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A model for managing edge effects in harvest scheduling using spatial optimization

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ABSTRACT

Actively managed forest stands can create new forest edges. If left unchecked over time and across space, forest operations such as clear-cuts can create complex networks of forest edges. Newly created edges alter the landscape and can affect many environmental factors. These altered environmental factors have a variety of impacts on forest growth and structure and can alter harvest yields and habitat for wildlife. For example, chances of windthrow and regeneration shading can increase, which in turn can reduce the expected yield of merchantable timber. Additionally, forest edges can compromise interior forest habitat for wildlife and expose sensitive species to harmful processes such as nest predation or parasitism. We introduce a harvest-scheduling model that can keep track of and control the spatiotemporal development of forest edges. This allows the forest resource analyst to put constraints on edge production in an attempt to meet a variety of production and sustainability objectives. To demonstrate the model's functionality and tractability, we apply it to a case study in the Pacific Northwest region of the United States.

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Introduction

Forest edges are abrupt changes in stand characteristics such as tree height, stem density, or species composition. Forest edges occur naturally for a variety of reasons, including environmental limits to plant species distributions such as altitude and moisture, or large-scale disturbances such as floods or landslides. Forest management practices can also contribute to edge development. Whether by altering stem density via thinning, or by changing species composition via replanting or habitat restoration, or by altering fuel loads for fire control, management actions can result in a complex network of edges.

Newly created edges alter the landscape and can have a variety of ecological repercussions. We can reduce the negative impacts, while promoting the beneficial ones by giving explicit and careful consideration to edge development in forest planning. However, determining the optimal spatial and temporal layout of management actions is a very complicated task. In this paper, we propose a spatial optimization model that accounts for individual edges. To illustrate the model in as simplistic terms as possible, we describe a case study where clear-cut forest harvesting is the sole management tool. Although the framework is broadly applicable to a variety of systems and management practices, clear-cut harvests serve as the most intuitive and illustrative example of how forest edges can develop in response to human interventions. Clear-cuts are also advantageous for demonstration purposes because edge effects associated with clear-cuts have been well researched (Chen & Franklin 1992; Chen et al. 1995; Mitchell et al. 2001; Burton 2002; Kalcounis-Rueppell et al. 2010; Irwin et al. 2013).

Before describing the mechanics of the model, we summarize the physical and ecological effects of forest edges that can result from clear-cut harvesting. We introduce our proposed modeling framework next. To demonstrate the functionality and tractability of the model, we present a case study in the Pacific Northwest United States. Finally, we discuss the model's limitations and broader applications.

Forest edge effects

When a forest stand is harvested using a patch- or clear-cut approach, it can create a new forest edge along any or all of the adjacent stands. In this case, the environmental changes on the exterior (cut side) of the edge are obvious. However, the new edge also affects the interior (forest side) of the edge. In general, newly created edges can alter the landscape in many different ways. Chen et al. (1995) investigated how climatic factors change along interior clear-cut edge in the Pacific Northwest. They found significant differences in air temperature, soil temperature, wind speed, short-wave radiation, humidity, and soil moisture. These differences extended between 60–240 m into the forest depending on the specific variable. The altered environmental factors can affect forest growth and structure including merchantable harvest yields, habitat for wildlife. In the following, we discuss these effects in detail starting with the effects on forest growth and structure.

Edge effects on forest growth and structure

The two biggest environmental factors affecting forest growth and structure due to new edges are increased or reduced sun

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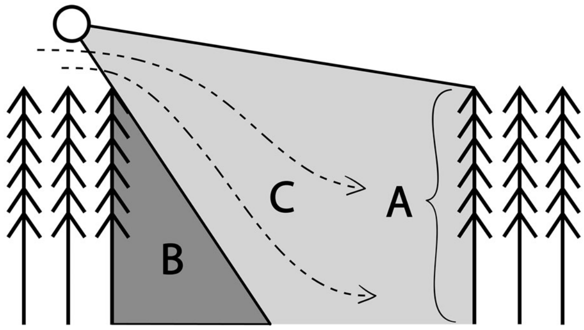

Figure 1. Possible physical effects of clear-cut edge. This figure demonstrates three possible edge effects: Increased sun exposure (A), shading of regenerating growth (B), and increased wind exposure (C).

exposure and increased risk of wind damage. Increased sun exposure (Figure 1 (A)) provides extra short-wave radiation, induces higher temperatures, and reduces humidity and soil moisture. In certain conditions, this extra exposure increases growth rate. Chen and Franklin (1992) found an increase in relative growth rate (RGR) for Douglas fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) near clear-cut edge. However, the increased sun exposure is not always beneficial to tree growth. As an example, Burton (2002) looked at edge effects in boreal Canada and found a decrease in radial incremental growth for lodgepole pine (*Pinus contorta*) growing near south facing edges. The increase in exposure can reduce humidity as well as available soil moisture. Although these effects may not be sufficient to compromise the growth of mature pines, they can harm mycorrhizae fungi and rhizosphere bacteria, both of whose health and integrity are indirectly tied to the growth of pines (Amaranthus et al. 1993).

