Effects of Orchard Characteristics and Operator Performance on Harvesting Rate of a Mechanical Sweet Cherry Harvester

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***Abstract*— A model was developed to simulate sweet cherry harvesting with a mirrored-pair mechanical harvest system that removes fruit by transferring vibrational energy to tree limbs through an impactor. Six orchard characteristic variables (S_T – tree spacing; S_R – row spacing; N_T – number of trees per row; N_R – number of rows; N_{TB} – number of branches per tree; and W_{TF} – total weight of fruit per tree) and three harvester/operator characteristic variables (v_H – forward speed of harvester, t_{IP} – time to position impactor on actuation point, and t_{PS} – shaking time per actuation point) were the main inputs to the model. Total harvest time (t_{TH}) and harvesting rate were the two output variables of the model. Harvesting rate was evaluated with three different measures: time rate of area coverage (R_{AC}), time rate of tree coverage (R_{TC}), and time rate of fruit removal by weight (R_{FR}). The model was validated with field data, showing very close predictions with modeling efficiencies of 99%, 86%, 82% and 84% respectively for t_{TH}, R_{AC}, R_{TC}, and R_{FR}. Local sensitivity analysis was conducted varying the input variables in five different levels in order to observe their effect on the output variables. A global sensitivity analysis was also performed to identify input variables with significant effects on the output variables. Data from a complete factorial experiment with three levels of input variables in 19,683 combinations was used to perform the global sensitivity analysis. . It was revealed that S_T and S_R only affected R_{AC} by defining the unit area occupied by a single tree. N_T and N_R only affected t_{TH} by determining the number of trees to be harvested, but had no effect on harvesting rate. N_{TB} greatly affected harvesting time and all measures of harvesting rate, and was identified as the most important variable. W_{TF} only affected R_{FR} by determining how much fruit is removed in a single shaking event. Of the harvester/operator variables, t_{IP} affected all the outputs the most whereas v_H affected none. Except for R_{AC}, which was least affected by S_R, t_{PS} had the least effect amid all the significant input variables. These results provide explanation for achieving different harvesting rates in different orchard settings, and can be used to optimize orchard characteristics and adjust operator behaviors for improved performance in mechanical sweet cherry harvesting.**

***Index Terms*—Sweet cherry, mechanical harvester, orchard characteristics, operator effect, harvesting rate.**

I. INTRODUCTION

Fully mechanized harvesting is an ultimate aspiration within the sweet cherry industry. Efforts to develop a fully mechanized harvester and harvest-assist systems are underway at the Washington State University Center for Precision and Automated Agricultural Systems, Prosser, WA. The fully mechanized system being studied is the two-unit harvest system originally developed at the Agricultural Research Services, United States Department of Agriculture (USDA-ARS) [1]–[3]. The original machine has been tested in various orchard conditions with varying performance results reported [3], [4]. Harvest efficiency and harvesting rate are two main performance characteristics reported. [5] reported on some improvements made to the harvest system, which included changing the fruit removal mechanism from rapid impact actuation to a continuous impact actuation and adding a remote control unit to run the entire machine.

It is established that harvest efficiency (percentage fruit removal) is very much influenced by pedicel-fruit retention force (PFRF) [6]. Some sweet cherry varieties (e.g. Skeena) naturally have low PFRF and thus easily release their fruit; others (eg. Chelan) have relatively higher PFRF. High PFRF results in low harvest efficiency, but improvement can be achieved by treating trees with an abscission chemical [7]. Nevertheless, not all sweet cherry varieties respond well to Ethephon, the most common abscission chemical used in Washington State [6]. This limitation has led to the selection of candidate varieties with either naturally low PFRF or with high response to abscission treatment [8]. Another factor influencing harvest efficiency is the tree architecture, which determines the fruit distribution within the canopy. Some architectures like the Spanish bush and central leader systems prevent access to some fruit-loaded branches by the shaker assembly end effector/impactor for fruit removal [3]. Thus, one of the best architectures compatible with the harvest system in question is the 'Y'-trellis system (Fig. 1 in 'Materials and Methods' section).

Several factors could affect harvesting rate of the harvesting system [5] compared results from different studies indicating a wide range of harvesting rate from 12 to 158 trees/h. The test with the highest harvesting rate was conducted with 45°-60° Y-trellis Bing trees having 6 to 8 scaffold branches and treated with an abscission compound to have a low PFRF of 150 g. Two to three rapid impacts were made at multiple actuation points per branch to remove fruit. The test with the lowest harvesting rate was carried out in a 55° Y-trellis Skeena orchard having 6 to 8 scaffold branches which were not treated

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with any abscission compound. Three to four continuous impacts lasting 15 s per actuation point were made at multiple points per branch. Ignoring intrinsic variation in performance of the harvesting system itself, several components of the orchard and behavior of the operator could separately or interactively affect harvesting rate. The major orchard characteristic variables that could affect harvesting rate are tree spacing, row spacing, number of trees per row, number of rows, number of branches per tree, and fruit load per tree. However, the extent of their influence is unknown as there is currently no report on how or how much these parameters affect harvesting rate. A major limitation to conducting a complete experimental study to gain understanding into the effect of various orchard and operator parameters on harvesting rate is the fact that it would require a great amount of resources, including time, financial resources and human resources.

