs presented on a USD ha^{-1} basis.

Slash Level	Frequency	Area	Treatment	Long-Term Impact	High Cost (USD ha^{-1})	Low Cost (USD ha^{-1})
High (t ha^{-1})	%	GPA:			USD	USD
		Roadside:				
		Notes:				
Medium (t ha^{-1})	%	GPA:			USD	USD
		Roadside:				
		Notes:				
Low (t ha^{-1})	%	GPA:			USD	USD
		Roadside:				
		Notes:				

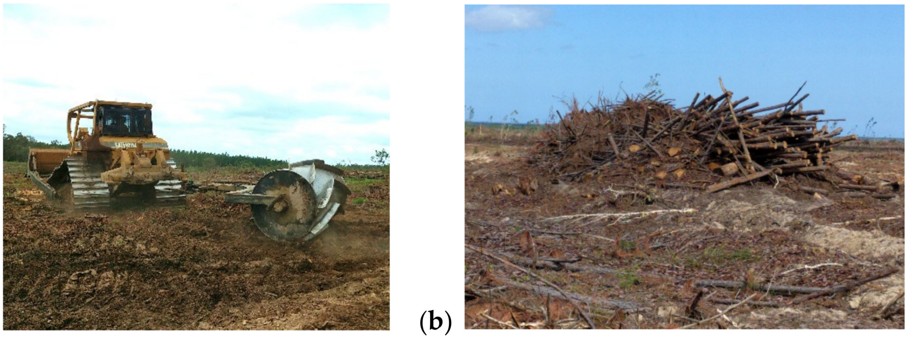
This framework would then be replicated, altered, and reviewed for differing biomass harvesting assumptions and appropriate site preparation techniques.

2.3. Site Preparation Example

To illustrate the framework, we sourced a range of regional values specific to Queensland, Australia. An informal operational survey from a regional forest grower was completed to generate data to populate the proposed decision support matrix and corresponding methodology to determine operational incentives for biomass harvesting. In the study region, site preparation best practices and costs were collated to develop an envelope of costs associated with site preparation for harvesting systems within a range of typical residue (left biomass) conditions. Information related to typical systems utilized along with relative costs corresponding to relative levels of remaining left slash were synthesized. Due to the commercially sensitive nature of exact operational costs and values, we provided approximate values for illustrative purposes. The study area corresponding to the example is that of southeast Queensland's hybrid pine (*Pinus elliottii* × *Pinus caribaea* var. *hondurensis*) plantations north of Brisbane, Australia, with roughly 30-year harvest rotations corresponding to trees on the order of 1.25 m^3 and roughly 300–400 stems ha^{-1} when clear cut with either CTL or WT operations. Both harvest systems were assessed for likely site preparation operations required to enable re-establishment of the next rotation of plantation.

2.3.1. Regional Operations

Within this region, typical mechanical site preparation operations include the use of a chopper roller (CR), a dozer-based machine towing a multi-tonne drum roller with blades to break up slash material, with an excavator used to windrow the material (move material into lanes away from the planting locations), or using an excavator to move roadside material (either to collect and burn or spreading roadside piles to allow for future planting (often referred to as lane clearing)) (Figure 1). Site preparation activities also include burning, herbicides, and other mechanical treatments (cultivating soils, mounding, trenching), although for this exercise these costs were assumed to be the same with and without biomass removal [31].



(a) (b)

Figure 1. Site preparation operational activities: (**a**) chopper roller and (**b**) roadside pile after excavator manipulation prior to burning. Photos taken by Michael Berry.

2.3.2. Slash Assessment

For this study, forest harvest residue conditions were rated from high to low for WT and CTL sites on the basis of normal conditions in this region where overall left slash may vary from 10 t ha^{-1} (on a low WT site excluding roadside slash) to 100 t ha^{-1} (on a high slash volume CTL site), where all tonnes are in green metric tonnes. In this case, slash refers to coarse woody debris remaining on site after harvest (>3 cm diameter), assuming 25% moisture content on a green basis. Operationally, a CTL biomass harvest reduces the available left slash on site in the GPA. Using this methodology, this altered condition would indicate the GPA goes from a higher level to a lower level of left slash in CTL operations. Similarly, with WT operations, biomass removal likely indicates a different treatment of consolidated roadside material and potential site preparation implications for the area depending on the level of biomass harvesting.