The other major edge effect on forest growth is increased risk of windthrow due to exposure (Figure 1 (C)). Both Chen and Franklin (1992) and Burton (2002) found increased amounts of wind damage along edges. In a census, the British Columbia Ministry of Forests found that 4% of the annual allowable cut was damaged by wind in 1991. This was a volume equivalent to the damage caused by insects and wildfire combined in that year (Mitchel 1995). In another study conducted across six forests in British Columbia (three coastal and three inland), clear-cut edges less than 10 years old were analyzed for windthrow damage (Lanquaye-Opoku & Mitchell 2005). The authors found that the average loss of 25 m-by-25 m edge components seriously damaged by wind varied between 4% and 24% depending on study site. Using regression analysis, they were able to relate the proportion of wind-thrown components to various edge-specific parameters such as elevation, slope, and aspect. These results corroborated Burton's (2002) earlier results about the effects of edge orientation on the amount of windthrow. In conclusion, these findings demonstrate that not all edges are equal and that individual edges can have very different effects on forest growth.

Edge effects on wildlife habitat

The effects of forest edges are not limited to tree growth. Wildlife habitat can also be impacted (Kimmins 2004). Some species benefit from, while others are harmed by, forest edges. Large mammals often browse along forest edges where understory plants are abundant, but at the same time, the safety of a dense forest is not far away. Similarly, some predators take advantage of forest edges to remain in cover while they stalk prey in the openings. For example, the northern spotted owl (*Strix occidentalis caurina*) hunts in old growth forests along edges where there is significantly less groundcover for their prey to hide (Irwin et al. 2013). Another example of wildlife that benefit from edges is bats that harness changing air currents along clear-cuts to for the purposes of more effective aerial predation of insects (Kalcounis-Rueppell et al. 2010). Conversely, forest edges can also compromise the well-being of some animal species. The marbled murrelet (*Brachyramphus marmoratus*), for instance, faces higher rates of nest predation by *Corvids* near forest edges (Malt & Lank 2009).

In a broader sense, edges affect habitat connectivity and fragmentation, which can, in turn, compromise overall habitat suitability. However, connected habitat for one species may be fragmented from the perspective of another species. The example of moose (*Alces alces*) vs. flying squirrels (*Pteromys volans*) are case in point. Although moose do not directly benefit from forest edges, edges between a recent harvest and a mature stand can satisfy both of its critical habitat requirements. That is because moose forage in openings and recent clear-cuts where understory plants are plentiful. At the same time, they seek cover and shelter in mature forests. For this reason, edge development can be used as a proxy for moose habitat (Kurttila et al. 2002). However, while moose benefit from landscapes rich in edges, from the flying squirrel's perspective, the very same landscape might prove to be too fragmented. That is because large openings are an impediment to the flying squirrels' ability to glide efficiently through the canopy from tree to tree in short distances. This is why minimizing edge development to create large contiguous forest patches would be good for this particular species (Kurttila et al. 2002).

In sum, the spatial and temporal layout of edge generation that is driven by the layout of management actions can have complex repercussions. Many species that inhabit forestlands are considered protected species or provide critical ecosystem services. Both the marbled murrelet and the northern spotted owl are currently listed as threatened species in the United States (Federal Register 2011, 2012). Because of this, forest managers must be careful to consider the impacts of harvest-scheduling decisions on edge development.

Optimal management plans

The spatial layout of management actions over a large area can lead to a combinatorial explosion of potential options to consider. By adding the temporal dimension, the permutations of a sequence of management actions must each be considered separately, which leads to an even greater number of possible alternatives. For example, choosing a sequence of 10 forest management units (FMUs) for some silvicultural treatment out of 100 represents more than 62 quintillion (10^{18}) possibilities. Additionally, these management alternatives must often meet various constraints and limitations. The sheer quantity of options quickly pushes these problems out of the realm of "eyeballing" a good, or even feasible solution.