Modeling and simulation can offer tremendous advantages by providing a platform to study parts of systems that otherwise cannot be studied under limited resource circumstances. This approach has been used to understand behaviors of a variety of machines and systems. [9] studied the effect of crop properties on the performance of a combine harvester by correlating mechanical properties of wheat and barley chaff and straw with combine separator and cleaner performance, and subsequently establishing prediction models. Due to complex interactions among several parameters, [10] installed additional sensors on a conventional combine harvester to measure actual cutting width, crop throughput and separation in order to develop a real-time monitoring algorithm for estimating grain separation performance. [11], [12] developed a model to simulate dispersion of airblast sprays and predict spray deposition in citrus canopies. [13] studied how aerodynamic loads affect the performance of wing-based piezoaeroelastic energy harvesters.

However, the potential for modeling and simulation of a sweet cherry harvesting system for harvest performance evaluation has not yet been explored leaving a knowledge gap that needs to be filled. The overall goal of this work is to understand how and to what extent orchard characteristics and harvester/operator variables affect harvesting rate. The specific objectives were to: 1) develop a model to predict harvesting rate of a prototype sweet cherry harvest system, taking into account various orchard and harvester/operator characteristic variables; and 2) carry out computer simulation to study the effect of different orchard and harvester/operator characteristic variables on harvesting rate.

II. MATERIALS AND METHODS

This paper presents the development and validation of a model to predict harvesting rate, as well as sensitivity analyses to study the effects of different orchard and harvester/operator characteristic variables on harvesting rate. Total harvesting time has also been presented with harvesting rate to give an appreciation of the fact that the input variables do not affect harvesting time and harvesting rate the same way. The reader should note that harvesting time is an absolute measure and immediate changes may be observed by varying input variables, which may or may not be intuitive. Harvesting rate on the other hand is a relative measure that may not be affected by changes in certain input variables. Therefore, efforts were made in the discussions to transition from the intuitive knowledge to the new knowledge gained through the study.

A. Model Development

A basic unit size dimension of a typical cherry orchard that defines the crop density is the intra-row tree spacing, S_T (m), x row spacing, S_R (m), dimension (Fig. 1). The number of rows, N_R, and number of trees per row, N_T, along with S_T and S_R, provides the overall size of the orchard. On average, each tree branch will have a certain fruit load which can be represented by the total weight of fruit per tree, W_{TF} (kg), parameter. Average number of scaffold branches per tree, N_{TB}, is another parameter that provides further details on trees trained to Y-trellis and most of the other tree architecture systems.

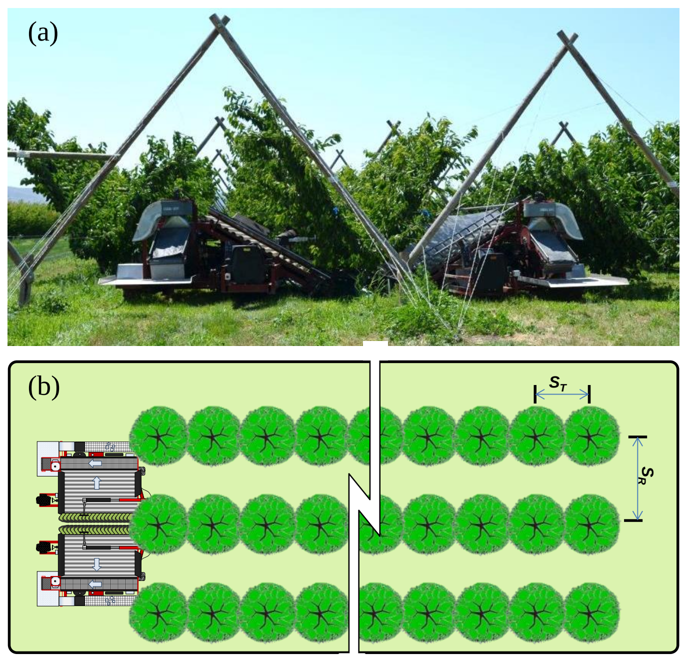

Fig. 1. Prototype mechanical harvest system in a 'Y'-trellis cherry orchard: Back view photograph (a) and top view schematic (b).

The mechanical harvesting system considered in this study (Fig. 1) consists of two half units that are mirrored version of each other (Peterson et al., 2003; Larbi et al., 2013). Each half of the mirror system is used simultaneously to harvest one side of the tree row. During harvesting, each fruit-loaded branch is shook for a few seconds at appropriate actuation points using the end effector of the harvester as the machines concurrently advance forward. For this study, it was assumed that: 1) each scaffold branch is shook only once to release fruit; 2) the duration of each shaking event is the same; and 3) the average fruit removal efficiency, η_{FR} (%) is fixed. The shaking time per branch, t_{BS} (s), comprises the end effector/impactor positioning time (i.e. time to locate actuation point), t_{IP} (s), and the shaking time per point, t_{PS} (s). In this study, since fruit removal efficiency was not a variable being studied (as it is neither a characteristic of the orchard nor the harvester/operator) it was necessary to make it a fixed parameter. Keeping it fixed was not expected to affect the learning gained in the study. t_{BS} is multiplied by N_{TB} to get the shaking time per tree, t_{TS} (s). The fruit removal rate, R_{FR} (kg/min) depends on the average fruit load per branch. Smaller fruit load in the branches is expected to give lower R_{FR}, and vice versa.

