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# The best forestry money can buy: Efficient contracting for silvicultural expertise (and the limits thereof)

John D. Foppert, [a*] Neal F. Maker, [b]

*a: Institute of Forestry, Paul Smith's College, Paul Smiths, NY, USA.*
*b: Forest Biometrics Research Institute, Portland, OR, USA.*
**Corresponding author: jfoppert@paulsmiths.edu*

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## ABSTRACT

From the typical forest owner's kitchen window, thoughtful silviculture looks no different from lazy silviculture. Thus, a landowner cannot directly compensate a forester based on their evaluation of the quality of the work performed. Is there an incentive contract, reliant only on observable outcomes, that could induce optimal effort from a skillful forester? We frame this contracting question as a bi-level optimization problem in which the forester (Agent) solves an integer programming problem to choose the individual-tree cutting schedule that will maximize her payoff, net of the cost of her effort, given the contract parameters specified by the forest owner (Principal). The forest owner optimizes his choice of those parameters so as to maximize the value of returns generated from the resulting cutting schedule, net of the forester's compensation. We apply this approach to empirical data collected from a hardwood forest in northern Vermont, USA. Harvest schedules differ noticeably between a naïve, costless baseline scenario, a scenario in which only management costs (but not contracting distortions) are accounted for, and the bi-level optimal contracting model. We observe not just a transfer of wealth between the landowner and forester, but a deadweight loss as the maximum feasibly contractable gross value production is less than the first-best level of output.

## INTRODUCTION

Good silviculture is hard to do. Consider a forester marking a thinning in a mixed hardwoods stand. Suppose that within that forester's field of vision there are 20 different trees that she could either mark to cut or leave unmarked and keep in the stand. In that moment, the forester must choose between 1,048,576 different ways to mark that one small group of trees, each of which will put the residual stand on a unique growth trajectory and yield a unique stream of cashflows. Serious time, attention, and cognitive strain must go into trying to find the most valuable, one-in-a-million solution to the particular puzzle those 20 trees present. Then, once found, she takes a few steps forward and confronts the next group of trees, which present a million new options to choose from.

Marking in this way requires a methodical approach, a deep well of experience, and a mandate to work slowly and deliberatively. Is it worth it? Do the gains from a truly expert approach to silviculture justify the cost of hiring a truly expert silviculturalist? Might some simpler alternatives prove to be "good enough" after accounting for the cost savings from hiring a less expert field forester (or no forester at all)? And, even if the juice is worth the squeeze, so to speak, how could a landowner trust that their costly expert is fully exerting herself? From the landowner's kitchen window, judicious, deliberative marking is indistinguishable from casual, careless work that spares the forester all that cognitive strain. Is there a contract that could induce optimal effort from an expert forester, even when that effort is unobservable?

This paper sets out to explore these questions in a rigorous, albeit still illustrative, way. We evaluate the management of a privately-owned northern hardwoods stand in the northeast USA as a case study, using a tree-level simulation-optimization approach across three different scenarios. We model a baseline scenario, specifying an optimal tree-by-tree harvest schedule over a 40-year planning horizon as if the stand were owned by a "hobby forester." That is to say, in this scenario, we assume that the management effort expert silviculture requires—the time and cognitively taxing deliberation—is costless, because the forester enjoys marking timber, as if a hobby. Next, we consider for the same stand a scenario with a "forester-owner" who *does* bear the cost of implementation. Here, we internalize the cost of management effort and endogenize the choice of management intensity, allowing the forester to choose from among several different silvicultural strategies that vary in their level of complexity and in their corresponding cost of implementation.

Finally, we consider the case of the inexpert landowner and his contracted forester. Here, the landowner chooses the contract terms that, in turn, determine the forester's payoff, subject to *observable* outcomes. That is, the landowner cannot pay the forester according to her effort, as this is unobservable in practice, and he cannot pay her conditioned on her actions (i.e., whether or not she made the correct harvesting decision in each case) because he lacks the expertise to judge. Instead, he can only offer some combination of a flat fee and incentive compensation based on *ex post* observable factors, such as the volume or land area harvested, the revenue received, or the value of the standing timber at the end of the management period. The forester then makes the harvesting decisions (including her choice of what level of intensity to exert) so as to maximize her own private payoff (net of the cost of her effort), subject to the contract offered. The landowner's objective is to specify the contract parameters that will maximize his own payoff (net of transfers to the forester), given the privately-maximizing decisions the forester will make in response to that contract.

The intent of this study is neither to predict the real-life behavior of foresters and landowners, nor to prescribe some purportedly ideal contract form through which landowners should procure silvicultural expertise. We hope, instead, to draw attention to some practical dimensions of forest management that have been overlooked by silviculturalists and under-studied by economists—namely, that the costs of silvicultural implementation are non-zero and vary with the complexity of the silviculture, and that Principal-Agent dynamics further complicate the implementation of complex silviculture.

The remainder of this paper is structured as follows: a *Background* section provides a survey of the relevant literature on modeling optimal harvesting strategies and on the economics of "moral hazard" or "hidden action" problems, and it reviews the literature on optimal contracting in forestry; a *Methods* section presents a theoretical model, our approach to numerical simulation-optimization, and details of the case study stand; a *Results* section reports the study's findings; a *Discussion* section offers interpretation and perspective on those results; and a *Conclusion* section brings the paper to a close.

## BACKGROUND

### The tree-cutting problem

The tree-cutting problem has been the object of serious analytical attention since at least the 17$^{th}$ century (Viitala 2013). The problem has traditionally been formulated at the stand scale within the context of identical, infinitely-repeated rotations (Amacher et al. 2009, Mei and Clutter 2023). Given a known biological production function that relates merchantable volume to age, what is the optimal time to end one rotation and begin the next?

Though not a simple problem, the standard solution is now well known. Faustmann (1849) is credited as the first to correctly valuate a series of infinite rotations. Samuelson's (1976) modern treatment of the problem ushered in the so-called "Faustmann revival," inspiring a still-growing body of related literature (Newmann 2002; Kant et al. 2013; McIntosh and Zhang 2024).

The textbook version of the Faustmann approach relies on several simplifying assumptions, including point-input, point-output production in which no intermediate treatments occur between the establishment and harvest of a stand (Amacher et al. 2009). In practice, however, intermediate treatments such as thinning are common in many silvicultural systems (see Matthews 1989). Accounting for thinning significantly complicates the tree-cutting problem. Thinning crowds some revenue forward, but forfeits the future excess returns the harvested growing stock could have earned. Most confoundingly, thinning affects the growth dynamics of the residual growing stock (see Oliver and Larson 1996, pp. 228-234 for a detailed discussion), potentially altering both the value and the timing of the final harvest. While some studies have approached optimal thinning analytically (e.g. Coordes 2014; Halbritter and Deegen 2015), the complexity of the problem typically requires either strongly simplifying assumptions or numerical solution methods. In many ways, the development of modern numerical methods marked an advance in the field as significant as Faustmann's original contribution.

Clark (1976) brought mathematical programming approaches to prominence in the forest economics literature. Getz and Haight (1989), Tahvonen and Salo (1999), and many others built on this approach. Most numerical thinning studies (e.g. Parkatti and Tahvonen 2020) work within a size-class model framework. They describe stand structure by the number of trees per unit area within successive size classes (see Weiskittel et al. 2011, pp. 61-67), and the proportion of growing stock removed from each size class serves as the decision variable.