One way to plan and schedule complex management tasks is to use spatial optimization models. These models optimize the spatial and temporal layout of management actions across a landscape over a finite planning horizon. Examples of spatial optimization applications to forest ecosystem management include habitat reserve selection (Haight & Travis 2008), fuel treatments (Wei et al. 2008), and harvest scheduling (Tóth & McDill 2009). Harvest-scheduling models optimize one or more management objectives (e.g. maximize revenues or harvest volume) over a set of planning periods while meeting a variety of financial and ecological constraints. The concept of edge effect requires knowing which units are adjacent to another, and is therefore inherently spatial. Spatial optimization models typically require binary decision variables that indicate which units to select for a particular management action. For harvest scheduling, this often translates to units being either cut or not. This is required to ensure the spatial integrity of the model; if a fraction of a unit is harvested, there is no way of knowing the amount or location of the resulting edge. By assuming the units can only be clearcut, we can define possible edges a priori and incorporate edge-specific data into the model.

Optimal land acquisition and reserve design models were the first to incorporate edge effects via spatial optimization. These models tried to minimize the length of exterior edges relative to reserve or land area to promote compact site selection (Wright et al. 1983; Fischer & Church 2003). The total edge projected to be present at the end of a given planning horizon was also used for similar purposes in forest harvest-scheduling models: as a measure of compactness or habitat fragmentation (Tóth & McDill 2009). A common shortcoming of these models is that they treated all edges equally regardless of edge orientation, aspect, or lifespan. Burton (2002) and Scott and Mitchell (2005) have shown that the orientation and aspect of edges can have dramatic impacts on exactly how edges would affect the silvicultural characteristics of adjacent forest stands. By lumping all edges together regardless of their individual characteristics, one can end up discounting or exaggerating their actual impact on habitat or yield. Moreover, individual forest edges arise and fade away dynamically in response to various silvicultural activities as well as to the growth and maturation of neighboring stands. One common boundary shared by two stands can be an abrupt edge during one period of time (e.g. one forest stand is harvested next to another one with forest cover) while the very same boundary could quickly cease to serve as an edge in a subsequent period (e.g. if the other stand is also harvested). Ignoring these "transitory" edges by focusing only on the minimization of the maximum length of edges between mature forest patches and all other stands over the planning horizon (as in Tóth & McDill 2009) can again lead to biased estimations of their true, dynamic impact on wildlife and timber yield.

The model we propose overcomes these shortcomings by accounting for each edge individually between pairs of adjacent forest stands. The proposed model has separate indicator variables for every single shared boundary between stands that switch on and off in response to the silvicultural actions scheduled to occur on those stands. This level of granularity allows one to capture the dynamic feedback between these transitory edges and the projected stand yields or wildlife habitat. Moreover, our new construct also makes it possible to model the directionality of individual edge effects over time. The presence of an edge affects the forest stands or reserve sites in drastically different ways depending on which side of the edge one is looking at. As an example, the effect of windthrow on yield occurs only on the intact, forested side of the edge and not on the side that had been clear-cut. The model we propose accounts for this directionality through a specific mathematical programming construct. We are not aware of any other documented optimization model that can capture all of these key components of edge effects whether they arise in forest harvest scheduling or in reserve selection. The closest others have gotten in utilizing the pair-wise relations of adjacent forest stands have done so in the context of spatially explicit harvest-scheduling models with maximum harvest opening size restrictions (e.g. Snyder & Revelle 1997; McDill et al. 2002). In these models, edges have been modeled to represent adjacency between units. This information allows managers to place constraints on adjacent harvest activities, thereby limiting the size of contiguous harvest openings. In our proposed model on the other hand, harvest activities in adjacent stands are coordinated in an attempt to control the negative or positive effects of edges. We present an optimization modeling framework that keeps track of the length, orientation, aspect, and directionality of each edge in each planning period. This allows us to model the various forms of edge effects, from windthrow to altered sun exposure, separately for each edge. Our framework tracks and identifies edges created in all planning periods, and can explicitly account for transitory edges that are not necessarily present at the end of the planning horizon. We discuss how the framework can be used in various management situations and demonstrate its functionality and tractability in a case study in the Pacific Northwest United States.

Modeling framework

The proposed model is a mixed integer program (MIP). The MIP optimizes the spatial and temporal layout of management actions, such as harvests, thinning or habitat restoration across a set of management units or reserve sites within a time horizon of, say, $|T|$ time-periods in pursuit of an objective function that represents the primary management or conservation objective:

$$\text{Max} \sum_{i,t} F(x_{i,t}) \; . \tag{1}$$

Here, $x_{i,t}$ is the binary decision variable that represents whether a given forest treatment should be applied to unit i during planning period t ($x_{i,t} = 1$) or not ($x_{i,t} = 0$). Function F is some linear function of these decision variables that relates the management actions (e.g. harvest or restoration actions) to overall management objectives (e.g. timber revenue maximization). The model optimizes this function while meeting a bevy of additional constraints.