3. Results

Typical mechanical site preparation activities for the next rotation of plantation establishment were identified and the information used to populate the proposed framework. Matrices for typical operations and costs of site preparation activities were developed for CTL (Table 3) and WT (Table 4) harvesting systems considering varying levels of harvest residuals. Importantly, there was no allocation for long-term value implications, and a single cost assumption (USD ha^{-1}) was provided for discussion with modifications to the template associated with systems and slash level.

For CTL systems, biomass harvesting incentives are approximated as a lower slash level (fundamentally the operation systems do not change going from high to low), with the difference being the economic incentive for biomass removal. For WT systems, the framework is used twice—once without biomass harvesting and once with biomass harvesting, with difference becoming the relative incentive for biomass operations from a site preparation perspective. Related to the proposed model, the SPB would be the cost of site preparation with biomass collection (low level) and SP would be the cost without collection (high level).

Table 3. Site preparation procedures and costs for the CTL system.

Slash Level	Frequency	Area	Treatment	Cost (USD ha^{-1})
High (>35 t ha^{-1})	75%	GPA:	Windrow	675
		Roadside:	None	
		Notes:	Too heavy to CR	
Medium–low (<35 t ha^{-1})	25%	GPA	Full chopper roll (CR)	225
		Roadside:	None	
		Notes:	Light enough for CR only	

Note: CR = chopper roller, GPA = general plantation area, windrow = excavator used to move material into windrow orientation.

Table 4. Site preparations procedures and costs for whole-tree harvesting systems with and without pile manipulation.

Slash Level	Frequency	Area	Treatment	Costs of Site Prep (USD ha^{-1}) Full Treatment	No Pile
High—no burn (>25 t ha^{-1})	25%	GPA:	CR full area	503	300
		Roadside:	Lane clear (none)		
		Notes:	Full CR and clear planting row		
High—burn (>25 t ha^{-1})		GPA:	CR full area	375	300
		Roadside:	Pile and burn (none)		
		Notes:	Burning is cheap but carries a risk		
Medium (15–25 t ha^{-1})	50%	GPA:	CR at tree line	387	225
		Roadside:	Lane clear (none)		
		Notes:	Targeted CR, clear planting row		
Low (<15 t ha^{-1})	25%	GPA:	CR at tree line	312	150
		Roadside:	Lane clear (none)		
		Notes:	Limited CR, clear planting row		

Note: CR = chopper roller, GPA = general plantation area, lane clear = excavator used to clear productive planting rows. Indicative slash levels are based on GPA, which is correlated to roadside residue volume. For the roadside treatment area, "none" relates to no special treatment necessary when no pile present.

3.1. Cut to Length Site Preparation Costs

For the CTL systems, the costs of a heavy plot (high biomass >≈35 t ha^{-1}) costs were estimated to be USD 675 ha^{-1}, necessitating the windrowing of material for planting while lower biomass levels allowed for chopper rolling the site in preparation for the next harvest (Table 3). Including frequencies, on average, one would assume approximately USD 562 ha^{-1} in site preparation costs for this region. If biomass harvesting occurs resulting in a lower slash level, the potential site prep savings may reach USD 450 ha^{-1} for those area that would have had a higher treatment level.

3.2. Whole-Tree System Site Preparation Costs

If a biomass harvesting plan was in place under the whole tree system, the resulting roadside residual pile would ideally be eliminated. Table 4 provides an estimate of the full treatment (area and roadside treatment (SP)) and an estimate without roadside pile treatment (SPB) to show the difference in site preparation costs and activities. For WT systems, the model would be recalculated with the difference becoming the relative incentive for biomass operations from a site preparation perspective. Related to the proposed model, SPB would be the cost of site preparation with full GPA and roadside treatment, while SP biomass collection and SPB would be the cost without roadside pile (no pile) depending on initial slash level.