An alternative approach to analyzing the tree-cutting problem has emerged somewhat recently, shifting analytical attention from the stand or size-class level to the individual-tree level. Early work by Härtl et al. (2010), Meilby and Nord-Larsen (2012), and Pukkala et al. (2015) set the stage for a string of recent studies (Lohmander 2019; Foppert 2019; Frannson et al. 2020; Pascual 2021; West et al. 2021; Koster and Fuchs 2022; Foppert 2022; Pascual and Guerra-Hernández 2022; Foppert and Maker 2024, Niemi et al. 2025). While this literature is still early in its development and many of the authors above have approached the problem differently, these studies all take up the challenge of evaluating harvesting decisions on a tree-by-tree basis. Tree-level optimization results in exponentially more complex problems than stand- or size-class-level approaches, but the added computational costs may be justifiable. Tree-level approaches are useful for analyzing complex stands (e.g., Lohmander 2019; Foppert and Maker 2024, Pukkala et al. 2025) and essential for studies that incorporate within-stand spatial structure into their objective functions (e.g., Bettinger and Tang 2015; Pascual 2021; Dong et al. 2022). Similarly, in heterogeneous-quality stands, where value production is unevenly distributed (as when it is concentrated in a small number of premium-quality stems), tree-level optimization mitigates the aggregation errors that result from modeling decisions at a coarser level of analysis (Foppert 2019). Finally, as we describe in the next subsection, information plays a critical role in many institutional settings. The tree-level approach allows the informational dimensions of thinning-and-harvest decisions to enter into analysis of settings susceptible to adverse selection (Foppert 2022) or moral hazard, as we explore in this study.

### The moral hazard problem

The moral hazard problem belongs to a general class of problems involving asymmetric information. Classical economic models assume that all parties to a transaction enjoy perfect information about the goods or services being exchanged, but this assumption is clearly unrealistic in many real-world situations. Very often, one party has more or better information than the other. Bargaining and exchange under these circumstances often lead to different outcomes than perfect-information price theory would predict (Akerlof 1970).

The archetypal moral hazard (or *hidden action*) problem is set in an insurance context (e.g. Ross 1973), but the framework has obvious relevance in more general management applications. Consider an unmonitored Agent facing the choice between either working hard at a task for which a Principal stands to benefit or withholding that effort. Hard work increases the probability of a large payout but requires costly effort, while shirking reduces the probability of a large payout but requires no effort. The contractual options available to the Principal to induce efficient effort are limited and none are perfect.

If the Principal simply offers a fixed wage, it would be in the Agent's self-interest to shirk, collecting the full wage without having to exert costly effort. Alternatively, the Principal could offer an incentive contract, under which the Agent's payoff depends entirely on the observed outcome. But this provides, at best, only a partial solution. Agents often act on different financial parameters than the Principal (e.g., a shorter planning horizon, higher risk aversion, constrained access to credit), which would tilt an Agent's decisions away from those that best serve the Principal. And in any case, the Agent bears the full cost of her effort but only takes home a portion of the output. The management decisions (including, but not limited to, the choice of how much effort to exert) that are best for the Agent again deviate from those best for the Principal.

Either the fixed wage or the incentive contract could be augmented with increased monitoring by the Principal. He could invest in monitoring the Agent's work effort, rewarding (or punishing) the Agent based on the actions she takes, but only at a cost. As with measuring output, there is a direct cost to monitoring input (i.e., work effort). This monitoring is inherently subject to error, which can have a distortionary effect on incentives (see Ostrom 1990, pp. 10-11 for a resource governance example).

All of these costs can be considered *transaction costs*. Transaction costs include (1) the resources spent by one party in an economic transaction to capture value from the other; (2) the resources spent to safeguard against such unauthorized appropriation; and (3) the deadweight loss resulting from the actions related to those attempts at capture or protection (Allen 1991).

Economists' standard treatment of the moral hazard problem approaches it in a contracting setting (e.g., Salanié 2005, pp. 119-160). The bargaining process is structured as a Stackelberg (or leader-follower) game, where the Principal makes a take-it-or-leave-it contract offer that the Agent accepts or rejects. The Principal chooses the contract terms that maximize his net payoff, subject to a pair of constraints. First, the contract must offer the Agent a payoff that induces her to freely choose the efficient level of effort (the *incentive compatibility constraint*). Second, the expected value of that payoff must exceed the outside option available to her if she were to seek employment elsewhere (the *individual rationality constraint*). In this context, the Principal will offer a contract with an expected transfer just high enough to match the Agent's outside option, and the Agent will exert just enough effort to maximize her own payoff within the terms of that contract, regardless of the Principal's interests or the technically optimal outcome. As the comedian George Carlin quipped, "most people work just hard enough not to get fired and get paid just enough money not to quit."

**Efficient contracting in forestry**

Several studies have examined contracting under asymmetric information in forestry settings, though relatively few explicitly relate these ideas back to the optimal rotation problem. Leffler and Rucker (1991) and later Leffler et al. (2000) applied the property rights approach to an analysis of timber harvesting contracts, and Wang and van Kooten (2001) analyzed planting, weeding, and cleaning, and other precommercial silvicultural interventions. Vedel et al. (2006) examined government consulting contracts for the provision of forest advisory services. Mason and Plantinga (2013) explored optimal contracting for forest carbon offsets, and Fenichel et al. (2019), Sun et al. (2022), and Li et al. (2022) examined efficient contract design in various payment-for-ecosystem-services or afforestation schemes.

Optimal forestry contracting studies that integrate thinning, rotation, or tree-cutting decisions are limited. Tatoutchoup (2015) developed an adverse selection model to characterize efficient royalty contracts when the harvesting firm has exclusive knowledge of their harvesting costs. Tatoutchoup's (2015) analysis accounted for adjustments in harvesting decisions by the license holder as the contract parameters change. Tatoutchoup and Njiki (2018) extended this analysis to a more complex setting with interdependent harvesting costs. Though not a contracting problem, *per se*, Deegen (2016) modeled public versus private forest ownership as a public choice problem under asymmetric information in which the forester's private cost of work effort plays a decisive role. Jensen et al. (2022) developed a single-rotation model to explore a situation where a regulator offers a landowner with different amenity preferences and asymmetric information a contract scheme to increase rotation age.

Our study extends this literature by more explicitly modeling forester and landowner choice environments and bringing more complex simulation methods to bear on the problem. This approach allows us to analyze tree-level harvesting decisions in a heterogeneous stand where a landowner's information disadvantage is especially acute and where the payoff from costly silvicultural expertise is especially high.

## METHODS

We develop a model of optimal contracting in three stages. We begin with a baseline scenario, abstracted from any implementation costs or contracting dilemmas. We then develop a scenario that accounts for the cost of management effort, which varies across a set of silvicultural strategies. Finally, we expand the model further to capture the dynamics of optimal contracting in a Principal-Agent context, where the forester economizes on her choice of management effort, subject to the contract terms the landowner offers. We situate each of these scenarios in the same case study stand, a privately owned forest in Vermont, USA. These forests are dominated by northern hardwoods such as sugar maple (*Acer saccharum*), yellow birch (*Betula alleghaniensis*), and American beech (*Fagus grandifolia*). As is typical in that region, the silviculture we depict is irregular rather than uniform and involves partial harvesting with tending of intermediate growing stock or establishment of regeneration in small group openings. Natural regeneration is used exclusively. Standing timber is sold directly to a logging contractor, and markets exist for all products from firewood/pulp, various assortments of industrial roundwood (pallet, mat, tie, and flooring logs), grade sawlogs, and premium quality veneer.