As a concrete example, consider the task of scheduling forest clear-cuts to maximize timber revenues or harvest volumes. In this case, $x_{i,t}$ denotes the decision whether to clear-cut unit i in period t, or not. Our objective function takes the form of:

$$\text{Max} \sum_{i,t} v_{it} x_{it}, \tag{2}$$

where v_{it} is the net discounted timber revenue associated with harvesting FMU i in period t. Objective function (2) attempts to maximize the revenues over all time-periods while meeting various sustainability and logistical restrictions including:

$$\sum_{t=0}^{|T|} x_{it} = 1 \qquad \forall i \in V, \tag{3}$$

where V is the set of all management units i. Constraint set (3) forces each unit to have only one treatment regime associated with it. In our case, this means each FMU can only be harvested at most once.

Edge identification

The key component of the modeling framework is the ability to detect and flag each possible edge in every planning period. To define and flag individual edges, the model compares adjacent units under all possible management scenarios using a *condition* table (a_{itp}). The table shows the "condition" of stand i in each period p under each possible management scenario t. The term "condition" refers to the specific parameter used to define edge in the context of the management problem at hand. For example, stand height, age, or species composition could all serve as "conditions" to determine whether an edge exists between two adjacent units in a particular period of time.

To determine the presence of edges, the model compares the values of a_{itp} between all adjacent units in all time-periods. If in any period the difference between a_{itp} values for two adjacent units is greater than a prescribed threshold, the model concludes that there is a directed edge between the units in that time-period. Mathematically:

$$\sum_{t=0}^{|T|} (a_{itp}x_{it} - a_{jtp}x_{jt}) \leq d_{ij} + Mz_{ijp} \qquad \forall [i,j] \in E, p \in T \tag{4}$$

$$\sum_{t=0}^{|T|} (a_{itp}x_{it} - a_{jtp}x_{jt}) \geq d_{ij} - M(1 - z_{ijp}) \quad \forall [i,j] \in E, p \in T, \tag{5}$$

where $z_{ijp} = 1$ if the model determines that there is an edge effect on unit i directed through the edge from unit j in period p, and 0 otherwise, $E =$ the set of all adjacent units $[i,j]$ in the forest, $d_{ij} =$ the difference in a_{itp} values required to trigger an edge effect on unit i from unit j, and $M =$ an arbitrarily large number, which is at least as much as the largest possible difference in a_{itp}'s. Constraint sets (4) and (5) control the binary indicator variable z_{ijp} in charge of flagging edge effects from unit j to i in period t. If in any period p, the a_{itp} value for unit i is greater than the a_{jtp} value for adjacent unit j by at least d_{ij}, then z_{ijp} is forced to be equal to 1 (constraint 4). If the difference is less than threshold d_{ij}, then z_{ijp} is forced to be equal to 0 (constraint 5). Note that edge effects are directional in our proposed model and therefore $z_{ijp} \neq z_{jip}$. Moreover, the constraints prevent z_{ijp} and z_{jip} from both taking the value of 1 in the same period.

With these two constraints, we create a binary indicator variable that tracks the presence of edge created by the management plan. We can then use these variables to set constraints on edge production and directly manage edge effects.

Incorporating edge into management goals

By controlling edge development in the optimization model, we can represent a variety of possible management objectives mathematically. A few brief illustrative examples that demonstrate the flexibility of the model follow. Note that the condition used to define edge is not assumed to be the same between examples.

Modeling total edge to account for bat or moose habitat: One of the most basic capabilities of this modeling framework is to track the total length of edges in each time-period as well as over the entire planning horizon:

$$\sum_{[i,j] \in E} z_{ijp} b_{ij} = C_p \qquad \forall p \in T. \tag{6}$$

Constraint set (6) is an accounting constraint that sums the total length of edge created in each period. Here b_{ij} is the length of the boundary between units i and j, and C_p is the total length of edge in period p. By comparing the total edge development due to harvest activities under different management scenarios we can examine the trade-offs of providing additional edge for those species that broadly benefit from it. For example, the model allows one to look at the cost trade-off for providing additional edge for bats that benefit from turbulent air conditions at and around forest edges for aerial predation (Kalcounis-Rueppell et al. 2010).

