The Effect of Hardwood Component on Grapple Skidder and Stroke Delimber Idle Time and Productivity – An Agent Based Model

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1. ABSTRACT

The forest industry is a capital intensive business and therefore high efficiency in management and forest operations is a must. Maine has millions of acres of forest stands with tree diameters smaller than 30 cm. The harvest productivity in such stands is low compared to stands with larger diameter trees. A recent harvest productivity study in Maine identified operational constraints for whole tree harvest systems, but efforts to improve active operations would be expensive and time consuming. A common practice to reduce costs and time consumption is to develop simulation models and implement new ideas within them. We developed a production efficiency model that leverages an agent-based modeling approach. The model is based on the interaction of two common forest machines (grapple skidder and stroke delimber) and incorporates empirical cycle time estimates from research in Maine. Four scenarios have been developed to investigate baseline conditions, two GPS/GIS improvements, and the use of two grapple skidders. The goal of this paper is to document a new agent based model and to investigate the effect of hardwood component on machine idle time and productivity. Results showed that system productivity was affected by skidding distance, bunch spacing, and removal intensity. An increase in hardwood component led to a decrease in stroke delimber idle time but did not affect grapple skidder idle. Further, hardwood component did not affect system productivity, and none of the three single-skidder scenarios tested performed any better than another. We validated the model by conducting a sensitivity analysis to confirm previous research results. The modeled waiting times are well within the range of observed values and therefore suggest that this model is accurate and well calibrated. Our conclusions are that when operating under average harvesting conditions there is no loss in productivity due to a change in hardwood component and that a stroke delimber idle time of 40% or more is unavoidable unless the stroke delimber can work independently. Future applications of this model may target specific production forestry conditions. Suggested analyses include productivity gains from technological improvements as well as the unit cost of production under a variety of stand and site conditions.

2. INTRODUCTION

Due in part to regenerating clearcuts from the spruce budworm era in the 1970s and 1980s, forest operations managers in Maine must manage an increasing percentage of stands that consist of small-diameter stems (dbh <30 cm). Approximately 11 million acres of forest land in Maine contain or are dominated by trees smaller than 30 cm in dbh (McCaskill et al.). Forest operations are an important part of the forest industry but are also very capital intensive (Purfürst). Due to the high capital investment in harvesting equipment, and the cost of running the machines, it is important to know machine productivity to fully utilize the individual machines. Effective management of forest operations therefore requires accurate estimates of harvest costs and productivity, although the monitoring of these variables may be difficult (Wang et al.; Holzleitner et al.). The two dominant and fully mechanized harvesting systems in Maine are whole-tree (feller-buncher, grapple skidder, stroke delimber) and cut-to-length (harvester, forwarder) (Leon and Benjamin). As the names suggest, whole-tree harvesting operations severe the tree from the stump and then transport it to the roadside including all branches as a whole tree, cut-to-length harvesting operations on the other side, severe trees from the stump and then cut off the branches and crosscut the bole into specific length logs, which are then transported to the roadside. These harvesting systems are generally very productive when operating in large diameter tree stands but have a reduced productivity when operating in small diameter tree stands (P Hiesl and Benjamin). With high investments in equipment it is therefore crucial to achieve high machine productivities to keep the unit cost at a low level. To increase the productivity of individual machines and the harvesting system it is therefore necessary to improve or change existing harvesting processes.

The primary goal of any logging contractor is to generate revenue to pay for the equipment and to create income. Maximizing machine utilization is one way to reach this goal and is described as the most important objective of a logging contractor (Bolding). In order to maximize the utilization of a machine it is important to know where bottlenecks are. Several methods are available to identify these bottlenecks. Time studies are a common tool to evaluate harvesting operations and identify bottlenecks, however, they can be rather time consuming (Bolding; Bazghandi; Bradley et al.). Another accepted method to analyze the productivity and impact of a harvesting system are simulation models (Polley; Baumgras et al.; Goulet et al.; Garner; Bradley et al.; Wang and LeDoux; Y. Li et al.). Also often used are individual tree growth simulators such as Forest Vegetation Simulator (FVS) (Dixon), and regional volume and taper equations (e.g. Li et al. 2012; Weiskittel and Li 2012). Individual tree growth models are especially useful in combination with cycle time equations for harvesting equipment that are based on individual trees (e.g. Hiesl and Benjamin 2015; Hiesl and Benjamin 2013a; Spinelli et al. 2010; Adebayo et al. 2007). Simulation models have several benefits compared to time and motion studies, such as fast execution of models and the possibility of changing system settings without changing the real system (Polley; Bazghandi; Bradley et al.). The use of simulation models is not new to the forestry community as simulation models have been available since the 1960's (Polley; Goulet et al.).

Before 2013, no harvesting productivity studies were conducted in Maine and therefore no up-to-date productivity information for harvesting systems operating in Maine's forests was available to conduct such computer simulations (P Hiesl and Benjamin). In 2012 and 2013, researchers at the University of Maine collected cycle time and productivity data for five pieces of equipment (feller-buncher, harvester, grapple skidder, forwarder, stroke delimber) commonly used in Maine, and developed cycle time and productivity equations (Hiesl; P Hiesl and Benjamin; Patrick Hiesl and Benjamin; P Hiesl and Benjamin). With these newly developed equations it is now possible to simulate the time consumption and productivity of different harvesting systems in a variety of site and stand conditions. The logical extension of the time and motion study conducted by Hiesl (2013) therefore is to use this data to identify bottlenecks and to develop simulations with the new productivity data to test various scenarios of possible improvements in forest operations. Observations during the field study showed that harvesting operations consist of a large amount of non-productive waiting time.

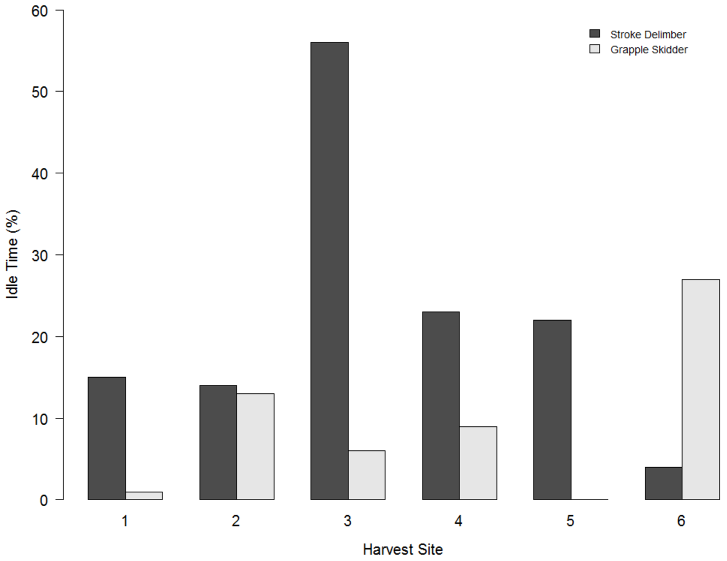
Harvesting equipment used in whole-tree and cut-to-length harvesting systems mostly operate independent from each other. The interactions between stroke delimbers (Figure 1) and grapple skidders (Figure 2) are an exception to this. The grapple skidder delivers wood to be processed by the stroke delimber and often has to wait for the stroke delimber to finish processing wood from the previous load. Polley (1987) found that waiting times between 20 and 40% have to be expected due to this dependency. The recommendation from Polley's research was to avoid such technological coupling of new equipment. Today, however, these two machines are still very much dependent on each other. Huth et al. (2004) commented that the existence of harvesting systems for many years and decades does not necessarily mean that their use is sustainable. Today with decreasing profit margins, large percentages of idle time due to technical coupling of grapple skidder and stroke delimber cannot be tolerated.

Whole-tree harvesting systems are the most important harvesting systems in Maine in terms of volume cut (Leon and Benjamin). Unpublished data of Hiesl (2013) showed that there is a waiting time ranging from 0% to 57% present when a grapple skidder and stroke delimber work together at a variety of commonly encountered site and stand conditions in Maine (Figure 3). With the feller-buncher working independently we can therefore identify the interaction of the grapple skidder and the stroke delimber as the bottleneck in most whole-tree harvesting systems. Research has further shown that the processing time of stroke delimbers is negatively impacted when processing hardwoods (Hiesl). As with harvesters (Glöde), the generally larger branch size increases the processing time for stroke delimbers as well. Maine's forest land consists of over 50% of hardwood forest types (McCaskill et al.), and land managers and logging contractors alike have to deal with the negative impact of hardwoods on harvesting productivity. This highlights the importance to understand the impact of an increasing hardwood component on stroke delimber and grapple skidder idle time.