For analytical purposes, we abstract from all non-timber costs (e.g., taxes, road and boundary maintenance) and income (e.g., recreational leases, maple syrup production, carbon offsets) or non-market amenities. We assume that no other outside parties are involved in management other than the forester, landowner, and logger, and that there is no regulatory nexus constraining management. Unrealistically, we assume that prices (or price functions) and costs (or cost functions), including the cost of capital, are known and constant across the 40-year horizon we evaluate. In practice, these components vary over time, but those dynamics are beyond the scope of this study.

We do allow timber quality to vary between individual stems (and even between individual bole sections within stems), but we assume that in each case quality is known and invariant over time. Note that invariant quality does not imply invariant product grades or unit prices; these factors *do* vary over time as a function of tree size. We assume that stand dynamics can be perfectly predicted, subject to the silvicultural decisions the forester dictates. The growth, mortality, and regeneration functions we use for modeling are all fully deterministic. We provide further explanation of our approach to numerical simulation in a subsequent subsection and in more detail in Maker and Foppert (2023) and Foppert and Maker (2024); we present additional details on the modeling for each scenario in the following three subsections.

**Benchmark harvest optimization**

The benchmark optimal harvesting scenario can be conceptualized as a "pure" application of silviculture, abstracting away from any implementation costs or Principal-Agent distortions. What is the exact, tree-by-tree schedule of harvesting that maximizes the present value of gross timber sale revenue? Which is as if to ask: how would an expert hobby-forester—who owns her own woodlot and for whom time spent marking trees for harvest entails no cost—choose which trees to cut and which to keep? We have argued elsewhere (Foppert 2019; Foppert and Maker 2024) that this problem is best approached at the neighborhood level of analysis (Canham and Uriarte 2006) and that the gap model framework from forest ecology (e.g., Botkin et al. 1972; Shugart and West 1980; Bugmann 2001) is especially well suited for optimization applications such as these. This framework models individual-tree growth and mortality subject to within-neighborhood competitive interactions but abstracts from any between-neighborhood dynamics. The gap model framework does not require spatially explicit tree location data but nonetheless accounts for the influence of structural heterogeneity within stands. For economic applications, neighborhoods can be modeled independently, substantially reducing the dimensionality of tree-level optimization problems without unduly forfeiting ecological realism.

Consider a neighborhood comprised of trees $i \in \{1, \dots, n\}$ at time $t = 0$. In any period $t$ each tree can be described by an index of physiological attributes, $z_{it}$, such as species, height, diameter at breast height, crown length and width, etc. Let $f_{it}(z_{it})$ denote merchantable volume of tree $i$ as a function of those attributes.

Let $k_{it}$ denote the competitive environment tree $i$ resides in from period $t$ to $t+1$, where $k_{it} = k_{it}(z_{it}, G_t)$ is a function of the attributes of tree $i$ and of neighborhood-level composition and structure, $G_t = G_t(z_{1t}, \ldots, z_{nt})$. The attributes of tree $i$ evolve from period $t$ to $t+1$ according to $\Delta z_{it}(k_{it})$, such that $\Delta f_{it} = f_{i,t+1} - f_{it}$. The equations above thus describe a dynamical system, in which the evolution of the system is determined by processes controlled by the initial state of the system.

Let $v_{it}$ denote the potential gross harvest revenue of tree $i$ at time $t$, such that $v_{it} = v_{it}(f_{it}; Q_i)$ where $Q_i$ denotes the timber quality class of tree $i$ and specifies the coefficients for the function that relates unit price, $p_{it}$, to tree volume, where $p_{it} = p_{it}(f_{it}; Q_i)$. Note that $Q_i$ is a fixed parameter of tree $i$. Foppert (2022) provides additional explanation of the approach to modeling price functions. The total potential gross harvest revenue of an individual tree is therefore given by $v_{it} = p_{it} \cdot f_{it}$.

Let $c_{it}$ denote the potential cost of harvesting tree $i$ at time $t$. Assume harvesting cost is strictly a function of tree size, such that $c_{it} = c_{it}(f_{it})$. Stumpage value (i.e. net revenue) is the difference between $v_{it}$ and $c_{it}$, provided tree $i$ is actually harvested in period $t$.

The economic dimension of the individual-tree harvesting problem entails the choice, in each period $t \in \{t_0, t_1, \ldots, T\}, T \in [t_0, \infty)$, of which trees to harvest and which to retain, and the valuation of the resulting cash flows. Let the binary variable $\chi_{it}$ denote that tree $i$ is harvested in period $t$ when $\chi_{it} = 1$. An $n$-dimensional neighborhood-level harvest vector, $\boldsymbol{h}$, specifies the timing of harvest for every individual tree $i$ such that $\boldsymbol{h} = \{h_1, h_2, \ldots, h_n\}, h_i \in \{0, 1, \ldots, T\}$. Define $\chi_{it}$ as $\chi_{it} = 1$ for $t = h_i$ and $\chi_{it} = 0 \; \forall \, t \neq h_i$ and modify $G_t$ to account for changes in neighborhood structure resulting from harvesting, $G_t = G_t(z_{1t}, \ldots, z_{nt}; \boldsymbol{h})$.

Realized stumpage, $s_{it}$, is given by $s_{it}(\boldsymbol{h}) = \chi_{it}(v_{it} - c_{it})$. Note the harvest vector, $\boldsymbol{h}$, controls $\chi_{it}$ directly and determines gross value, $v_{i\tau}$, and harvesting cost, $c_{i\tau}$, indirectly through their dependence on tree volume, $f_{i\tau}$, as controlled by $\Delta f_{it}$ for all periods $t < \tau$, which is determined by the competitive environment, $k_{it}$, resulting ultimately from neighborhood structure contingent on harvest and retention decisions, $G_t(\boldsymbol{h})$.

The expected present value at time $t = 0$ of realized stumpage from harvesting tree $i$ at time $t = h_i$ is given by $u_i = s_{it}(1 + r)^{-t}$, where $r$ is the exogenously specified per-period discount rate. Let $U$ denote the aggregated neighborhood-level present value, $U = \sum_{i=1}^{n} u_i$.

By assumption, the neighborhood regenerates naturally following the harvest of the last mature tree. Natural regeneration is a stochastic process, so the structure and composition of the regenerated cohort will not necessarily replicate that of the initial neighborhood. Here, to restrict attention to the setup and solution of the basic optimal harvesting problem, we assume the capitalized value of future cashflows from a regenerated area ($LEV$, or land expectation value) is a fixed value specified exogenously. The silvicultural optimization problem can therefore be stated as an integer programming problem:

$$\max_{\boldsymbol{h}} \left[ U(\boldsymbol{h}) + \frac{LEV}{(1 + r)^{T(\boldsymbol{h})}} \right] \quad \text{Eq. 1}$$

s.t.

$$\boldsymbol{h} \in \{0, 1, 2 \dots\} \quad \text{Eq. 2}$$

$$T(\boldsymbol{h}) = max\{h_1, h_2, \dots, h_n\} \quad \text{Eq. 3}$$

A closed-form analytical solution to the objective function above would require strong concavity assumptions on the production function. Even then, problems involving more than a few trees and a few timesteps quickly become unmanageable. Numerical simulation and heuristic optimization methods provide a feasible alternative. Independently optimizing neighborhood-scale harvest schedules across the multiple neighborhoods that comprise a stand—regardless of the resulting spatial or demographic structure—represents a model of optimized irregular silviculture.