Similarly, using this modeling framework, one can set a minimum amount of edge between harvested and mature forests ($C_{\min}$) to be present in all periods as a proxy for having available moose habitat:

$$\sum_{[i,j] \in E} z_{ijp} b_{ij} \geq C_{\min} \qquad \forall p \in T\,. \tag{7}$$

Modeling edges with specific attributes for northern spotted owl and marbled murrelet habitat: Apart from accounting for total edge development in each planning period, our proposed modeling framework can also account for each specific edge individually. For example, the northern spotted owl often hunts on the forest side of edges between recent clear-cuts and old growth stands (Irwin et al. 2013). Our model can be used to require an edge to be present within a certain distance of each owl reserve in each time-period:

$$\sum_{i \in A_R} z_{iRp} \geq 1 \qquad \forall R,\ p \in T. \tag{8}$$

Constraint set (8) requires that at least one edge occurs within a certain distance of each owl reserve during each time-period. Here R is an FMU marked as an owl reserve, and A_R is the set of units that have borders within a certain distance from reserve unit R. Conversely, marbled murrelets face higher rates of nest predation near edges (Malt & Lank 2009), so one may want to limit the amount of edge within a certain distance from marbled murrelet reserves:

$$\sum_{i \in A_R} z_{iRp} b_{ij} \leq C_R \qquad \forall R,\ p \in T. \tag{9}$$

Constraint set (9) limits the total length of edge near marbled murrelet reserves. Here, R is a unit marked as a marbled murrelet reserve, as well as its surrounding buffers where logging is prohibited, and C_R is the maximum amount of edge allowed on these units plus their buffers in each time-period.

Modeling the feedback between management objectives and increased exposure due to edges: Using our proposed model framework, one can also associate a cost or revenue with each edge being produced. For example, harvested volumes can be adjusted to capture increased sun exposure or windthrow due to newly created edges between specific pairs of adjacent stands.

For simplicity, we assume for this example that edge effects arising in multiple periods are additive in their impact on yield or habitat (this assumption can be relaxed):

$$f_{it} = 1 + \sum_{p<t, j \in A_i} z_{ijp} G_{ij} \qquad \forall i \in V, t > 1 \in T, \tag{10}$$

$$y_{it} \leq N x_{it} \qquad \forall i \in V, t \in T\ , \tag{11}$$

$$y_{it} \leq f_{it} \qquad \forall i \in V, t \in T, \tag{12}$$

$$f_{it} - y_{it} \leq N(1 - x_{it}) \qquad \forall i \in V, y \in T, \tag{13}$$

$$\text{Max} \sum_{i,t} v_{it} y_{it}. \tag{14}$$

Constraint set (10) defines the value of yield adjustment factor f_{it} for unit i harvested in period t, by adding all edge effect adjustments that are projected to occur prior to period t. Here f_{it} denotes the percentage of total volume lost in unit i by period t. Parameter set G_{ij} represents the individual yield adjustments for unit i in only one planning period via its shared edge with unit j. Set A_i denotes all the units adjacent to unit i. In constraint set (10), we only sum over $p < t$ because edges that arise post-harvest can no longer alter the already harvested yields. Lastly, there is no yield adjustment in the first period of the planning horizon due edges that might have developed in the past. For simplicity, we assumed that the data on current yields already captured past edge effects.

Constraint sets (11–13) linearize the product of the binary harvest variable x_{it} and the continuous adjustment variable f_{it}. Here N is an arbitrarily large number at least as large as the largest possible total adjustment. Variable y_{it} represents the product $x_{it} f_{it}$. As a last step, we replace objective function (1) with (14) using the adjusted harvest variables y_{it}.

Together these constraints create a harvest-scheduling model with yields adjusted by the presence or absence of forest edges. The coefficient set G_{ij} can represent a wide variety of edge effects, such as reductions or increases in yield or wildlife habitat, making the model very flexible. Additionally, the temporal dimension of the adjustment factor f_{it} allows the user to account for different responses to edge effects in stands that are of a different age. For example, an older stand might respond differently to wind or nest predation than a younger one, everything else being equal. In the next section, we will use this set-up to demonstrate the functionality of the model in a case study where edge effects reduce overall yield due to wind damage.

Case study

Model configuration

As a proof of concept, we configured our proposed model to adjust harvest yields based on projected wind damage. We set the adjustment factor for windthrow to represent the percentage of volume lost due to windthrow events. Based on Lanquaye-Opuku and Mitchell (2005), we assume there is a probability p of wind to damage a 25 m-by-25 m segment of forest edge. To calculate this probability for each individual shared boundary between adjacent units, one can take a wide variety of factors into account such as aspect, slope, and soil type. We defined Function G_{ij} as:

$$G_{ij} = -\left(\frac{b_{ij} p}{sl} \times \frac{sl^2}{\text{Area}_i}\right), \tag{15}$$

where the shared boundary (b_{ij}) is divided by the segment length ($sl = 25$ m in this study) to calculate how many segments are found along the boundary between i and j. Then, by multiplying by p we find how many segments were likely to be damaged. From there, we convert the number of damaged segments into a percentage of total area. This value represents the percentage of total area projected to be lost due to windthrow associated with the shared boundary between units i and j. Although we used uniform windthrow probabilities for this particular case study, models like WINDfarm (Lanquaye-Opoku & Mitchell 2005) could be used to estimate probabilities that are more realistic and determined by site-specific factors.