Figure 1: A stroke delimber generally processes one tree at a time by cutting of branches and the top above a specific merchantable diameter.

Figure 2: A grapple skidder generally transports several trees in a bunch from the forest to the roadside where the whole trees get processed by a stroke delimber.

Figure 3: Observed percent idle time for stroke delimber and grapple skidder from six different harvest sites observed during the summer of 2012 by Hiesl (2013). The sites represent a common range of site and stand conditions in Maine.



Presently, there are three computer simulation methods available for modeling different abstraction levels, such as System Dynamics, Discrete Event, and Agent Based (Borshchev and Filippov). All methods have their strengths and weaknesses, and we therefore focus on Agent Based Modeling (ABM) only. ABM is versatile and can be used in a range of low to high abstraction levels, depending on the needs of the simulation. With ABM the focus is on individual objects (agents) that can vary in their scope and nature, such as people, vehicles, machines, customers, competing companies, etc. (Borshchev and

Filippov). The novel aspect of ABM is that behavior rules of individual agents and their interactions can be specified. This is the most outstanding difference of ABM from the other simulation methods, and makes this method especially useful in modelling forest harvesting with different machines. We have chosen an agent-based modeling technique because we are focused on individual agents (stroke delimber and grapple skidder) with unique and interacting behaviors. Epstein (1999) described five characteristics of agent based modeling (ABM) that aid in the decision making of the applicability of ABM to a certain research question: (1) heterogeneity of the agents, (2) autonomy of the agents, (3) explicit space, (4) local interactions, and (5) bounded rationality. All five characteristics hold true in our simulation of stroke delimber and grapple skidder interactions. Although often used in social sciences, agent based modeling (ABM) experiences widespread popularity among other disciplines (Manson; Bazghandi; Gilbert). There is growing interest among researchers in using agent based models to explore ecological and silvicultural consequences of harvesting prescriptions (Arii et al.) and to investigate the harvest decision making of forest landowners (Leahy et al.). Our model will expand the use of agent based models to include forest operations research questions at the machine level.

Due to the large amount of data generated by this model and the multitude of research questions that can be asked we will focus in this paper on a detailed model description and investigate the effect of an increasing hardwood component on stroke delimber and grapple skidder idle time and productivity. The analysis shown in this paper focuses on the hardwood aspect only, as a separate analysis of skidding distance, payload, and a two skidder scenario is part of a different article (Hiesl et al., submitted).

3. MATERIALS AND METHODS

To better understand the interactions of stroke delimber and grapple skidder and to test new processing techniques we create the stroke delimber and grapple skidder agent based model (SDGS-ABM). The model was created using the agent based modeling tool NetLogo v5.0.5 (Wilensky). We present this model according to a modified version of the overview, design concepts, and details (ODD) protocol (Grimm, Berger, Bastiansen, et al.; Grimm, Berger, DeAngelis, et al.). The ODD protocol represents a well-adapted standard to communicate model descriptions consistently and effectively. The model has been developed in English units as the model is based on harvesting conditions in the Northeastern US and intended for the use in this region.

3.1. Purpose

The purpose of the model was to investigate the productivity of stroke delimber and grapple skidder working on harvest tracts of different sizes and removal intensities. The goal was to gain knowledge about the productivity and time consumption of four different skidding and delimbing behaviors (Table 2). As in real life, bunches consisted of different number of trees with different tree sizes. With results from this model it will be able to judge if the development of new technological communication features would in fact increase machine productivity and reduce waiting times.

Table 2: Description of four different skidding and delimbing behaviors as included in the model.

Scenario	Description
1	In this scenario there is no active communication between grapple skidder and stroke delimber going on. There is no optimization of skidding times through additional processing information. This is our baseline scenario.

2	In this scenario the stroke delimber knows the processing time for each bunch. In addition to that the grapple skidder knows the traveling time for each bunch. Through the combination of the two sources of information the grapple skidder is able to select a bunch that will keep the waiting time for the stroke delimber at a minimum.
3	This scenario uses the same information as scenario 2, but in addition a process improvement feature for the stroke delimber is introduced. The processing time for each tree is reduced by 1 second to improve the stroke delimber productivity.
4	This scenario is similar to scenario 1 but uses two grapple skidders instead of one. This will increase the stroke delimber productivity by reducing the waiting time. (This scenario will not be analyzed in this paper as it is part of a more in-depth analysis)

3.2. Entities, State Variables, and Scales

The model has four kinds of entities: grapple skidder, stroke delimber, bunch, and square patches of land. Grapple skidder and stroke delimber have no state variables, however, several pieces of information are recorded in global variables after each skidding cycle (Table 3). Each bunch has two state variables to describe the bunch size and the distance of the bunch to the landing following a previously laid out trail network. Patches are described by their patch size and the patch color based on landuse such as trail or forest land.

The grapple skidder is a moving agent that travels along a trail network and collects one bunch at a time. A bunch is placed along the trail network with a user-defined spacing between individual bunches. Bunches can only move when a grapple skidder picks them up and carries them to the landing where they are processed by the stroke delimber. The stroke delimber is a static agent that sits permanently at the landing and processes individual trees from a bunch. Several environmental variables are defined by the user; length of the main trail, removal per acre, bunch spacing, hardwood content, delimber processing time improvement, stroke delimber machine rate, and grapple skidder machine rate. The user can further choose to create bunches with equal sizes and select one of the four scenarios. Total width of the harvest tract is predefined at 612 feet. The road is 36 feet wide and next to a landing of 144 feet by 300 feet. The trail system consists of one main trail with side trails leaving the main trail in a 45 degree pattern and 60 foot trail spacing. The temporal extent of the model is the time it takes to skid and process all bunches along the trail.

Table 3: State and global variables of the four model entities.

Entity	State / Global Variable
Grapple Skidder	Total waiting time in minutes Current waiting in minutes Current skidding time in minutes

	Total number of bunches skidded
Stroke Delimber	Total waiting time in minutes
	Current waiting time in minutes
	Current delimbing time in minutes
	Total number of bunches delimbed
Bunch	Bunch size in tons
	Distance to the landing along trail in feet
Patch	Patch size (12 feet x 12 feet)
	Landuse type (trail, forest, landing, road)

3.3. Process Overview and Scheduling

During the model setup the following information is calculated and displayed in output monitors: area harvested (acres), average bunch size (tons), length of main trail (feet), maximum skidding distance (feet). The trail system is put in place during the model setup by the submodel *"create trail"* and populated with bunches by the submodel *"place bunches"*. The model further includes the following processes that are executed in this order during each time step.

Skid bunch. The grapple skidder moves to the nearest bunch along the main trail and brings the bunch back to the landing. Once the main trail is cleared the skidder moves to the nearest bunch amongst the side trails. If the user selects scenario 2 or 3 the skidder moves to the farthest bunch that is within the distance that the skidder can travel during the time the delimber takes to process the previous bunch. The total skidding time is calculated using a regional grapple skidder cycle time function (Table 4).

Skid Two Bunches. This process is only called for in scenario 4 when two grapple skidders are skidding wood from the harvest tract. The process is similar to *"skid bunch"*, however, each skidder delivers wood to their own drop zone at the landing, so that the stroke delimber has two bunches to work with.

Process bunch. During the first run of the "*skid bunch"* process the stroke delimber has no trees to process and therefore has to wait for the skidder to come back. After the skidder brings a bunch the sub-model "*select trees*" calculates the number of trees and individual tree sizes for the bunch. The stroke delimber then processes one tree at a time. The time consumption for each tree is calculated using a regional cycle time function for stroke delimber estimated from empirical data (Table 4).