For the WT system, it is estimated that site preparations for a typical WT harvested site may include chopper rolling the full area and preforming a lane clear of the roadside residue to prepare for future planting with costs ranging from USD 312 to 503 ha^{-1}, while without roadside material handling, this could be reduced to USD 150–300 ha^{-1}. Under certain high roadside debris loads, burning is also considered a viable option, with piling and burning used operationally instead of traditional land clearing techniques. Including frequencies, on average this is likely to be USD 384 ha^{-1} (no biomass harvest) or USD 225 ha^{-1} (including biomass harvest). In this case, the WT savings from a site preparation perspective is generally in the neighborhood of USD 75–203 ha^{-1}, depending on biomass level. The relative biomass removal incentive varies depending on the specific site, though appears to be in a fairly narrow band for the given assumptions, with an average savings of USD 160 ha^{-1} in the region.

The removal incentives are highly dependent on the particular site with additional factors including future planting considerations/costs, drainage/slope, species, current row spacing, current mounding conditions, machine constraints (clearance, access, availability, etc.), time since last harvest (regrowth/wildling conditions), and other legacy issues including row orientation affecting the relative incentive; ideally, these are all considered when developing appropriate SP and SPB variables for the proposed model.

3.3. Model Break-Even Analysis

The general model was constructed to optimize whether or not biomass harvesting should be completed for each harvest system in order to maximize net revenue of the whole plantation area; as such, the unique circumstances of when biomass harvesting should be completed depends on those unique inputs of market and site conditions, which will be highly dependent on the specific location. This paper provides the underlying framework to judge financial viability for a wide suite of complex conditions including variable market values, product and biomass tonnages, and harvesting and site preparation costs related to multiple harvesting systems. In order to exemplify the concept, we can connect the above referenced site preparation cost examples with the simplified model to determine whether or not biomass harvesting creates a higher net revenue, with this thus becoming the preferred financial and operational option. For example, evaluating the developed break-even biomass pricing equation (Equation (9)) when assuming a 1 ha area, biomass harvesting costs of USD 30 t^{-1} and 15 t ha^{-1} of biomass removal with high levels of slash on both CTL and WT systems (SPincentive = USD 450 ha^{-1} and USD 203 ha^{-1}, respectively, and SP = USD 675 ha^{-1} and USD 503 ha^{-1}, respectively) have break-even pricing equating to USD 45 t^{-1} and USD 50 t^{-1}, respectively. These values would then become the cornerstone for determining whether or not biomass harvesting would be used in the general optimization model. This calculation can be completed for any sequence of input conditions and will vary accordingly. For example, given the exemplar input criterion, the CTL and WT system break-even pricing varies from USD 41–53 t^{-1} and USD 45–60 t^{-1}, respectively, when the tonnage of biomass recovered varies from 10–20 t ha^{-1}.

4. Discussion

Harvesting systems and associated pre- and post-biomass harvesting slash levels dictate site preparation costs and potential subsequent incentives for removal. For CTL systems, a biomass harvest is most likely approximated as a high to low biomass profile associated with up to USD 450 ha^{-1} cost savings for area requiring biomass reduction. This is consistent with other reports, indicating a CTL system with high slash volumes may save USD 400–500 ha^{-1} [18,19]. This paper, however, provides a more granular look, suggesting this cost savings may not apply for lower initial slash volumes, which would require additional research to evaluate. With WT harvesting, the cost savings results from not having to handle the roadside residues built up from roadside processing. From a site preparation perspective, it is generally in the neighborhood of USD 75–200 ha^{-1}, depending on biomass level. These values generally support the range of previously published values for WT systems from the USA (USD 65–250 ha^{-1}) [17,22,23], although we provide more insight to potential difference in incentives with regards to systems and biomass level. From this work, we see that, unlike CTL, WT systems across a broad range of biomass levels appear to be correlated with a more constant site preparation economic incentive (<15 t ha^{-1} being USD 162 ha^{-1} while >25 t ha^{-1} being USD 203 ha^{-1}). This work also indicates that burning may provide less direct financial incentive (USD 75 ha^{-1}), although this does not account for the enhanced operational risk and should be an element of further research. Additionally, as this work connects remaining slash volumes and composition to site preparation costs, it is likely relatable to regions and circumstances beyond Australian southern pine plantations (provided the site preparation mechanical systems are similar) though further research would be required in each setting.