For this case study, our management objective was assumed to maximize harvest yield. Hence v_{it} in the objective function represents the projected volume of stand i in period t. In addition to constraints (3–5) and (10–13) we include two operational constraints commonly applied to harvest-scheduling models: harvest flow constraints, and ending age requirements. Inequalities (16) and (17) create the harvest flow constraints:

$$LH_{t-1} \leq H_t \qquad \forall t > 1 \in T, \tag{16}$$

$$UH_{t-1} \geq H_t \qquad \forall t > 1 \in T. \tag{17}$$

These constraints force the difference in total harvest volume (H_t) between consecutive time-periods to be within a certain range defined by the upper- and lower-bound parameters U and L. Inequality (18) is an ending age constraint:

$$\sum_{i} \text{Area}_i \left(a_{i01} - \frac{1}{2} l \right) \leq \sum_{i,t} \text{Area}_i \left(a_{it10} + \frac{1}{2} l \right) x_{it}, \quad (18)$$

where Area_i = the area of management unit i, and l = the length of the planning period. This constraint ensures that the area weighted average age of the units at the end of the planning horizon is greater than or equal to the area weighted average age at the start of the planning horizon.

To demonstrate the value of the proposed model, we compared its performance in terms of lost harvest volumes to that of a control or naïve model that ignored the edge effects in its objective function. However, the control model was still formulated in such a way so that the timber volumes along edges effected by windthrow would still suffer from the same losses as the proposed model. In the control model, the objective function and harvest flow constraints reference the unadjusted harvest variables x_{it} instead of the y_{it}'s present in the proposed model. This causes the optimization model to assume there is no edge effect feedback on the objective function; although the actual harvest yields are still adjusted based on the appropriate windthrow probabilities. We used harvest accounting variables in the control model to keep track of total harvest volumes adjusted for windthrow.

Parameterization and data

The data used in this case study are from the Charles L. Pack Experimental and Demonstration Forest, located 2.3 miles southwest of Eatonville, WA. The 1740 ha forest is divided into 186 stands of varying slopes, aspects, soil types, ages, and species composition. Data used from this forest included stand locations and adjacencies, boundary lengths, and stand ages. Boundary lengths were calculated from polygon layers in a geographical information system (vector data). The data are freely available online through the FMOS database hosted by the University of New Brunswick (Figure 2).

We ran both the proposed and the control models under a variety of wind probability scenarios using a planning horizon of 50 years with five 10-year planning periods. The threshold difference in age to trigger edge effects (d_{ij}) was set to 15 years for all pairs of harvest units sharing a common boundary. Maximum percent fluctuations in harvest volumes between adjacent planning periods were set to 25% ($U = 1.25$, $L = 0.75$). We tested four scenarios with uniform windthrow probabilities of 0%, 5%, 15%, and 25%.

Once formulated, all models were solved using IBM ILOG CPLEX 64-bit 12.6.0. We solved the control models to full optimality for all scenarios, while we gave the edge effect model four hours of solution time for each scenario. We used default values for all other CPLEX parameters.

Case study results and discussion

The optimal harvest values for each model under varying probabilities of windthrow are shown in Table 1. For the proposed edge effect model, all runs finished with an optimality gap of less than 2%, but did not achieve full optimality. This means that the results shown in Table 1 could be even more drastic since the proposed model may have a higher optimal objective function value. In all cases, it is clear that our model performs better than the control model that ignores edge effects. For the extreme "heavy wind" scenario where a quarter of every edge blows down, the edge effect model was able to avoid more than half of the volume losses due to wind when compared to the control model. This shows that even in extreme scenarios, the proposed model can alter the spatial and temporal layout of management actions to significantly reduce edge effects on yield.