Update output. This process updates all output monitors and advances time accordingly. Output monitors record the following information: total skidded volume, total time consumption, current grapple skidder time for this cycle, current grapple skidder waiting time for this cycle, total grapple skidder waiting time, grapple skidder waiting time in percent of total time, current stroke delimber time for this cycle, current stroke delimber waiting time for this cycle, total stroke delimber waiting time, stroke delimber waiting time in percent of total time, system productivity (tons/PMH), grapple skidder and stroke delimber total cost ($), grapple skidder and stroke delimber harvest cost ($/ac), and grapple skidder and stroke delimber unit cost of production ($/ton).

Table 4: Description of values used in this model, including source of information.

Description	Value	Source
Cycle time equation for grapple skidder	Cycle Time (min) = exp(1.618 + 0.0005 x OneWayDistance (ft))	Hiesl and Benjamin (2013c)
Cycle time equation for stroke delimber	Cycle Time (min) = exp(-1.247 + 0.099 x DBH (in) – 0.135 x SpeciesGroup (1 = softwood, 2 = hardwood))	Hiesl and Benjamin (2013c)
Standard deviation for the spread of bunch sizes across a harvest site	0.8	unpublished results of Hiesl (2013)
Lamda-value for a poisson distribution that represents the distribution of tree diameters in a given bunch	8.43	unpublished results of Hiesl (2013)
Average removal intensity used in this study (in tons/acre)	40	unpublished results of Hiesl (2013)
Average spacing between individual bunches (in ft)	48	unpublished results of Hiesl (2013)

3.4. Design Concepts

The *basic principle* is to simulate the interactions between grapple skidder and stroke delimber in four different scenarios that include (1) a “normal” harvest, (2) a harvest with perfect knowledge of processing times, (3) a harvest with perfect knowledge of processing times and increased delimbing speed, and (4) the use of two grapple skidders. The choice of perfect knowledge is based on potential technological developments (such as enhanced communication and location-tracking technology) within equipment cabs to accurately estimate processing times.

Grapple skidders *interact* with bunches by removing them from the trail and skidding them to the landing. The stroke delimber processes one bunch, tree by tree, and in scenarios 2 and 3 estimates the processing time for each bunch. In these scenarios grapple skidder and stroke delimber interact directly with each other by exchanging information which alters the skidding behavior of the grapple skidder.

The bunch size is *randomly* chosen using the average bunch size - calculated based on the user chosen removal intensity, bunch spacing, and length of trails – and a previously observed standard deviation of common bunch sizes (Table 4). The tree diameters in each bunch were randomly chosen using a previously observed Poisson distribution (Table 4). A differentiation is made between hardwoods and softwoods, as tree heights and volumes at a given diameter are different.

3.5. Initialization

The simulated harvest tract is created with a fixed height of 51 pixels (612 feet) and a user defined length of between 40 and 210 pixels (480 to 2520 feet). The main trail is located in the center of the world at a height of 26 pixels. Side trails are spurring in 45 degree angles at a spacing of 5 pixels (60 feet). Bunches are placed along the trail system with user defined bunch spacings. One grapple skidder and one stroke delimber are created in scenarios 1 to 3, while a second grapple skidder is created in scenario 4. All equipment starts at the landing.

All time and productivity counters are set to zero. Each bunch has a randomly assigned bunch volume and a distance to the landing calculated based on their location on the trail. The harvest area in acres is calculated during the setup based on the trail system and a 25 foot swath on each side of the trail to represent feller-buncher reach. The average bunch size, main trail length, and maximum skidding distance are also calculated during the setup.

3.6. Submodels

Create Trail: The main trail is placed at the center of the World at a height of 26 pixels (312 feet). Starting at the landing the side trails are spurring off in a 45 degree angle and reach all the way to the boundary. The Spacing between trails is 5 pixels (60 feet).

Place Bunches: The number of bunches on the main trail and for each side trail are calculated during the trail setup based on the user defined bunch spacing. Based on harvest area, removal intensity, and number of bunches the average bunch size is calculated. Using a standard deviation of 0.8 (Table 4) the bunch size for each bunch is randomly drawn. All bunches are placed at the end of each side trail and trails are then populated with bunches towards the main trail. This feature represents common harvesting techniques used in whole-tree harvesting in Maine. During the placement the model periodically checks the total bunch size of all bunches placed on trails and compares it with the total removal for the harvest tract and makes the necessary adjustments in bunch size if the total bunch size is too high.

Select Trees: When a bunch is being processed by the stroke delimber the bunch size is divided into softwood (SW) and hardwood (HW) size based on the hardwood content chosen by the user. SW and HW tree diameters are chosen from a Poisson distribution (Table 4). Each diameter is associated with an average tree size. Individual tree sizes were calculated using Honer's equations (Honer). Balsam fir (*Abies balsamea* (L.) Mill.) and red maple (*Acer rubrum* L.) were used as reference species for softwood and hardwood, respectively. We used average tree heights from unpublished data of Hiesl (2013) for the calculations (Table 5). The tree size of each tree is added up until the bunch size for SW and HW is reached.

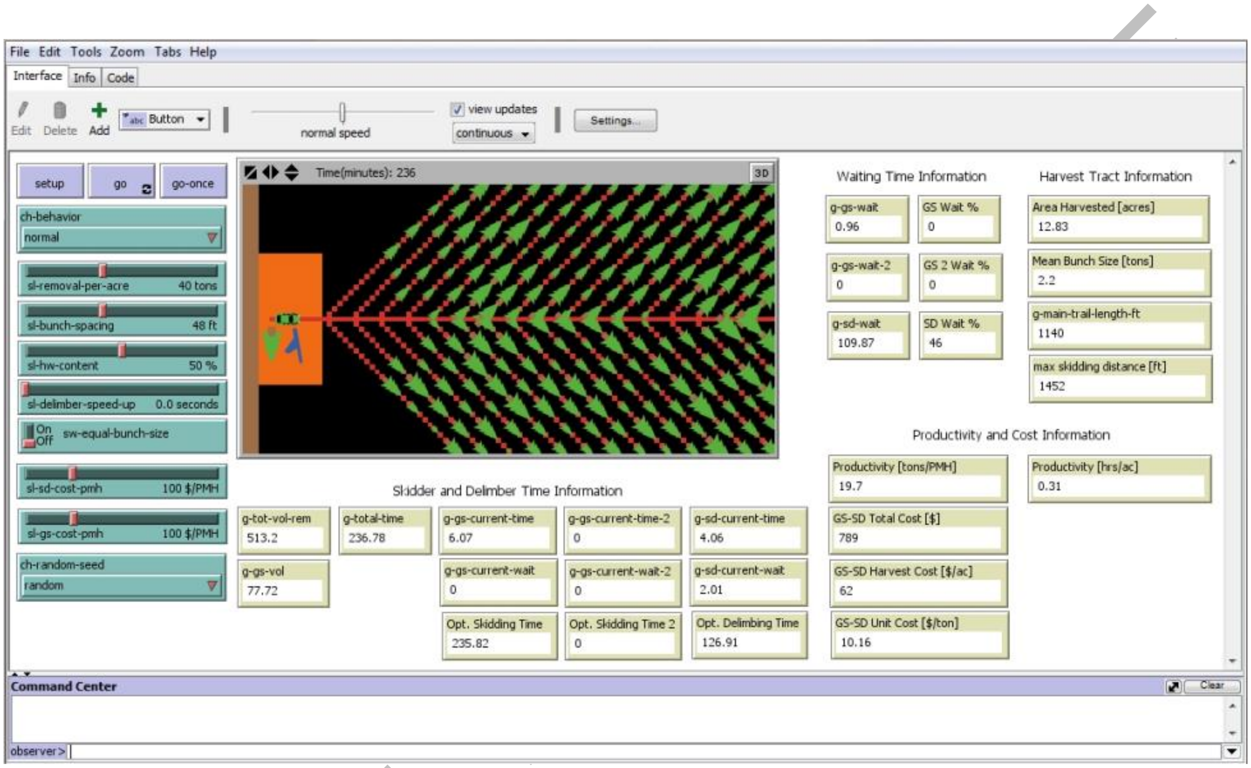
Table 5: Tree diameter, height, and volume for softwood and hardwood trees used in the model (as observed during a study by Hiesl (2013)).