### Optimal harvesting with costly management effort

Costly management effort adds an important dimension to the baseline harvesting problem. Management effort has traditionally been incorporated into a multivariate production function alongside rotation age (Chang 1983; Amacher et al. 2009). In the standard formulation, the partial and cross-partial derivatives across age and management effort are “well behaved” (i.e., marginal physical products are positive and decreasing over the relevant ranges of age and effort). Management effort is typically conceptualized as silvicultural intensity and operationalized through production variables such as initial planting density or fertilization. The further one moves from the simplified production context of plantation silviculture, however, the less useful such approaches become. In a complex, natural forest, in which multiple species are present and individual trees vary widely in their quality and vigor, management effort is less a matter of silvicultural *intensity*, measured in terms of costly physical inputs, and more a matter of silvicultural *sophistication*, corresponding to the extent of an expert forester's costly deliberation. Management effort, in this context, is a composite of the forester's diagnostic skill, prescriptive vision, and talent for aligning silvicultural opportunities within operational constraints, and of the time and cognitive effort she exerts in deploying those faculties.

Operationalizing this conception of management intensity presents distinct challenges. To motivate our modeling approach, we begin with the example of a forest owner capable of expertly managing her own property (thus sidestepping, for the time, the Principal-Agent issues we take up in the next subsection), but who *is* sensitive to management costs (unlike the hobby-forester invoked in the benchmark case). The forester-owner is capable of evaluating the exact structure of each neighborhood she comes to and of specifying the optimal selection of harvest and retention among the trees initially present. All of which, of course, requires time and effort. Alternatively, she could prescribe silvicultural treatments (i.e., *patterns* of cutting) delegatable to less expert silviculturalists (Dickinson and Cadry 2017; Foppert et al. 2025). We consider four potential categories of lower-effort treatments: no action, clearcutting, high grading, and worst-first thinning.

The easiest of these is to simply prescribe no action, retaining every tree and allowing the neighborhood's natural development to continue. Clearcutting decisions are also easily delegated, in that the intended action is unambiguous and is *ex post* verifiable at a glance. This treatment nevertheless requires more effort than taking no action at all, in that the harvesting contractor's actions must still be monitored and managed along non-silvicultural margins (e.g., operational considerations such as protecting water quality).

Between clearcutting and fully-optimized individual-tree silviculture lies a set of easier-to-implement heuristic treatments that would require less effort from the expert forester or that she could subcontract to a less-expert forester—what might be thought of as "sending out an intern". Much of the effort required in designating individual trees can be avoided if the treatment is incentive compatible with the logging contractor's own cutting preference. High grading, or "creaming," is when trees are removed in descending order of their current value without regard to the impact on long-term value production (Foppert 2022; Dhungel et al. 2024). From the logger's perspective, high-grading is the efficient choice of cutting pattern for timber purchased via a lump sum contract without silvicultural restrictions (Leffler and Rucker 1991). A forester can moderate the intensity of high-grading by establishing a target level of stocking for the residual (post-harvest) stand or neighborhood. Verbal instructions to the logger can be as simple as a target level of basal area and permission to reach that target by selecting trees at their discretion. If a forester were to mark a high-grade harvest, the technical and analytical effort required would be minimal: simply identifying the most valuable trees and assessing whether stocking is within its target range. Monitoring *ex post* compliance is straightforward as well because the relevant attribute (stocking) is easily observable.

With additional effort, the high-grading approach can be modified into a more sophisticated strategy, more productive of gross value. A forester again specifies a target level (or range) of residual stocking, but, unlike high grading, that target is reached by removing trees in *ascending* order of *potential* value (corresponding, in the previous subsection's notation, to $Q_i$). Such "worst-first" harvesting is no longer incentive compatible for the logger, who—if not by contract, then at least by instinct—would prefer to cut high-quality trees instead of low-quality ones. Thus, the forester must actively select individual trees for harvest and then bear higher *ex post* monitoring costs to ensure that only designated trees are removed. Worst-first harvesting is, however, what we will refer to as "intern-implementable," in that its decision criteria depend only on observable current conditions, rather than requiring accurate projections of complex and conditional future growth processes. Even if the task is not literally delegated to an intern, the expert forester could implement it in less time and with less cognitive effort than the fully-optimized treatment would require. Because the worst-first and fully-optimized treatment strategies both explicitly designate which trees to harvest and which to retain, *ex post* monitoring is similarly costly for both approaches.

To summarize, a hierarchy of silvicultural effort exists, as illustrated in Table 1. The costs of *ex ante* and *ex post* effort vary among treatment strategies and are strictly ordered, though the gains from implementing increasingly sophisticated treatments are not always similarly ordered. Sometimes, no action is the best action. Similarly, it can be the case that the fully-optimized prescription overlaps perfectly or nearly perfectly with either clearcutting or the worst-first heuristic. In such cases, there is no payoff from the added expense of sending in the expert forester to mark every tree, versus telling the intern how to mark it or just pointing the logger in the right direction. And even where the cutting decisions from these more cheaply implemented strategies diverge from those that maximize gross value production, the savings from lower management costs may outweigh the losses from cruder silviculture.

*Table 1. Comparison of timing and cost of effort across silvicultural treatments.*

| Treatment | *Ex ante* effort | *Ex post* effort |
|---|---|---|
| No action | 0 | 0 |
| Clearcut | 0 | + |
| High grade | + | ++ |
| Worst-first | ++ | +++ |
| Optimized | +++ | +++ |

Conceptually, the simplest approach to operationalizing this effort-cost schema would be to impose a uniform-treatment constraint. That would be to say, the forester chooses which implementation strategy to follow and that choice binds on the tree-selection decision for every neighborhood in the stand. This would reflect the case where the forester literally delegates the task of choosing trees to a third party (i.e., the logger or an intern). Such a scenario could be set up as a bi-level optimization problem and solved along similar lines as Tahvonen and Rämö (2016). There are three shortcomings to this approach. First, the Principal-Agent problem motivating this paper depends on the Principal's inability to monitor the agent. Uniform, stand-wide treatments, such as no action, clearcutting, or even to some extent the high grading and worst-first treatments, would provide an easily discernable signal to the landowner that the forester was not exerting a high level of effort.

Second, the question of optimal contracting over a rugged solution space is interesting at the margins, but the implementation of uniform, categorical treatment strategies would overwhelm most marginal variations. Thus, even if *delegatability* proves useful for conceptualizing management effort in this context, here we operationalize the cost of management effort as largely a function of time and attention. We envision the expert forester actually heading out into the woods, deciding neighborhood by neighborhood whether to work or to shirk, rather than making a call from the office whether or not to go out into the woods at all. The cost structure presented in Table 1, and much of the narrative logic developed to justify that cost structure, holds just as well when decisions are made within stands and the forester directly bears the costs of her deliberativeness as when decisions are made about stands and the forester (possibly) delegates the field work to a subordinate.

Finally, from a practical perspective, adding a third level to the optimization problem significantly complicates the search process without adding insight into the contracting dynamics. The computational costs might be justifiable if the phenomenon of interest mostly operated at a spatial level higher than the stand scale (i.e., ownership-scale, landscape-scale, etc.). For example, it might be informative to evaluate silvicultural implementation strategies in conjunction with ownership-level harvest scheduling models that accounted for fixed costs, capacity constraints, or fiber-supply commitments (e.g. Paradis et al. 2018). These are not the questions we choose to examine. The model we develop here operates at a different (and, we contend, more interesting) level where more is gained by freeing the agent to vary effort on the fly.