When choosing a harvesting system, a grower may also want to consider the cost–benefit of site preparations in general, as this work suggests WT system site preparation cost may be USD ≈188 ha^{-1} less than CTL systems. That said, there could also be a slight disincentive for whole-tree harvesting from a site preparation cost perspective when slash materials are low, given the additional excavator (lane clearing) work likely required to handle the WT roadside material (USD −87 ha^{-1}), and thus a manager must know the full implications of their operational decisions. This work also indicates that future work should look to integrate, more broadly, the value chain associated with biomass harvesting (harvesting costs, transportation, product value, etc.) to more fully understand the broader economic incentives and drivers of biomass harvesting.

To operationalize these data, the forest manager must consider the site preparation incentive within the context of how much merchantable biomass will be recovered from the sites. For traditional sites in this region, this often amounts to 10–20 t ha^{-1}, thus equating to a potential economic incentive of USD 22–45 t^{-1} for CTL systems and USD 4–20 t^{-1} for WT systems. Assuming biomass is valued at USD 30 t^{-1}, this may not be economically viable on its own, but with the inclusion of the site preparation incentive, this effective value may increase by 13–150% (or valued at USD 34–75 t^{-1}), depending on an individual's assumptions. This is also illustrated by the break-even analysis concept where the threshold market price (biomass value) can be directly calculated for a single harvesting system and single unit given site prep costs, harvesting costs, and tonnage of biomass extracted. Related to early studies indicating a potential savings of USD 4–8 t^{-1} in 1984 (USD 11–20 t^{-1} in 2020 dollars), this incentive also seems generally constant over time for WT systems [8]. This can easily make biomass an attractive market opportunity, even in challenging biomarkets.

To fully utilize the proposed model, one must integrate the site preparation costs with merchantable volume harvesting costs and revenue streams for both biomass and traditional products. It is recommended that future research be aimed at evaluation of the full proposed model under a range of different conditions, especially those with unique, niche, or potentially high-valued bioproduct markets where biomass removal may be highly lucrative. It should also be noted that biomass harvesting and any associated nutrition removal should also be evaluated from an environmental sustainability focus to ensure long-term productivity. Additionally, related to system selection, further research may focus on traditional product verses biomass product quantity and associated economics (harvesting costs and revenues), for which the proposed model provides the foundational framework in terms of material flow and financial analysis of competing systems. This study also highlights the need for a holistic view of forestry value chains, with growers, markets, and contractors working together to help enable the highest value usage of natural resources.

5. Conclusions

Harvesting systems and biomass removal directly impact site preparation costs, and the economic ramifications of these decisions should be considered when developing a harvest and subsequent regeneration plan. This study proposed a general mathematical model to evaluate the full cost and revenue suite of operations (harvesting, product revenues, biomass collection, site preparation). This work also proposes a framework to populate the key variables related to site preparation costs with and without biomass harvesting (SPB and SP), which is largely absent in the literature. Additionally, a simplified derivation of the model concept to evaluate a single harvest unit and harvest system with and without biomass harvesting and associated breakeven biomass market pricing was presented to illustrate the concept at a local scale. This work clearly identified a reduction in site preparation costs due to biomass harvesting in Queensland, Australia, with incentives likely varying from USD 75–450 ha^{-1}. On the basis of the results presented, it appears that the economic incentive for biomass harvesting depends largely on the current and future state of the anticipated residue profile. Specifically, it was found that for CTL systems, biomass removal may save up to USD 450 ha^{-1} for most areas, while WT systems may save up to USD 75–200 ha^{-1}, depending on biomass level, equating to a potential economic incentive of USD 22–45 t^{-1} for CTL systems and USD 4–20 t^{-1} for WT systems (when assuming 10–20 t ha^{-1} in recoverable biomass). These savings may initiate the viability of biomass recovery (depending on biomass harvesting costs and revenues) in certain markets. Ultimately, the viability of biomass recovery may depend not only on the cost of recovery and market conditions but also on the willingness of forest managers to share in system savings and re-evaluate their underlying harvest system selection to ensure the highest net value is recovered.