Dbh (in)	**Tree height (ft)**	**Tree volume (tons)**	
		Softwood	**Hardwood**

4	37	0.078	0.071
5	43	0.138	0.126
6	48	0.215	0.201
7	53	0.315	0.280
8	56	0.429	0.408
9	59	0.563	0.540
10	61	0.711	0.657
11	63	0.880	0.854
12	64	1.059	1.030
13	66	1.270	1.241
14	70	1.532	1.512
15	74	1.825	1.819
16	76	2.112	2.116
17	78	2.425	2.440
18	78	2.719	2.736
19	79	3.054	3.080
20	86	3.570	3.658

3.7. Graphical User Interface

To increase the usability of this model a user friendly interface was created (Figure 3). This interface includes several sliders with pre-defined settings to adjust various input variables such as the removal per acre, bunch spacing, or hardwood content. Four grouping of output monitors exist to show the user (1) important time information during each skid, (2) cumulative waiting time information, (3) cumulative productivity and cost information, and (4) general harvest tract information.



Time(minutes): 236

ch-behavior: normal
sl-removal-per-acre 40 tons
sl-bunch-spacing 48 ft
sl-hw-content 50 %
sl-delimber-speed-up 0.0 seconds
On Off sw-equal-bunch-size
sl-sd-cost-pmh 100 $/PMH
sl-gs-cost-pmh 100 $/PMH
ch-random-seed: random

Skidder and Delimber Time Information

g-tot-vol-rem: 513.2
g-total-time: 236.78
g-gs-current-time: 6.07
g-gs-current-time-2: 0
g-sd-current-time: 4.06
g-gs-vol: 77.72
g-gs-current-wait: 0
g-gs-current-wait-2: 0
g-sd-current-wait: 2.01
Opt. Skidding Time: 235.82
Opt. Skidding Time 2: 0
Opt. Delimbing Time: 126.91

Waiting Time Information

g-gs-wait: 0.96
GS Wait %: 0
g-gs-wait-2: 0
GS 2 Wait %: 0
g-sd-wait: 109.87
SD Wait %: 46

Harvest Tract Information

Area Harvested [acres]: 12.83
Mean Bunch Size [tons]: 2.2
g-main-trail-length-ft: 1140
max skidding distance [ft]: 1452

Productivity and Cost Information

Productivity [tons/PMH]: 19.7
Productivity [hrs/ac]: 0.31
GS-SD Total Cost [$]: 789
GS-SD Harvest Cost [$/ac]: 62
GS-SD Unit Cost [$/ton]: 10.16

Figure 3: Screenshot of the model interface.

3.8. Simulation Analysis Methods

To analyze the effect of hardwood component on stroke delimber and grapple skidder idle time the model was run using an average bunch spacing of 48 ft (Table 4), an average removal intensity of 40 tons/acre (Table 4), and varying degrees of hardwood composition (Table 6). To analyze the effect of the different one skidder scenarios we run this setup for Scenarios 1 to 3. We used NetLogo's BehaviorSpace module to run each configuration. The output was analyzed using the statistical software package R (R Core Team). To analyze the effect of bunch spacing and removal intensity on the baseline scenario (Scenario 1) we included a total of six bunch spacings and six removal intensities in the simulation.

Table 6: Variables used in the simulation to analyze the effect of hardwood component on stroke delimber and grapple skidder idle time.

User-Defined Variable	Min-Value	Max-Value	Step-Size	# values tested
Scenario	1	3	1	3
Removal per acre (tons)	40	40	0	1
Bunch spacing (ft)	48	48	0	1
Hardwood content (%)	0	100	25	5
Max One-Way Skidding distance (ft)	732	2,892	240	10
			Parameter Combinations	**150**
			Simulations	**15,000**

3.9. Sensitivity Analysis

A local sensitivity analysis was conducted based on the Railsback and Grimm (2012) analysis structure. The goal of any sensitivity analysis is to understand how sensitive a model is to small changes in the value of input variables. Such information can help to validate the model structure by assessing whether or not specific sensitivities are represented in the model. A local sensitivity changes one input parameter at a time and therefore represents the sensitivity to such one parameter at a baseline of the other input parameter only. In contrast to that, a global sensitivity analysis changes several input values at the same time over a wide range of baseline scenarios to fully investigate the sensitivity of a model. For this local sensitivity analysis we increased the input values of three variables by 10% to calculate the sensitivity value. The baseline values of the three input variables reflect average skidding and delimbing conditions in Maine. These baseline values were determined from unpublished data of Hiesl (2013). The three input variables were chosen based on their known influence on system productivity from other research.

4. SIMULATION RESULTS

Results of baseline scenario (Scenario 1) of the model showed that the system productivity of grapple skidder and stroke delimber was heavily influenced by skidding distance, removal per acre and bunch spacing (Figure 4). System productivity increased with increasing removal intensity, increasing bunch spacing and decreasing skidding distance. Bunch spacing (p<0.001) and removal intensity (p<0.001) clearly indicated a difference in system productivity.

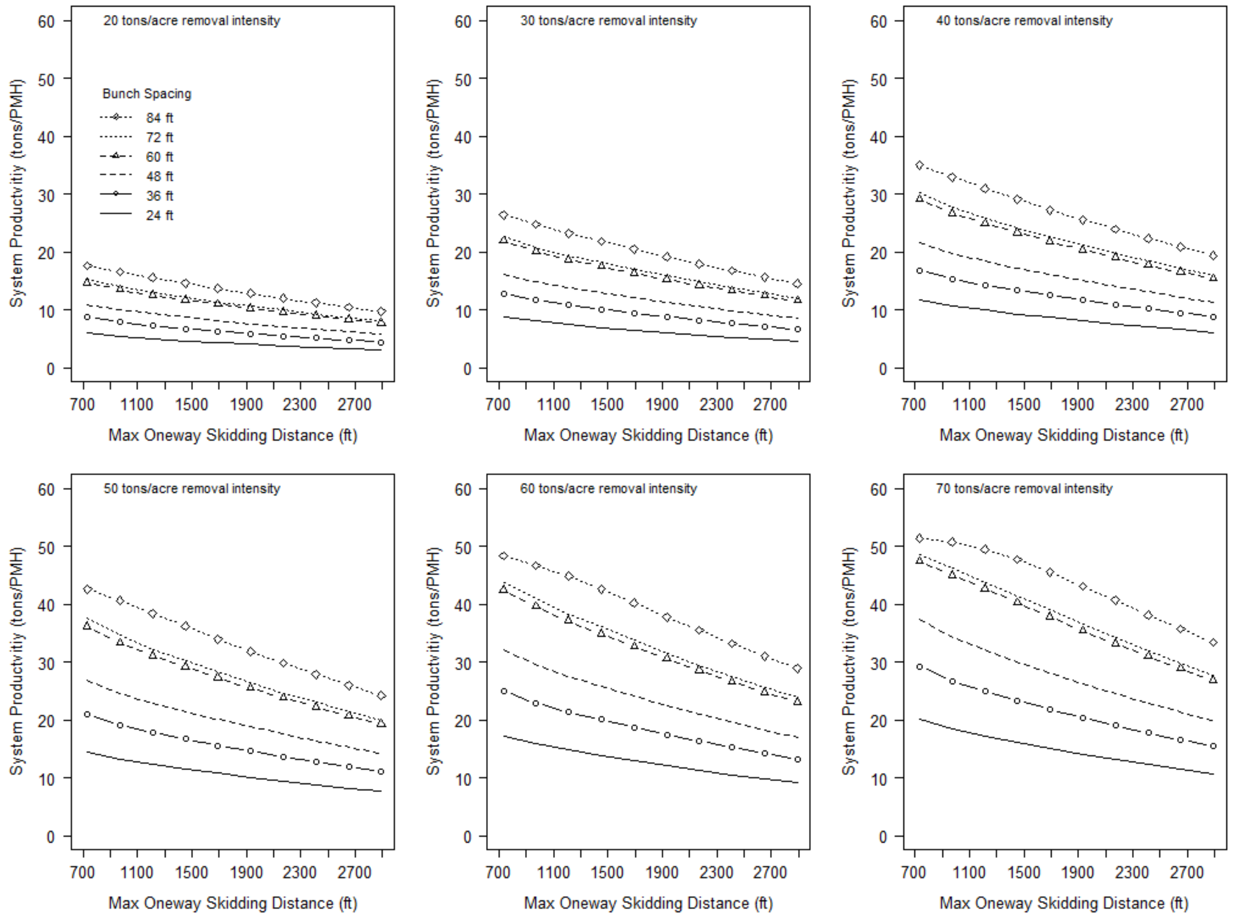


Figure 4: Grapple skidder and stroke delimber system productivity based on removal intensity and bunch spacing with a 50% hardwood component when using the baseline scenario (Scenario 1). PMH = productive machine hours.