The objective function from the frictionless baseline model can be modified to account for the forester's effort without restructuring the overall model. Let $w_t = w_t(\boldsymbol{h})$ denote the forester's internal cost of management effort at a given time $t$, which the forester bears in full but is unobservable from the outside. The private cost of effort is a function of the forester's choice of silvicultural strategy, as revealed through the specified harvest vector, $\boldsymbol{h}$, where $w_t \in \{w^0,\ w^\forall, w^+, w^-, w^*\}$ and the elements of this set are defined below. Let $W$ denote the capitalized cost of management effort, where

$$W = W(\boldsymbol{h}) = \sum_{t=0}^{T} \frac{w_t(\boldsymbol{h})}{(1+r)^t} \qquad \text{Eq. 4}$$

The forester's effort-inclusive objective function can thus be written as

$$\max_{\boldsymbol{h}} \left[ U(\boldsymbol{h}) + \frac{LEV}{(1+r)^{T(\boldsymbol{h})}} - W(\boldsymbol{h}) \right] \qquad \text{Eq. 5}$$

s.t.

$$\boldsymbol{h} \in \{0, 1, 2 \dots\} \qquad \text{Eq. 6}$$

$$T(\boldsymbol{h}) = max\{h_1, h_2, \dots, h_n\} \qquad \text{Eq. 7}$$

where $U(\boldsymbol{h})$ is the sum of discounted stumpage revenue from every harvested tree, as in Eq. 1.

The elements in the management effort cost set correspond to the five different silvicultural treatment strategies outlined above. The no action strategy, $w^0$, entails retaining every tree in the initial neighborhood in time $t$, such that $w_t = w^0$ if $\chi_{it} = 0 \; \forall \, i$. Inversely, the clearcut strategy, $w^\forall$, entails removing every tree standing at the start of time $t$, such that $w_t = w^\forall$ if $\max \, h_i = t$.

The high grading and worst-first strategies each entail harvesting that results in residual plot-level basal area as close as possible to a target level, $BA^*$, subject to the strategy-specific criteria that dictate the order of removal of trees from the plot. In the case of high grading, trees are removed in descending order, starting from the highest valued tree, stopping once removal of the next tree would have increased the difference between the residual basal area and the target.

Formally high grading is defined as $w_t = w^+$ if $\min v_{h_i=t} > \max v_{h_i \neq t}$ and $|BA_t - BA^*| < |BA_t - ba_{i+1,t} - BA^*|$ and $|BA_t - BA^*| < |BA_t - ba_{i-1,t} - BA^*|$, where $BA_t$ denotes the stocking (basal area) at time $t$, $BA^*$ denotes target stocking, $ba_{i,t}$ denotes individual-tree basal area, and trees are ordered by current value, such that $v_1 > v_2 > \cdots > v_{i-1} > v_i > v_{i+1} \dots > v_n$ in time $t$.

The cost of implementing a worst-first harvest, $w^-$, is structured similarly. Here, $w_t = w^-$ if $\min Q_{h_i>t} > \max Q_{h_i=t}$, $|BA_t - BA^*| < |BA_t - ba_{i+1,t} - BA^*|$, and $|BA_t - BA^*| < |BA_t - ba_{i-1,t} - BA^*|$ when trees are ordered by $Q_1 < Q_2 < \cdots < Q_{i-1} < Q_i < Q_{i+1} < \cdots < Q_n$.

Optimizing the harvest vector, $\boldsymbol{h}$, in the costly management effort scenario proceeds exactly as in the baseline scenario. Aside from adjusting the forester's objective function, as described above, no further modifications to the model or the optimization procedure are required.

**Efficient contracting**

Introducing contract choice to the optimal harvesting problem changes the structure of the problem substantially. The forester is no longer the full residual claimant, so her payoff function depends on the parameters of the management contract. Consider the following five contractual devices, the first four of which issue regular (per management period) compensation, and the last of which provides exit compensation at the close of the contract. Let $\theta$ denote a fixed payment per unit area managed, independent of cutting decisions (i.e. a salary); let $\gamma$ denote a contingent payment per unit volume harvested; let $\rho$ denote a contingent payment per unit area harvested; let $\lambda$ denote a contingent payment as a percent of timber sale revenue generated (i.e. a sale commission); and let $\phi$ denote a contingent payment as a percent of standing timber value (or "current timber value," $CTV$) at the end of the last management period within the contract horizon. The forester's objective function thus becomes

$$\max_{\boldsymbol{h}} \pi^A = \sum_{t=0}^{T} \frac{\left[\sum_{i=1}^{n} \chi_{it}(\gamma f_i + \lambda v_i)\right] + \theta + \rho X_t - w_t}{(1+r^A)^t} + \frac{\phi \sum_{i=1}^{n} \prod_{t=1}^{T}(1-\chi_{it})\,(v_{iT} - c_{iT})}{(1+r^A)^T} \qquad \text{Eq. 8}$$

where $X_t$ denotes the occurrence of harvest in period $t$, $\mathrm{X}_t = \begin{Bmatrix} 1 & if & \sum \chi_{it} \geq 1 \\ 0 & if & \sum \chi_{it} = 0 \end{Bmatrix}$, and $r^A$ denotes the forester's (i.e. Agent's) discount rate.

The forest owner's objective function is given by

$$\max_{\theta\,\rho\,\lambda\,\gamma\,\phi} \pi^P = \sum_{t=0}^{T} \frac{\sum_{i=1}^{n} \chi_{it}\big((1-\lambda)v_i - \gamma f_i\big) - (\theta + \rho X_t)}{(1+r^P)^t} + \frac{(1-\phi)\sum_{i=1}^{n} \prod_{t=1}^{T}(1-\chi_{it})\,(v_{iT} - c_{iT}) + LEV}{(1+r^P)^T} \qquad \text{Eq. 9}$$

s.t.

$$\chi_{it} = \chi_{it}(\boldsymbol{h}^*)\ , \qquad \boldsymbol{h}^* = \operatorname{argmax} \pi^A \qquad \text{Eq. 10}$$

$$\pi^A(\boldsymbol{h}^*) \geq \omega \qquad \text{Eq. 11}$$

where $\omega$ denotes the forester's reservation payoff, such that the constraints on the forest owner's objective function correspond to the standard incentive compatibility (IC) and individual rationality (IR) constraints. Note that the landowner's discount rate, $r^P$, differs from the forester's and, by assumption, $r^P < r^A$, reflecting not divergent risk preferences but the Principal's presumed diversified portfolio position relative to the Agent's presumed overexposure to the idiosyncratic (i.e. diversifiable) risks of the specific forest asset.

**Numerical solution methods**

We modeled a stand represented by four plots drawn from a system of permanent monitoring plots on a private forest in central Vermont. The 7.32 m radius fixed-area plots (0.02 ha) follow the design of US Forest Service Forest Inventory and Analysis (FIA) subplots (Woudenberg et al. 2010). Plots were inventoried in the summer of 2022, with the following attributes recorded for each tree larger than 14 cm: species, $DBH$ (diameter at breast heigh, measured in inches, converted to centimeters), height (measured in feet, converted to meters), $CR$ (live crown ratio, estimated to the nearest 10%-class), and quality assessments for each potentially-merchantable 2.5 m bole section. Consistent with the methods described in Demchik et al. (2018), quality scores corresponded to the highest product class a log could potentially attain (pulp, pallet, sawlog or veneer) evaluated irrespective of current diameter.