Figure 3 compares the spatial configurations of harvests for the control and edge effect models under the moderate wind scenario. The maps imply that the proposed model spatially concentrates the clear-cuts to minimize losses in timber

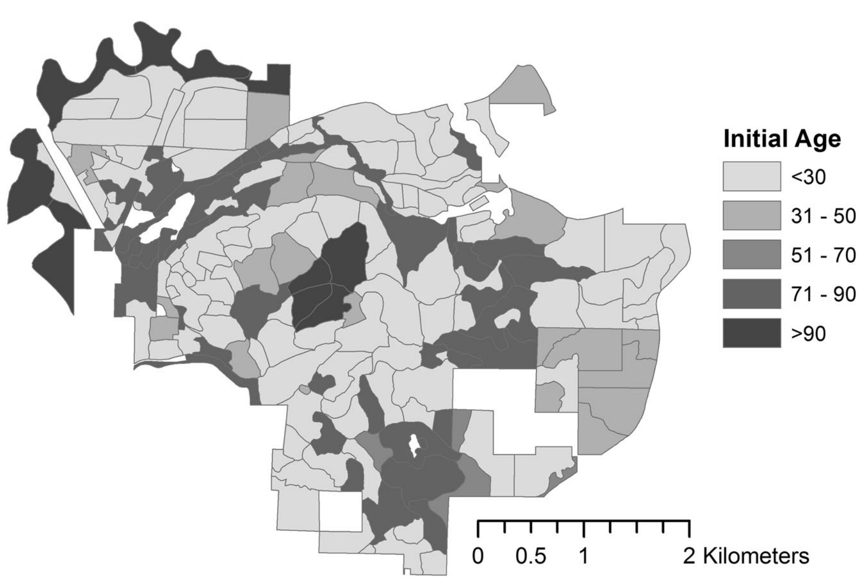

Figure 2. Initial age distribution of the Charles L. Pack Experimental and Demonstration Forest.

Table 1. Results from the case study. The table details total volume harvested under a variety of wind probabilities for the edge effect and control models. Numbers in parenthesis represent percent of maximum harvest ($p = 0$).

Probability of windthrow p	Accounting for edge effects	Ignoring edge effects
$p = 0$ (no wind)	116,539 (100%)	116,539 (100%)
$p = .05$ (light wind)	115,429 (99.05%)	114,841 (98.54%)
$p = 0.15$ (moderate wind)	114,163 (97.96%)	111,214 (95.43%)
$p = 0.25$ (heavy wind)	112,967 (96.93%)	108,412 (93.02%)

volumes due to windthrow (larger contiguous shaded areas). Additionally, the model minimizes edge loss by sequencing harvests, demonstrated by fewer instances of dark grays next to light grays.

Although many simplifying assumptions were made for this case study, it demonstrates how the proposed model can incorporate the complexity of edge effects on harvest yield at relatively low-computational costs. The exact benefit of accounting for windthrow will be location specific, however. Different jurisdictions might have different spatial restrictions on logging and these restrictions can easily interact with constraints on edge development. Of particular importance are the green-up and maximum clear-cut size restrictions. The ability to minimize edge is dependent on the model's freedom to aggregate management actions spatially and temporally. However, green-up and maximum clear-cut size regulations place limitations on the temporal and spatial aggregation of harvests. A number of published models for limiting maximum clear-cut openings are also driven by binary harvest variables (x_{it}). As a result, the two modeling frameworks are compatible and there is nothing that would prevent the analyst from integrating the two.

Discussion and conclusion

Management decisions often come with unintended consequences. The spatial and temporal arrangement of forest management actions can produce complex networks of edges. These edges in turn can have a variety of effects on forest growth and yield and on wildlife habitat. In this paper, we have presented a modeling framework that directly considers the development of edges when creating optimal management plans. To illustrate the general applicability of the proposed model framework, we discussed several potential edge effects that can occur due to logging, as well as the potential management solutions that our model could identify to overcome the negative repercussions of these effects. In a case study, we configured the modeling framework to represent biomass loss due to an increase in windthrow probability due to newly formed edges. Our model outperformed the control model in all instances, generating harvest schedules that minimized the expected damages of windthrow.

Although we demonstrated the mechanics and the benefits of our model in the context of clear-cut harvesting, it is important to note that edge effects could also arise in the context of other silvicultural activities such as thinning. If such effects were found to be significant, the same mathematical structure can be used in the harvest-scheduling models to account for these effects as the one presented here. Thinning-induced edge effects would have to be quantified empirically before they can be incorporated in the harvest-scheduling models. While no such empirical data are available today, our proposed modeling framework could be used to address this issue once data availability is no longer an issue.