The analysis of the effect of hardwood component on stroke delimber waiting time showed that there is a reduction in waiting time with increasing hardwood component (p<0.001). This reduction is up to 13% at short skidding distances and decreases to 7% at the longest skidding distance (Figure 5). No difference was found in the stroke delimber waiting time between Scenario 1 and Scenario 2 (p=0.999), however, there was a difference between Scenario 3 and the other two scenarios (p=0.004). Grapple skidder waiting time was not affected by the change in hardwood component and stayed below 1%.

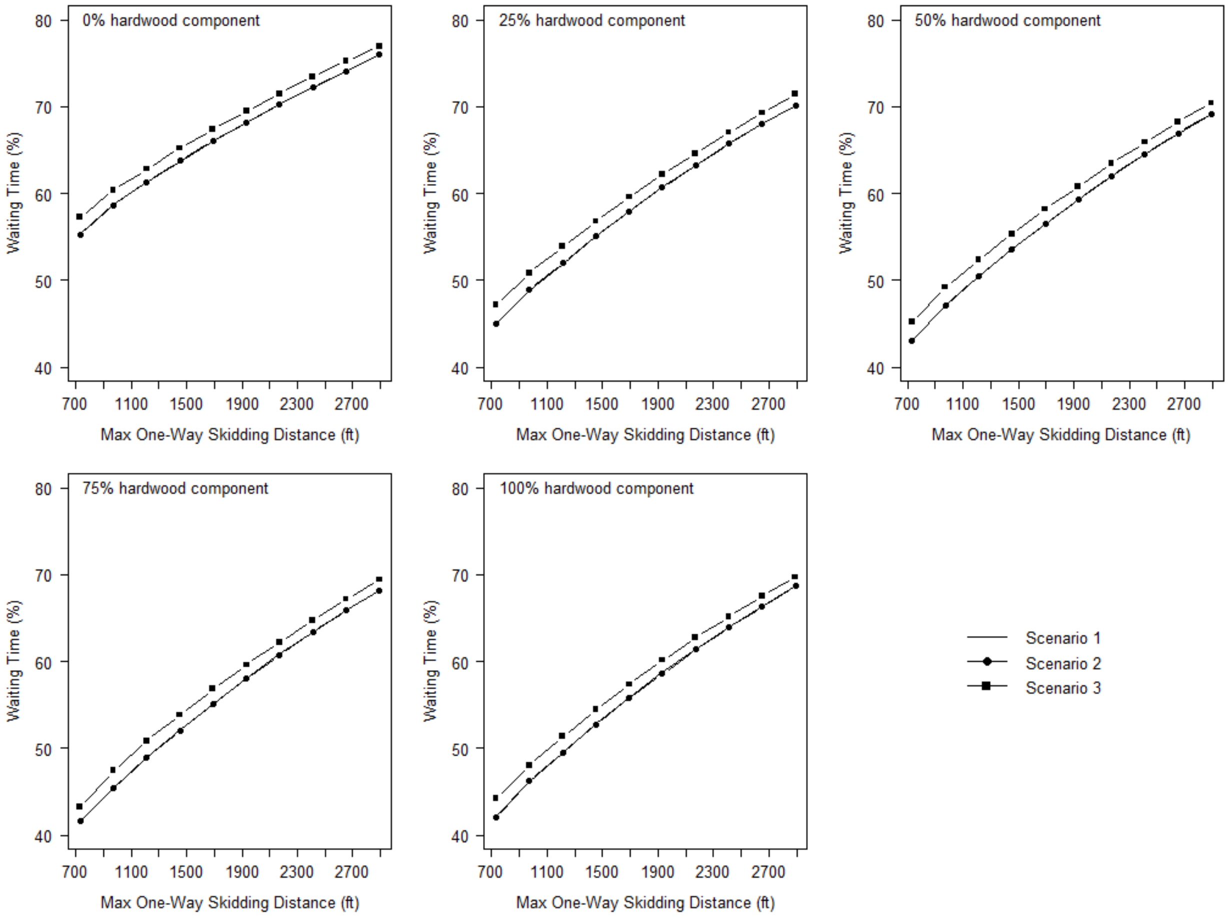


Figure 5: Stroke delimber waiting time based on various hardwood components and an average bunch spacing of 48 ft and a removal intensity of 40 tons per acre. No difference was found between Scenario 1 and Scenario 2 and both lines are approximately on top of each other.

Even though there is a decrease in stroke delimber idle time with increasing hardwood component, our results show that the system productivity is not affected by hardwood component (p=0.922). Further, there was no difference (p=0.998) found in system productivity between the three tested scenarios (Figure 6). Thus, the productivity stays the same whether or not the hardwood component increases, new GIS/GPS tools are used (Scenario 2), or the stroke delimber increases processing speed (Scenario 3). The only influential factor on system productivity is skidding distance (p<0.001). An increase in skidding distance causes a decrease in system productivity.

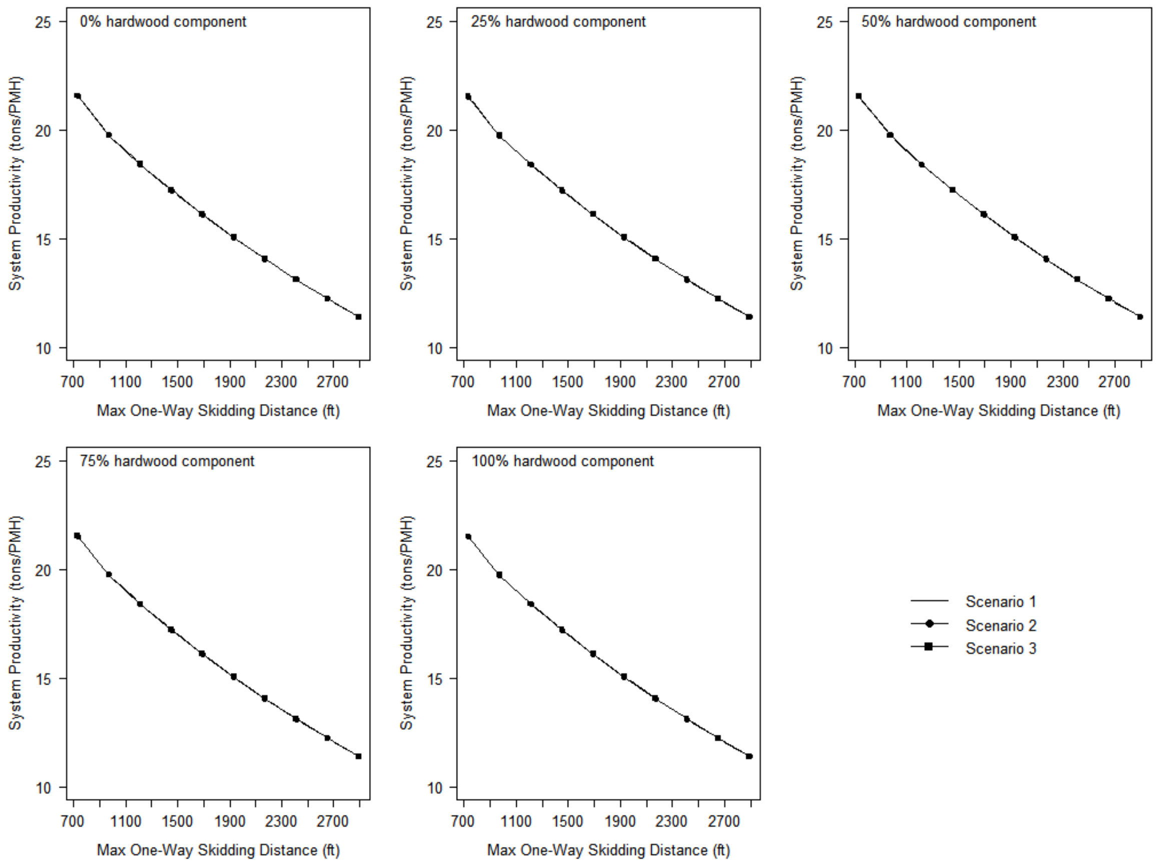


Figure 6: System productivity of a grapple skidder and stroke delimber system based on various hardwood components and an average bunch spacing of 48 ft and a removal intensity of 40 tons per acre . The productivity of all three scenarios is similar and thus the individual lines are overlaying each other.