We simulated growth and mortality over 5-year timesteps using the nonlinear least squares models of mortality and of $DBH$-, $CR$-, and height-increment, described in Maker and Foppert (2023). Opportunities to harvest occurred at four discrete times, $t = 0$, 10, 20, and 30. Following the Year 30 harvest, any residual growing stock was grown forward until time $t = 40$, at which point the residual inventory was valuated (on the basis of $CTV$), any exit compensation was awarded, and the contract was closed. Stumpage prices were assigned according to the relative price functions, references price list, and harvest and transport cost functions described in Foppert and Maker (2024). Volume- or area-based prices, costs, and contract payoffs used local measurement units, such as cords (roughly equivalent to 2.5 m$^3$) and acres (2.471 ha).

We assigned a cost (US$) per 0.02-ha plot of $w^0 = 0$ for no removal and $w^\forall = 1.75$ for clearcutting. The per-plot cost of implementing high grading varied as a function of the number of trees harvested: marking a high grade is not hard, but the more trees there are, the longer it takes. We specified the implementation cost function for high grading as $w_t^+ = 0.70 + 1 \cdot \sum \chi_t$. We generalized target stocking for our northern hardwoods application from Leak et al. (2014) as $BA^* = 15$ m$^2$/ha.

To operationalize the quality ranking in the worst-first algorithm, we defined $Q_i = q_{i1} + 0.25q_{i2} + SG_i$, where $q_{i1}$ and $q_{i2}$ denoted the individual-bolt quality score of the first and second bolt (2.5-m log section) of a given tree, $q_{ib} \in \{1, 2, 3, 4\}$, corresponding to pulp-, pallet-, sawlog-, and veneer-potential logs, respectively; $SG$ is a constant assigned by species group, corresponding to the relative preference for some species groups over others, $SG \in [0,2]$ with high $SG$ values corresponding to high species desirability. $Q_i$ is thus weighted to reflect the disproportionate importance of the first bolt and to discriminate against undesirable species. We specified $w_t^- = 0.70 + 1.5 \cdot \sum \chi_t$, so that implementation of the worst-first strategy entails the same per-plot fixed cost as high grading but higher per-tree variable costs.

Finally, the fully-optimized treatment strategy is the default management effort cost function: $w_t^* = 3.5 + 2 \cdot \sum \chi_t$. In the simulation environment, unless the pattern of tree selection for a given plot and a given timestep conformed to one of the strategies described above, the forester was assumed to have exerted maximum effort and $w_t^*$ was applied. We specified the forester's discount rate, $r^A$, as 6% and the landowner's discount rate, $r^P$, as 3%. We assigned a value of 0 for the forester's reservation payoff, $\omega$, reflecting a competitive market for forestry services.

We first modeled optimal thinning-and-harvest decisions under the benchmark and costly-management scenarios. We then modeled the moral hazard scenario, in which trees were selected for removal by an unmonitored Agent, subject to the contract the Principal offers. This scenario was evaluated as a bi-level optimization problem, with the specification of contract parameters as the top-level problem and the choice of harvest vector, $\boldsymbol{h}$, as the bottom-level problem.

For all scenarios, we used the **rgenoud** package for R (Mebane and Sekhon 2011) to optimize $\boldsymbol{h}$. The **rgenoud** software package employs a genetic algorithm and, where appropriate, combines it with a derivative-based (quasi-Newton) method (Mebane and Sekhon 2011). The genetic algorithm is an evolutionary search algorithm that accommodates local maxima and discontinuities in the solution space and can thus handle problems characterized by complex production functions and integer decision variables. However, the genetic algorithm is relatively ineffective at hill climbing and is computationally inefficient. The derivative-based method solves local hill climbing tasks effectively and is relatively parsimonious, but it is poorly suited for handling irregularities and may fail to discover a global optimum. Combining these approaches, **rgenoud** assumes that the solution space is globally irregular but locally regular and uses evolutionary approaches generally with a derivative-based approach applied locally to the best solution in each generation (Mebane and Sekhon 2011). Both methods are employed in solving the top-level (continuous variable) problem.

## RESULTS

The benchmark harvest optimization scenario generated $NPV$ of \$5,085/ha at the 3% discount rate. The observed cutting pattern illustrates the complexity of precision hardwood silviculture (Table 2). In general, the highest quality, most vigorous stems were favored for retention. Four out of five veneer-quality stems were retained through exit. The one veneer tree selected for removal had low vigor ($CR$=20%) and was competing with two other veneer-quality trees. Many, but not all, low-value species and poor-quality stems were removed in the initial entry. For trees with pallet- or pulp-quality butt logs, removal rates in the first entry were 60% and 75%, respectively. All remaining pallet trees and all but one pulp tree were removed in the second or third entry. Retention and removal decisions on sawtimber-quality trees were more varied but generally reflected a pattern of retention up to approximately 40 cm $DBH$.

Residual stocking was generally lower than conventional management recommendations. Stand-level residual basal area ranged from 8.9 to 12.5 $m^2$/ha, compared to "B-line" stocking of around 15 $m^2$/ha for northern hardwoods (Leak et al. 2014). Plot-level residual stocking was naturally more variable, ranging from 6.2 to 16.2 $m^2$/ha. Lower stocking also resulted in less gross production than a fully stocked stand could produce: annual basal area increment varied from 0.21 to 0.25 $m^2$/ha/yr, approximately half of the production potential expected locally on a good hardwood site. Thus, the baseline optimization revealed a clear strategy of favoring the individual growth of the best stems even at the cost of lower stand-level production.

*Table 2: Initial plot composition and current timber value (CTV) by year; bold CTV values indicate realized value from harvest or exit valuation; species codes: BE = American beech, BF = balsam fir, PB = paper birch, SM = sugar maple, YB = yellow birch, WA = white ash; quality score indicates the assessed maximum potential product class of each of the first three 2.5 m log sections: 1 = veneer (4 clear faces [cf]), 2 = sawtimber (1-3 cf), 3 = pallet (0 cf, straight, sound), 4 = pulp (defective).*

| Plot # | Species | DBH (cm) | CR (%) | Quality score | CTV, by year ($/tr) 0 | 10 | 20 | 30 | 40 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | BF | 25 | 30 | 4-3-4 | **$0.13** | - | - | - | - |
| | SM | 38 | 30 | 2-2-2 | $37.55 | **$60.68** | - | - | - |
| | SM | 25 | 30 | 1-1-2 | $3.93 | $7.16 | $14.59 | $28.19 | **$50.19** |
| | SM | 14 | 20 | 1-1-3 | **$0.16** | - | - | - | - |
| | SM | 22 | 40 | 1-2-3 | $2.22 | $4.02 | $7.99 | $14.65 | **$24.93** |
| 2 | PB | 32 | 30 | 2-2-2 | $4.22 | $7.71 | **$13.09** | - | - |
| | SM | 17 | 40 | 2-2-3 | $0.43 | $1.00 | $1.97 | $4.00 | **$7.61** |
| | SM | 53 | 40 | 3-4-3 | **$34.02** | - | - | - | - |
| | SM | 16 | 50 | 4-2-3 | $0.30 | $0.76 | $1.48 | $2.84 | **$4.86** |
| | SM | 52 | 40 | 2-2-3 | **$109.16** | - | - | - | - |
| | SM | 21 | 30 | 2-2-3 | $1.40 | $2.90 | $5.52 | $11.27 | **$21.13** |
| | YB | 33 | 30 | 3-4-3 | **$2.46** | - | - | - | - |
| 3 | SM | 29 | 50 | 3-4-3 | $6.47 | **$9.16** | - | - | - |
| | WA | 15 | 50 | 2-2-3 | $0.67 | $1.61 | $3.14 | $5.26 | **$7.98** |
| | BE | 19 | 90 | 2-4-4 | $1.20 | $2.30 | $3.88 | $5.90 | **$8.51** |
| | WA | 34 | 30 | 1-2-2 | $22.46 | $39.31 | $64.48 | $98.43 | **$138.35** |
| 4 | BE | 18 | 60 | 4-4-4 | **$0.25** | - | - | - | - |
| | SM | 30 | 30 | 1-2-2 | $12.04 | $21.79 | $36.65 | $64.74 | **$99.95** |
| | SM | 26 | 20 | 3-2-4 | **$3.52** | - | - | - | - |
| | SM | 24 | 10 | 4-4-4 | **$1.06** | - | - | - | - |
| | SM | 35 | 20 | 3-2-2 | $13.56 | $23.55 | **$37.21** | - | - |