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References

1. Bisson, J.; Han, H.-S. Quality of feedstock produced from sorted forest residues. *Am. J. Biomass Bioenergy.* **2016**, *5*, 81–97. [CrossRef]
2. Sahoo, K.; Bilek, E.; Bergman, R.; Kizha, A.R.; Mani, S. Economic analysis of forest residues supply chain options to produce enhanced quality feedstocks. *Biofuels Bioprod. Biorefin.* **2019**, *13*, 514–534. [CrossRef]
3. Han, H.-S.; Lee, H.W.; Johnson, L.R. Economic feasibility of an integrated harvesting system for small-diameter trees in southwest Idaho. *For. Prod. J.* **2004**, *54*, 21–27.
4. Kizha, A.R.; Han, H.-S.; Montgomery, T.; Hohl, A. Biomass power plant feedstock procurement: Modeling transportation cost zones and the potential for competition. *Calif. Agric.* **2015**, *69*, 184–190. [CrossRef]
5. Parliament of Australia. *Renewable Energy Targets*; Australian Government: Canberra, Australia, 2010.
6. CEFC. The Australian Bioenergy and Energy from Waste Market, Clean Energy Financial Corporation. November 2015. Available online: https://www.cefc.com.au/media/107567/the-australian-bioenergy-and-energy-from-waste-market-cefc-market-report.pdf (accessed on 12 December 2020).
7. Thiffault, E.; Hannam, K.; Paré, D.; Titus, B.; Hazlett, P.; Maynard, D.; Brais, S. Effects of forest biomass harvesting on soil productivity in boreal and temperate forests—A review. *Environ. Rev.* **2011**, *19*, 278–309. [CrossRef]
8. Watson, W.F.; Stokes, B.J.; Savelle, I.W. Site preparation savings through better utilization standards. In *Forest Resources Management-the Influence of Policy and Law*; The Congress Forestier International Forest Congress: Quebec, QC, Canada, 1984; pp. 389–392. Available online: https://www.fs.usda.gov/treesearch/pubs/7382 (accessed on 5 August 2020).
9. Ghaffariyan, M. Remaining slash in different harvesting operation sites in Australian plantations. *Silva Balcanica* **2013**, *14*, 83–93.
10. Ghaffariyan, M.; Apolit, R. Harvest residues assessment in pine plantations harvested by whole tree and cut-to-length harvesting methods (a case study in Queensland, Australia). *Silva Balcanica* **2015**, *16*, 113–122.
11. Tuomasjukka, D.; Martire, S.; Lindner, M.; Athanassiadis, D.; Kühmaier, M.; Tumajer, J.; Vis, M.; Spinelli, R.; Dees, M.; Prinz, R.; et al. Sustainability impacts of increased forest biomass feedstock supply—A comparative assessment of technological solutions. *Int. J. For. Eng.* **2018**, *29*, 99–116. [CrossRef]
12. Barrett, S.; Aust, W.; Bolding, C. Potential Impacts of Biomass Harvesting on Forest Resource Sustainability. In Proceedings of the 32nd Annual Council on Forest Engineering Meeting, Kings Beach, CA, USA, 15–18 June 2009; p. 6.
13. Westbrook, M.D., Jr.; Greene, D.W.; Izlar, R.L. Utilizing Forest Biomass by adding a Chipper to a Tree-Length Southern Pine Harvesting Operation. *South J. Appl. For.* **2017**, *31*, 165–169. [CrossRef]
14. Hall, J.P. Sustainable production of forest biomass for energy. *For. Chron.* **2007**, *78*, 391–396. [CrossRef]
15. Cambero, C.; Taraneh, S. Assessment and optimization of forest biomass supply chains from economic, social and environmental perspectives—A review of literature. *Renew. Sustain. Energy Rev.* **2014**, *36*, 62–73. [CrossRef]
16. Sutinen, R.; Gustavsson, N.; Hänninen, P.; Middleton, M.; Räisänen, M.L. Impact of mechanical site preparation on soil properties at clear-cut Norway spruce sites on mafic rocks of the Lapland Greenstone Belt. *Soil Tillage Res.* **2019**, *86*, 52–63. [CrossRef]