Waiting time data from Figure 1 shows that a stroke delimber generally waits between 4% and 56% of the time, while a grapple skidder waits between 0% and 27%. These values have been collected from harvest sites with removal intensities ranging from 25 tons/acre up to 67 tons/acre. The waiting times produced by this model (Figure 7) are similar to the range of observed waiting times. This shows that the model is an accurate representation of a stroke delimber and grapple skidder harvesting system.

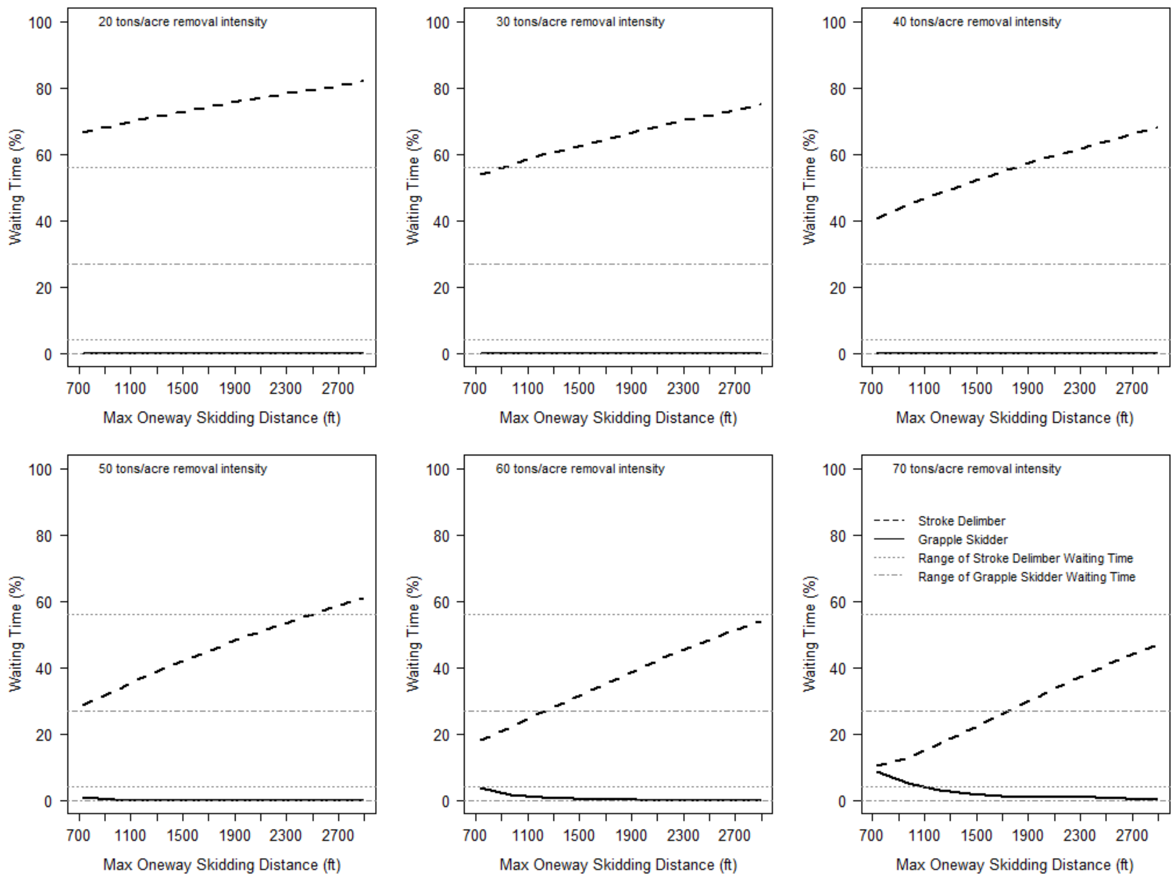


Figure 7: Waiting time for grapple skidder and stroke delimber based on skidding distance and removal intensity with a 50% hardwood component using the baseline scenario (Scenario 1).

5. MODEL EVALUATION

The relationship between system productivity and site specific variables such as skidding distance and removal intensity, in combination with the correct representation of waiting times leads us the assumption that this model is valid and well calibrated. To increase the usefulness of this model to other researchers and the logging community, however, it is crucial to test the model for its sensitivity to parameter combinations.

Local and global sensitivity analyses were used to evaluate the sensitivity of our model to a change in input variables. Results showed that average bunch size had the greatest impact on system productivity, followed by skidding distance (Table 7). The impact of hardwood content on system productivity was very low compared to the other two input variables. Such an analysis is a snapshot of the effect of input variables on system productivity based on baseline conditions that represent average harvesting conditions in Maine. To gain more insight of the effect of these variables based on a variety of harvesting conditions we conducted a global sensitivity analysis (Figure 8).

The global sensitivity analysis shows that the effect of bunch size on system productivity is less intensive at short skidding distances and high bunch sizes and increases with skidding distance and a reduction in bunch size. The effect of skidding distance on system productivity intensifies with an increase in skidding distance. This effect, however, is reduced with an increase in bunch size. A higher softwood component increases system productivity at short skidding distances and high bunch sizes but loses intensity with longer skidding distances.

Table 7: Local Sensitivity Analysis of three input variables.

Parameter	**Reference value**	**Sensitivity value**	**Change in productivity (%)**	**Change in productivity (tons/PMH)**
Skidding Distance (ft)	1,380	-10.51	-4.82	-1.05
Hardwood Content (%)	50	-0.20	-0.09	-0.02
Average Bunch Size (tons)	3.0	22.44	10.29	2.24

Note: Parameter values were increased by 10%.