Effort and agency costs significantly affected the patterns of cutting and the resulting output. For the costly effort scenario, the gross capitalized value of harvest revenues and terminal inventory decreased to $4,883/ha, and the owner-forester bore $135/ha in capitalized costs of effort (also discounted at 3%; $188/ha undiscounted), for a net present value of $4,748/ha.

For the efficient contracting scenario, optimal contract parameters were specified as follows: $\gamma$ = 0.988114; $\lambda$ = 0.05122812; $\rho$ = 42.01945; $\theta$ = 0; $\phi$ = 0.1669698. That is to say, the optimal incentive contract offered the forester approximately $0.99 per cord harvested, 5.1% of all harvest revenue, $42 per acre ($103/ha) harvested, and 16.7% of $CTV$ at exit. The gross value of harvest revenue and terminal inventory, discounted at the landowner's rate of 3%, was $4,616/ha. Of that capitalized value, the landowner transferred 13% ($603/ha) to the forester, leaving a net value for the landowner of $4,013/ha. Applying the forester's discount rate of 6% to those transfer payments, the present value of the forester's compensation was $335/ha and she bore $56/ha in capitalized costs of silvicultural effort. The undiscounted cost of effort was $126/ha, 33% less total effort than when agency costs were unaccounted for. Table 3 summarizes the cashflows resulting from the efficient contracting scenario.

*Table 3. Modeled harvest revenue (or Year 40 CTV), incentive compensation transfers, and silvicultural effort cost schedules under efficient contracting.*

| Year | Gross revenue | Net revenue | Transfer | Effort cost |
|---|---|---|---|---|
| **0** | $2,260 | $2,085 | $175 | $22 |
| **10** | $333 | $285 | $48 | $23 |
| **20** | $19 | -$37 | $56 | $51 |
| **30** | $41 | $10 | $31 | $29 |
| **40** | $6,786 | $5,653 | $1,133 | $0 |
| ***NPV (r = 3%):*** | ***$4,616*** | ***$4,013*** | ***$603*** | ***$80*** |
| | | ***NPV (r = 6%):*** | ***$335*** | ***$56*** |

Each scenario provided 16 opportunities for plot-level treatments. A set of five treatments was implemented under costly effort, and a different set of five treatments was implemented under the efficient contract, compared to seven treatments in the benchmark scenario (Table 4). Costly effort treatments consisted of three high-grade harvests, one worst-first harvest, and one optimized harvest. Under the efficient contract, treatments were one clearcut, one high-grade, three worst-first, and no optimized harvests.

*Table 4. Sequences of treatment types in Years 0 | 10 | 20 | 30, by scenario: no treatment (0), clearcut (∀), high-grade (+), worst-first (-), and optimal harvesting (*).*

| Plot # | Benchmark | Effort cost | Agency cost |
|---|---|---|---|
| **1** | * \| * \| 0 \| 0 | 0 \| 0 \| + \| 0 | 0 \| 0 \| - \| 0 |
| **2** | * \| 0 \| * \| 0 | + \| * \| 0 \| 0 | ∀ \|   \|   \| |
| **3** | 0 \| * \| 0 \| 0 | 0 \| 0 \| - \| 0 | 0 \| 0 \| 0 \| 0 |
| **4** | * \| 0 \| * \| 0 | 0 \| 0 \| + \| 0 | 0 \| + \| - \| - |

Accounting for silvicultural effort changed the harvest decision relative to the benchmark scenario on nine out of 21 trees in the simulation, in each case delaying harvesting or retaining the tree through exit; accounting for agency costs changed the harvest decision on 12 out of 21 trees relative to the benchmark and 11 out of 21 trees compared to the costly effort scenario (Table 5).

*Table 5. Harvest year comparison, by scenario, with treatment types indicated next to harvest years for effort cost and agency cost scenarios; see Table 2 for species codes and quality score criteria and Table 4 for treatment codes.*

| Plot # | Species | DBH (cm) | CR (%) | Quality score | Harvest year and treatment type | | |
|---|---|---|---|---|---|---|---|
| | | | | | Benchmark | Effort cost | Agency cost |
| 1 | BF | 25 | 30 | 4-3-4 | 0* | -- | $20^{-}$ |
| | SM | 38 | 30 | 2-2-2 | 10* | $20^{+}$ | -- |
| | SM | 25 | 30 | 1-1-2 | -- | -- | -- |
| | SM | 14 | 20 | 1-1-3 | 0* | -- | -- |
| | SM | 22 | 40 | 1-2-3 | -- | -- | -- |
| 2 | PB | 32 | 30 | 2-2-2 | 20* | -- | $0^{\forall}$ |
| | SM | 17 | 40 | 2-2-3 | -- | -- | $0^{\forall}$ |
| | SM | 53 | 40 | 3-4-3 | 0* | $0^{+}$ | $0^{\forall}$ |
| | SM | 16 | 50 | 4-2-3 | -- | -- | $0^{\forall}$ |
| | SM | 52 | 40 | 2-2-3 | 0* | $0^{+}$ | $0^{\forall}$ |
| | SM | 21 | 30 | 2-2-3 | -- | -- | $0^{\forall}$ |
| | YB | 33 | 30 | 3-4-3 | 0* | $10^{*}$ | $0^{\forall}$ |
| 3 | SM | 29 | 50 | 3-4-3 | 10* | $20^{-}$ | -- |
| | WA | 15 | 50 | 2-2-3 | -- | -- | -- |
| | BE | 19 | 90 | 2-4-4 | -- | -- | -- |
| | WA | 34 | 30 | 1-2-2 | -- | -- | -- |
| 4 | BE | 18 | 60 | 4-4-4 | 0* | -- | $20^{-}$ |
| | SM | 30 | 30 | 1-2-2 | -- | -- | -- |
| | SM | 26 | 20 | 3-2-4 | 0* | -- | -- |
| | SM | 24 | 10 | 4-4-4 | 0* | -- | $30^{-}$ |
| | SM | 35 | 20 | 3-2-2 | 20* | $20^{+}$ | $10^{+}$ |

## DISCUSSION

Ashton and Kelty (2018) observe that "[t]he most profitable forest type is not necessarily the one with the greatest potential for growth or the one that can be used or harvested at lowest cost. One must also consider the silvicultural costs of growing the crop" (p. 13). Silviculturalists (and economists!) typically limit their consideration of these "silvicultural costs" to the direct costs of production, such as site preparation, planting, pruning, precommercial thinning, and harvesting costs, if they consider them at all. Rarely do they take account of the variable costs of implementation. And never, to our knowledge, has the concept of "silvicultural costs" been extended to include the information-induced transaction costs associated with different silvicultural treatments.