17. Gan, J.; Smith, C.T. Co-benefits of utilizing logging residues for bioenergy production: The case for East Texas, USA. *Biomass Bioenergy* **2007**, *31*, 623–630. [CrossRef]
18. Wrobel-Tobiszewska, A.; Boersma, M.; Sargison, J.; Adams, P.; Jarick, S. An economic analysis of biochar production using residues from Eucalypt plantations. *Biomass Bioenergy* **2015**, *81*, 177–182. [CrossRef]
19. Ximenes, F.; Ramos, J.; Bi, H.; Cameron, N.; Sigh, B.; Blasi, M. Determining Biomass in Residues Following Harvesting in Pinus Radiata Forests in New South Wales. Australian Government RIRDC Publication No. 11/177. 2012. Available online: https://agrifutures.com.au/product/ (accessed on 5 August 2020).
20. Bérubé, M.A. *Conditions de Terrain Affectant la Qualité du Travail des Scarificateurs*; FPInnovations: Pointe-Claire, QC, Canada, 2011; p. 8.
21. Kizha, A.R.; Han, H.-S. Processing and sorting forest residues: Cost, productivity and managerial impacts. *Biomass Bioenergy* **2016**, *93*, 97–106. [CrossRef]
22. Harrill, H. Costs and Productivity of Woody Biomass Harvesting in Integrated Stand Conversation and Residue Recovery Operations. Master's Thesis, Humboldt State University, Arcata, CA, USA, 2015. Available online: http://humboldt-dspace.calstate.edu/bitstream/handle/2148/600/ThesisFinal.pdf?sequence=1 (accessed on 5 August 2020).
23. Megalos, M.; Parajuli, R.; Lambert, C. NC State Extension—Managing Forests for Biomass Potential. North Carolina State University Extension Publication. 2020. Available online: https://content.ces.ncsu.edu/managing-forests-for-biomass-potential (accessed on 10 August 2020).
24. Miller, D.E.; Straka, T.J.; Stokes, B.J.; Watson, W. Productivity and Cost of Conventional Understory Biomass Harvesting Systems—USFS Miscellaneous Publication. 1987. Available online: https://www.fs.usda.gov/treesearch/pubs/7324 (accessed on 10 August 2020).
25. Cambero, C.; Sowlati, T.; Marinescu, M.; Roser, D. Strategic optimization of forest residues to bioenergy and biofuel supply chain. *Int. J. Energy Res.* **2014**, *39*, 439–452. [CrossRef]
26. Shabani, N.; Akhtari, S.; Sowlati, T. Value chain optimization of forest biomass for bioenergy production: A review. *Renew. Sustain. Energy Rev.* **2013**, *23*, 299–311. [CrossRef]
27. Sharma, B.; Ingalls, R.G.; Jones, C.L.; Khanchi, A. Biomass supply chain design and analysis: Basis, overview, modeling, challenges, and future. *Renew. Sustain. Energy Rev.* **2013**, *24*, 608–627. [CrossRef]
28. Acuna, M. Timber and biomass transport optimization: A review of planning issues, solution techniques and decision support tools. *Croat. J. For. Eng.* **2017**, *38*, 279–290.
29. Berry, M.; Sessions, J. The Economics of Biomass Logistics and Conversion Facility Mobility: An Oregon Case Study. *Appl. Eng. Agric.* **2018**, *34*, 57–72. [CrossRef]
30. Adebayo, A.B.; Han, H.-S.; Johnson, L. Productivity and cost of cut-to-length and whole-tree harvesting in a mixed-conifer stand. *For. Prod. J.* **2007**, *57*, 59–69.
31. Magnus, L.; Ersson, B.T.; Hjältén, J.; Nordfjell, T.; Oliet, J.; Willoughby, I. Site Preparation Techniques for Forest Restoration. In *Restoration of Boreal and Temperate Forests*; CRC Press: Boca Raton, FL, USA, 2016; pp. 85–102.