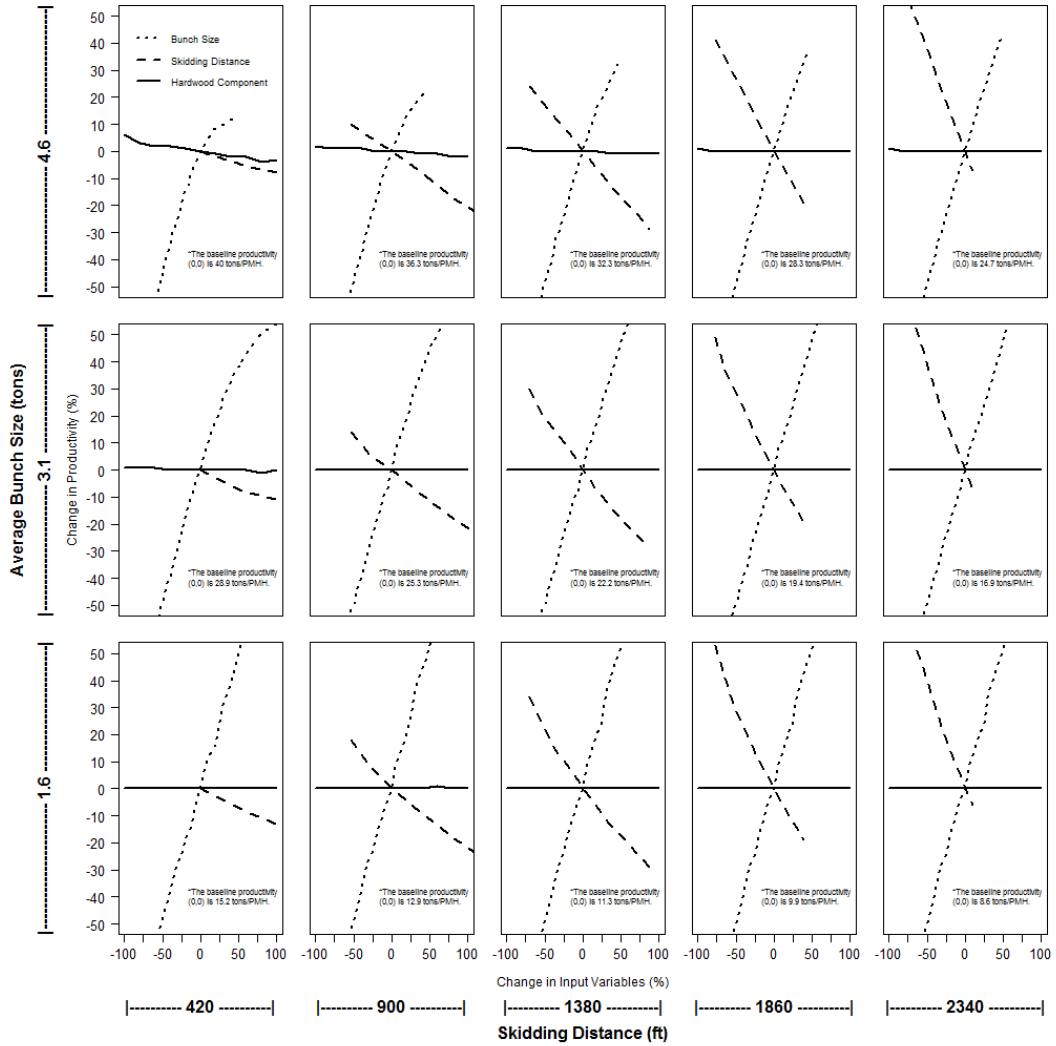


Figure 8: Global Sensitivity Analysis of three input variables based on baseline conditions consisting of a variety of skidding distances (x-axis), average bunch sizes (y-axis), and a 50% hardwood component.

6. DISCUSSION

The use of agent based modeling in forestry is fairly new. Agent-based modeling has been used to investigate and model harvesting decision making of landowners (Leahy et al.), simulate landscape-scale forest ecosystem dynamics (Seidl et al.), and model harvesting scenarios in mangrove forest plantations (Fontalvo-Herazo et al.). Our model is one of the first to apply an agent-based approach to production forestry in a developed country. We further created a graphical user interface in NetLogo (Wilensky) that allows users to vary input variables such as removal intensity, hardwood content, and bunch spacing.

This model uses cycle time equations specifically developed for harvesting systems in Maine. In addition to that all the values and probabilities used in this simulation are from unpublished data of a harvesting cycle time and productivity study by Hiesl (2013). Such empirical data increases the applicability and plausibility of this model. For example, the sensitivity analysis returned skidding distance and bunch size as important factors affecting system productivity. Skidding distance is a well-known factor that affects skidder productivity and has been reported by several researchers (Han et al.; Kluender et al.; Andersson and Evans; Hiesl). Bunch size, or payload, has also been described as a factor influencing grapple skidder productivity (Kluender et al.; Wang et al.). As our model aligns with this previous literature we are confident that the core model dynamics are accurate and well calibrated including the relationship between input variables and system productivity. With the open source characteristic of this model it is possible for other researchers to extend the existing model to include other harvesting systems and management treatments. Such extension could include further calibration, development of other sub-models, or the inclusion of new data. The benefit of our agent-based model is that these changes are relatively simple to implement.

Our results showed that an increase in hardwood component can reduce the waiting time for a stroke delimber but has no effect on the waiting time of a grapple skidder. This results is not surprising as the literature indicates that the stroke delimber processing time is higher for hardwood than it is for softwood species (Hiesl). One reason for this increase in time consumption can be found in the larger branch size and the increased number of forks in the crown. Research with harvesters showed that a large branch size negatively affects processing speed and productivity (Glöde). A stroke delimber uses a similar movement to delimb trees as a harvester does, so it is a reasonable assumption that the same reasons apply here. With the lowest waiting time being approximately 40% it is not surprising that the grapple skidder waiting time is close to zero. Even though there is a negative effect of hardwoods on processing speed, there was a positive effect on waiting time. This is due to the large number of excess time that a stroke delimber has before the grapple skidder can deliver a new bunch. The presented simulation, however, was done based on average bunch spacing and removal intensity. In many situation a land manager or logging contractor has to deviate from these standards and may encounter a more positive or negative effect of a change in hardwood component.

A decrease in stroke delimber idle time, however, does not necessarily mean that there will be an increase in system productivity. Our results showed that hardwood component did not affect system productivity. This can be attributed to the fact that in the presented case the skidding time is not affected by the species mix in each bunch and thus stays the same regardless of hardwood component. This further means that the overall time consumptions stays the same, even though the stroke delimber spends less time waiting for a new bunch. Research indicated that grapple skidder productivity is affected by payload (Hiesl; Kluender et al.; Wang et al.; Y. Li et al.) and thus the results might be different when changing the average bunch size in our simulation. In our analysis, however, we were interested in the effect of varying hardwood components on system productivity and machine idle time when operating under average harvesting conditions. The fact that there is no effect on system productivity therefore indicates that mixed-wood and hardwood stands in Maine can be treated without losing any productivity or increasing harvest costs.

When looking at the system productivity the results further showed that there is no difference in productivity between the three tested scenarios. The surprise was that the use of GIS/GPS (Scenario 2) did not result in any production increase. One reason for this might be the use of one main trail only. This fact limits the grapple skidder in the number of bunches that can be chosen to minimize stroke delimber waiting time. Another reason might be the chosen behavior rule of selecting the bunch that is farthest away but does not cause any more stroke delimber delay. This behavior rule did not include the clearing of the main trail first and thus limited the number of bunches that were accessible. The third scenario included an increase in processing speed of 1 second per tree. This increase in processing time resulted in an increase in stroke delimber idle time. This can be attributed to the fact that the grapple skidder was not delivering bunches any faster and thus the increased processing time left more time for the stroke delimber to wait for the grapple skidder.

In Figure 4 system productivity is shown for varying removal intensities and bunch spacings. Individual productivity curves are fairly uniformly distributed among the different bunch spacings with the exception of the 60 and 72 ft bunch spacing. These two productivity curves are very close and almost overlay each other. The reason for this lies in the bunch placing process of the simulation. Bunches were placed on a side trail starting at the end of a trail and then spacing them by the user defined bunch spacing. For all bunch spacings the number of bunches per side trail decreased with increasing bunch spacing, with the exception of the 60 and 72 ft bunch spacing. In this special case, the number of bunches in each side trail stayed the same, with the exception of a few side trails at the end of the harvest block. Lengthening or shortening the side trails only shifted this process to a different pair of bunch spacings. It is important to notice, however, that this effect also happens at real harvest sites, and thus a change in bunch spacing might not have the sought after effect of increasing bunch size.

Next, this model needs to be applied to investigate system productivity change, and skidder and delimber wait time that emerge from real world harvesting scenarios. For instance, an analysis might seek to answer the question whether or not an investment in various types of communication or spatial awareness technology will result in any productivity gains across varying stand and site conditions, and if so, whether or not this investment will pay for itself during the lifetime of these machines. Further economic calculations should include the unit cost of production as a measure of applicability of any system in the real world at the current market conditions. Many additional alternative management configurations are also possible with an agent-based system because the design of machine behavior and machine-machine interaction is greatly simplified over traditional approaches.

7. CONCLUSION

Our conclusion is that under average harvesting conditions in Maine it does not pay to invest in new GIS/GPS technology, at least not with the proposed behavior rules for such a system. Further, an increased hardwood component, under these average harvesting conditions, does not affect system productivity. This leaves current market conditions as one of the few limitations of treating mixed-wood and hardwood stands in Maine.

Unless the system of grapple skidder and stroke delimber is de-coupled, logging contractors and land managers have to accept that under average harvesting conditions the stroke delimber will wait for trees to be processed at least 40% of its operational time. With machine rates upwards of $100 USD/PMH this means that over $40 USD/PMH are paid for sitting at the landing and waiting for wood. This is money spent without getting any return. Clearly there is a need to find new ways to use these to machines to further reduce the waiting time of either machine and to limit to money spent on processes that do not return any revenue.

8. LITERATURE CITED

Adebayo, A. B., H.-S. Han, and L. Johnson. Productivity and cost of cut-to-length and whole-tree harvesting in a mixed-conifer stand. *Forest Products Journal* 57 (6): 59–69.

Andersson, B., and C. M. Evans. *Harvesting overmature aspen stands in central Alberta*. *Special Report SR-112*. Pointe Claire, PQ, Canada: Forest Engineering Research Institute of Canada (FERIC).