Consider first the direct implementation costs of sophisticated silvicultural treatments. The creative prescriptions contemporary silviculturalists often envision demand correspondingly more time and skill from the forester on the ground to implement. Beyond acknowledging the potentially "higher treatment costs due to [their] more complex prescriptions" (Palik et al. 2021, p. 17), silviculturalists rarely evaluate (much less optimize) the costs and benefits of such complexity. For their part, forest economists have generally been unhelpful in this setting, as well. The practical examples of management intensity economists analyze are almost always physical inputs or interventions such as increased planting density, improved genetics, or fertilization (e.g. Chang 1983; Nautiyal and Williams 1990; Amacher et al. 1991; Halbritter and Deegen 2015). In the accompanying abstract models, management effort enters into the production function. It is taken for granted that the forester can then costlessly optimize production decisions. This approach maps awkwardly onto the notion of costly silvicultural sophistication pertinent to quality hardwood management.

In our model, effort does not enter directly into the production function but operates instead through the forester's "decision technology". We represented management effort as a discrete choice between different modes of silvicultural decision making, from crude, uniform treatments to relatively cheaply implementable heuristics to complex, optimized tree-by-tree selection. Optimization is feasible, but not free. Only in the most general sense can landowners or foresters "undertake (costly) actions that improve the growth conditions of their stands," as Amacher et al. (2009, p. 34) describe management effort. In our setup, "growth conditions" were fixed; only the decision technology was responsive to investment.

We employed reasonable (though admittedly arbitrary) cost parameters for this study. Our aim was not to precisely quantify the costs of implementing sophisticated silviculture, but merely to introduce such cost considerations into a more general framework for the economic analysis of complex stands. Our results showed clearly that these costs affected the forester's decision calculus. Overall, less work was carried out and the intensity of that work clearly decreased. Over 16 potential plot-level treatment opportunities, optimal tending was implemented just once.

Though often overlooked, the economic logic of costly management effort is nonetheless uncomplicated: intensive management is only efficient if the resulting gains exceed their added costs. Apparently, in many cases, they don't. Thoughtful tree marking at times creates less value than it costs. When the high implementation costs of better silviculture are properly accounted for, mild high grading or other forms of apparent silvicultural underinvestment can sometimes be efficient.

It is tempting to assume it would be in the best interest of all parties to manage the resources they were contracting over to maximize value production, net of the cost of parties' contributions. The crux of the contracting problem, then, would be in haggling over the division of that surplus value. In fact, such outcomes are unobtainable. Given asymmetric information, the most efficient *feasible* contract, consistent with the incentive compatibility and individual rationality constraints, cannot induce first-best resource management. The Principal is willing to forfeit some gross production for a contracting arrangement that lets him retain a larger residual. The forest grows less but the forest owner keeps more. Compared to the benchmark scenario, agency costs reduced the gross value of production by 9% and the landowner's net payoff by 16%, but he would have netted even less under any other contract arrangement, either through increased transfers to the forester or further decreased gross production.

The landowner's scope for losses increases as the contracting space gets more complex. Early, exploratory runs of the contracting problem optimized the contract parameters for single plots at a time. In these scenarios, the landowner consistently drove the forester's payoff (net of her private cost of effort) down toward the reservation wage, for example, \$1.736e-19/ha, which is to say, minimally in excess of zero. However, in the multi-plot scenario we modeled here, the contract terms could not be tailored as finely. At the plot level, the forester's net payoff (capitalized at 6%) varied from \$156 to \$615/ha. A contract forced to span multiple plots in a heterogeneous stand necessarily cedes rents to the forester.

The operative mechanism here is the individual rationality constraint, which binds at the plot level. The forester's option to do nothing establishes a lower bound of zero on the payoff of any action she chooses. The landowner cannot recoup excessively generous compensation in one period through negative transfers back from the forester in another. She would simply walk away, in the moment, from any given plot rather than take a loss on it. And in many cases, she does: the forester exerted one-third less effort as a contractor than she would have if she owned the stand herself.

While we caution against over-interpreting the results of this early and exploratory study, the structure of the optimal contract is notable. All four parameters appeared in the optimal arrangement, suggesting a calibrated contract in which each component binds on the forester's actions.

We are unaware of any such "four-factor" contract, in practice, but have often seen service contracts that combine two bases for payment, such as a per-acre rate plus a commission as a percent of stumpage. Individually, the optimized contract parameters in our model are all lower than rates observed in practice (Hersey and Kittredge 2005; Nelli et al. 2007; Wright and Munn 2013), but together they add up to compensation commensurate with fees commonly charged.

Interestingly, the most important parameter in our results—a percentage share of $CTV$ on exit—is also the least common, in practice. The heart of the Principal-Agent dilemma is how to get a manager to act like an owner; this contracting device works toward that goal directly, giving the forester "skin in the game" and aligning her decision horizon with that of the landowner (even if her risk appetite is not as easily aligned). Though uncommon among consulting foresters, this structure is essentially the norm among private equity funds (Witney 2021), including those operating in the timberland space (Mei 2019; Zhang 2021). The structure modeled here roughly resembles the classic "2-and-20" private equity incentive compensation scheme of a 2% annual management fee and 20% profit share at exit, which mitigates much of the shirking or short-termism that other contract arrangements would induce. The truly distinctive feature here is the horizon. 40 years might only represent one third of the lifespan of a veneer-quality sugar maple grown to maturity, but it is a longer time frame than most finance practitioners would find familiar.

Taken together, our overall results call attention to the potential for thoughtful contracting to facilitate increased value production from complex forests (relative to the widespread high grading currently observed). A pure commission contract on a job-by-job basis, without any commitment to a continued relation between the landowner and forester, is a recipe for high grading. Better specified, longer-term contracts disincentivize some (though not all) of that behavior.

At the same time, our results also point clearly to the limits of a purely contractarian approach to governing the relationship between landowners and foresters. The most efficient contract design leaves a significant portion of the forest asset's potential capitalized value on the table. That uncaptured value represents what could be thought of as the landowner's "governance budget". Rather than relying exclusively on contractual mechanisms of governance, savvy or creative landowners could invest in non-contractual arrangements that more effectively economize on transaction costs or even cultivate intrinsic motivation (Ryan and Deci 2000; Grant and Shin 2012). Aggressive incentive contracting—premised on greed and untrustworthiness—can have the opposite effect. It signals that self-interested behavior is expected, that other social norms should be ignored, and that those who feel otherwise need not apply. Thus, the real limit of efficient contracting is not in the rents it cedes or the value it leaves uncaptured, but the risk that it "crowds out" exactly the type of unmonitored effort and far-sighted behavior it was intended to induce (Frey and Jegen 2001).

## CONCLUSION

This study explored novel economic dimensions of silvicultural decision making. Quality hardwood forests are responsive to silvicultural effort, though in this context, effort takes the form of an expert forester's costly deliberation rather than investment in physical inputs. The time a forester takes and the cognitive effort she exerts in making individual-tree harvest and retention decisions are unobservable to a landowner in the moment and unverifiable after the fact. This study asked, is there an incentive contract a landowner could offer, conditioned only on observable outputs, that would induce the forester to exert an efficient level of silvicultural effort? In short, no. Employing bi-level optimization methods, we modeled optimal contracting and demonstrated that the most efficient feasibly contractable outcome results in a significant deadweight loss relative to the first-best management strategy.

## CONFLICTS OF INTEREST

The authors confirm there are no conflicts of interest.

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