Beyond forest harvesting, the proposed model can be applied to fuel treatment allocations for wildfire management, habitat restoration, and invasive pest management. The flexibility stems from the way the model determines the presence of edge effects using the condition parameter a_{itp}. In the case study, we defined edge effects based on the difference in stand age between two stands sharing a common boundary (a_{itp}). However, these values can also represent other metrics as well. For fire management, edge could be

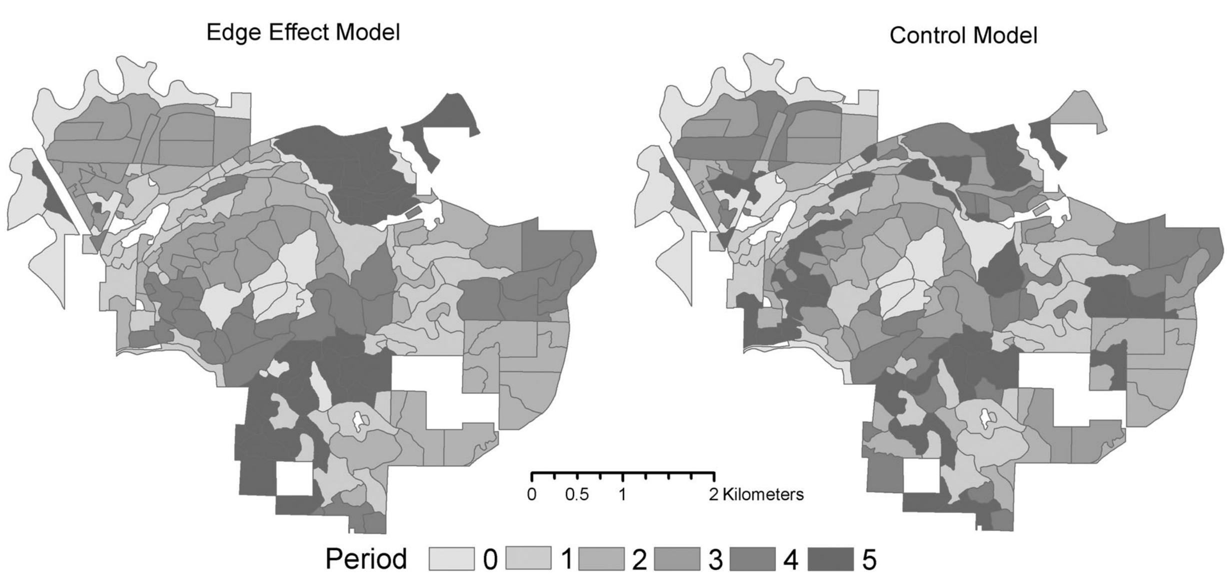

Figure 3. Comparison of harvest layouts under the moderate wind scenario. The edge effect model groups harvests together to minimize loss associated with windthrow along edges.

defined based on the difference in the amount of coarse woody debris or ladder fuels between two adjacent plots. For habitat restoration, edges might be defined based on species composition percentages or a binary comparison of treated vs. untreated units. For invasive species monitoring, we could define edge based on the time since a unit was last monitored or treated. Even within our case study, we could model edge in different ways. For example, since stand growth tapers off beyond a certain age, a difference in age will mean less of a difference in height over time. We could set the a_{itp} values to represent projected tree height, which would more accurately capture the presence or absence of edges as it pertains to windthrow – at the cost of requiring additional knowledge about the system. Similarly, the value of threshold parameter d_{ij} could depend on site-specific information such as dominant species or site class. Even the edge effect adjustment factor G_{ij} could be redefined by converting windthrow into pulp salvage instead of volume loss.

The applicability of the modeling framework still has its limitations. The main limitation of the model is its reliance on predefined management areas and binary management actions. Both of these assumptions are required to define the exact size, location, and characteristics of possible edges. Because edge effects are highly contextual and can vary with location and orientation, we need information about an edge's exact characteristics to be able to model its effects on the system. Compounding this issue, raster data are often used in natural resources, but does not accurately reflect edge metrics. For example, all edges in a raster are represented with vertical or horizontal lines, which does not accurately represent a curved border. This can cause the length of the edge to be under- or overestimated. Because this can introduce bias into edge metrics, we should exercise special care and caution when quantifying edge metrics using raster-based data. Another limitation is the assumption that harvests occur at the mid-point of planning periods. Under this assumption, the model effectively measures the average amount of edge produced. However, the exact amount will depend on the tactical implementation of the strategic harvest plan.

Lastly, the inclusion of binary variables and constraints that can introduce endogenous feedback can add a significant level of complexity to the optimization model. Depending on the spatial and temporal scope of the management problem, this may be a considerable drawback.

Finally, we emphasize that the management scenarios discussed in this paper were simplifications used to illustrate possible applications of the modeling framework and did not attempt to capture the true complexity of the underlying systems.

In conclusion, we can help to mitigate the negative effects of edges and provide more ecologically sound management plans by explicitly considering the broader aspects of our management decisions. Edge effects are a wide-ranging phenomenon that can have a variety of impacts. By directly modeling edges within our proposed spatial optimization framework, one can add constraints that control where and when edges might arise on the landscape in an attempt to provide optimal bundles of ecosystem services.

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