Arii, K., J. P. Caspersen, T. A. Jones, and S. C. Thomas. A selection harvesting algorithm for use in spatially explicit individual-based forest simulation models. *Ecological Modelling* 211 (3-4): 251–266.

Baumgras, J. E., C. C. Hassler, and C. B. LeDoux. Estimating and validating harvesting system production through computer simulation. *Forest Products Journal* 43 (11/12): 65–71.

Bazghandi, A. Techniques , Advantages and Problems of Agent Based Modeling for Traffic Simulation. *International Journal of Computer Science Issues* 9 (1): 115–119.

Bolding, M. C. Increasing Forestry Machine Utilization. *Sawmill & Woodlot* February: 23–27.

Borshchev, A., and A. Filippov. From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools. In *The 22nd International Conferences of the System Dynamics Society*, 23. Oxford, England.

Bradley, D. P., F. E. Biltonen, and S. A. Winsauer. *A Computer Simulation of Full-Tree Field Chipping and Trucking*. *Research Paper NC-129*. St. Paul, MN, USA: U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station.

Dixon, G. E. *Essential FVS: A user's guide to the Forest Vegetation Simulator*. *Internal Report (Revised: October 16, 2012)*. Fort Collins, CO: U.S. Department of Agriculture Forest Service, Forest Management Service Center.

Epstein, J. M. Agent-Based Computational Models And Generative Social Science. *Complexity* 4 (5): 41–60.

Fontalvo-Herazo, M. L., C. Piou, J. Vogt, U. Saint-Paul, and U. Berger. Simulating harvesting scenarios towards the sustainable use of mangrove forest plantations. *Wetlands Ecology and Management* 19 (5): 397–407.

Garner, G. J. *Simulation: A decision making aid for managers. Technical Report TR-30*. Pointe Claire, PQ, Canada: Forest Engineering Research Institute of Canada (FERIC).

Gilbert, N. *AGENT-BASED MODELS*. Quantitative Applications in the Social Sciences. Thousand Oaks, CA, USA: Sage Publications, Inc.

Glöde, D. Single- and double-grip harvesters - productive measurements in final cutting of shelterwood. *International Journal of Forest Engineering* 10 (2): 63–74.

Goulet, D. V, R. H. Iff, and D. L. Sirois. Tree-to-Mill Forest Harvesting Simulation Models: Where Are We? *Forest Products Journal* 29 (10): 50–55.

Grimm, V., U. Berger, F. Bastiansen, S. Eliassen, V. Ginot, J. Giske, J. Goss-Custard, et al. A standard protocol for describing individual-based and agent-based models. *Ecological Modelling* 198 (1-2): 115–126.

Grimm, V., U. Berger, D. L. DeAngelis, J. G. Polhill, J. Giske, and S. F. Railsback. The ODD protocol: A review and first update. *Ecological Modelling* 221 (23): 2760–2768.

Han, H.-S., H. W. Lee, and L. R. Johnson. Economic feasibility of an integrated harvesting system for small-diameter trees in southwest Idaho. *Forest Products Journal* 54 (2): 21–27.

Hiesl, P. Productivity standards for whole-tree and cut-to-length harvesting systems in Maine. Master Thesis, Orono, ME, USA: University of Maine - School of Forest Resources.

Hiesl, P., and J. G. Benjamin. A multi-stem feller-buncher cycle-time model for partial harvest of small diameter wood stands. *International Journal of Forest Engineering* 24 (2): 101–108.

Hiesl, P., and J. G. Benjamin. *Harvesting Equipment Cycle Time and Productivity Guide for Logging Operations in Maine*. Miscellaneous Publications 762. *Miscellaneous Publications 762*. Orono, ME, USA: Maine Agricultural and Forest Experiment Station.

Hiesl, P., and J. G. Benjamin. Applicability of international harvesting equipment productivity studies in Maine, USA: A literature review. *Forests* 4 (4): 898–921.

Hiesl, P., and J. G. Benjamin. Estimating processing times of harvesters in thinning operations in Maine. *Forest Products Journal*.

Holzleitner, F., K. Stampfer, and R. Visser. Utilization rates and cost factors in timber harvesting based on long-term machine data. *Croatian Journal of Forest Engineering* 32 (2): 501–508.

Honer, T. G. *Standard volume tables and merchantable conversion factors for the commercial tree species of central and eastern Canada*. *Information Report FMR-X-5*. Ottawa, Ontario: Canadian Department of Forestry and Rural Development. Forest Management Research and Service Institution.

Huth, A., M. Drechsler, and P. Köhler. Multicriteria evaluation of simulated logging scenarios in a tropical rain forest. *Journal of environmental management* 71 (4): 321–33.

Kluender, R., D. Lortz, W. McCoy, B. J. Stokes, and J. Klepac. Productivity of Rubber-tired Skidders in Southern Pine Forests. *Forest Products Journal* 47 (11/12): 53–58.

Leahy, J. E., E. G. Reeves, K. P. Bell, C. L. Straub, and J. S. Wilson. Agent-Based Modeling of Harvest Decisions by Small Scale Forest Landowners in Maine, USA. *International Journal of Forestry Research* 2013: 1–12.

Leon, B., and J. G. Benjamin. *A Survey of Business Attributes, Harvest Capacity and Equipment Infrastructure of Logging Businesses in the Northern Forest*. *The Northern Forest Logging Industry Assessment*. Orono, ME, USA: University of Maine.

Li, R., A. Weiskittel, A. R. Dick, J. A. K. Jr, and R. S. Seymour. Regional stem taper equations for eleven conifer species in the Acadian Region of North America: Development and Assessment. *Northern Journal of Applied Forestry* 29 (1): 5–14.

Li, Y., J. Wang, G. Miller, and J. McNeel. Production economics of harvesting small diameter hardwood stands in central Appalachia. *Forest Products Journal* 56 (3): 81–86.

Manson, S. M. Validation and Verification of Multi-Agent Systems. In *Complexity and Ecosystem Management: The Theory and Practice of Multi-Agent Approaches*, ed. M. A. Janssen, 63–74. Northhampton, MA,USA: Edward Elgar Publishers.

McCaskill, G. L., W. H. McWilliams, C. J. Barnett, B. J. Butler, M. A. Hatfield, C. M. Kurtz, R. S. Morin, W. K. Moser, C. H. Perry, and C. W. Woodall. *Maine's Forests 2008*. *Resource Bulletin NRS-48*. Newtown Square, PA: U.S. Department of Agriculture Forest Service, Northern Research Station.

Polley, H. Anwendung eines digitalen stochastischen Modells zur Kalkulation technologisch bedingter Wartezeiten. *Beiträge für die Forstwirtschaft* 21 (2): 72–77.

Purfürst, F. T. Learning Curves of Harvester Operators. *Croatian Journal of Forest Engineering* 31 (2): 89–97.

R Core Team. *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.

Railsback, S. F., and V. Grimm. Sensitivity, Uncertainty, and Robustness Analysis. In *Agent-Based and Individual-Based Modeling. A Practical Introduction*, 291–308. Princeton, NJ, USA: Princeton University Press.

Seidl, R., W. Rammer, R. M. Scheller, and T. A. Spies. An individual-based process model to simulate landscape-scale forest ecosystem dynamics. *Ecological Modelling* 231: 87–100.

Spinelli, R., B. R. Hartsough, and N. Magagnotti. Productivity standards for harvesters and processors in Italy. *Forest Products Journal* 60 (3): 226–235.

Wang, J., and C. B. LeDoux. Estimating and Validating Ground-Based Timber Harvesting Production Through Computer Simulation. *Forest Science* 49 (1): 64–76.

Wang, J., C. Long, and J. McNeel. Production and cost analysis of a feller-buncher and grapple skidder in central Appalachian hardwood forests. *Forest Products Journal* 54 (12): 159–167.

Weiskittel, A., and R. Li. *Development of regional taper and volume equations: Hardwood species*. Ed. B. E. Roth. *Cooperative Forestry Research Unit 2011 Annual Report*. Orono, ME, USA: University of Maine.

Wilensky, U. *NetLogo*. Evanston, IL, USA: Center for Connected Learning and Computer-Based Modeling, Northwestern University.