Total time to harvest a single tree row is the sum of t_{TS} and the average tree-to-tree drive time, t_{TT} (s) all multiplied by the number of trees in the row, and then subtracted by t_{TT}. The time to harvest multiple rows includes the turnaround time, t_{TA} (s), from one row to another. The t_{TT} and t_{TA} depend on the mean harvester speed, v_H (km/h). For simplicity, it was assumed that the t_{TA} is equivalent to the time taken to travel half the circumference of a circle with radius equal to S_R. Therefore, the total harvest time, t_{TH} (h), is calculated as:

$$t_{TH} = k\left[\frac{N_R\left[t_{TS}\left(N_T\right)+t_{TT}\left(N_T-1\right)\right]+\left[t_{TA}\left(N_R-1\right)\right]}{3600}\right] \quad (1)$$

where

$$t_{TS} = \frac{N_{TB}\times\left(t_{IP}+t_{BS}\right)}{2} \quad (2)$$

$$t_{TT} = \frac{3600\times S_T}{1000\times v_H} \quad (3)$$

$$t_{TA} = \frac{3600\pi\times S_R}{1000\times v_H} = \frac{3.6\pi\times S_R}{v_H} \quad (4)$$

and the constant, k, is the maneuver correction factor (*MCF*). The *MCF* is required to compensate for limitations to maneuverability in between tree rows which results in a much lower effective forward travel speed.

Harvesting rate represents how fast the harvesting process is accomplished. Harvesting rate may be quantified differently based on the need. The various forms used in this study are as follows: 1) area coverage rate, i.e. area covered per unit time; 2) tree coverage rate, i.e. number of trees harvested per unit time; and 3) fruit removal rate, i.e. fruit recovered per unit time. The reciprocals of the above-mentioned forms could also be used, i.e. time per unit area, time per tree, and time per unit fruit weight. The equations to represent these definitions are as follow:

Area coverage rate (ha/h), $$R_{AC} = \frac{S_R\times N_R\times S_T\times N_T}{10000\times t_{TH}} \quad (5)$$

Tree coverage rate (trees/h), $$R_{TC} = \frac{N_T\times N_R}{t_{TH}} \quad (6)$$

Fruit removal rate (kg/min), $$R_{FR} = \frac{N_T\times N_R\times W_{TF}\times \eta_{FR}}{6000\times t_{TH}} \quad (7)$$

B. Model Validation

The model was validated using data extracted from two field tests conducted in 2012. One test was conducted in a Y-trellis Skeena cherry plot in Prosser, WA. The orchard had row spacing of 4.3 m and tree spacing of 1.7 m with a fruit load of 24 to 66 kg per tree. The other test was conducted in a Y-trellis Sweetheart cherry plot in Selah, WA with 3.4 m tree spacing and 4.3 m row spacing. Fruit load varied from 17 to 44 kg per tree in this orchard. In each test, continuous blocks of trees (7 blocks x 5 trees per block in Prosser; 6 blocks x 4 trees per block in Selah) were harvested, shaking one branch at a time. The following variables were recorded for one side of the row: number of branches harvested (1 to 5), duration from start of shaking of the first branch to end of shaking of the last branch on a tree (20 to 715 s), and time to move harvester from one tree to another (9 to 69 s). The shaking time per actuation point was fixed at 10 s for 4 blocks in Prosser and 3 blocks in Selah. Similarly a shaking duration of 15 s was used for 3 blocks in Prosser and 4 blocks in Selah. Fruit removal efficiency in these tests was estimated as a percentage of weight of fruit removed over fruit load on a tree, which varied from 50 to 93% for different test runs. Sixty-one data points were extracted from these two tests for t_{TH}, R_{AC}, R_{TC}, and R_{FR}. Fifteen data points from the Prosser test was used to estimate *MCF* (k = 0.567) and the rest of the entire data (20 from Prosser and 26 from Selah) was used to validate the model.

The model was evaluated by three measures of agreement between the measured and predicted outputs (Table I) based on the entire 46 data points. Bias measured overall deviation of the model from reality and determined for each output whether it over-predicted (negative bias) or under-predicted (positive bias). Correlation coefficient measured the strength of the linear relationship between the measured and predicted outputs. With a range from 0 to 1, a value close to or equal to 1 indicated an excellent model. Modeling efficiency measured the performance of the model against using the mean of the measured output as predictor of each data point. Modeling efficiency has a maximum value of 1 or 100% and the higher the value the better the model. A zero value indicates that the model performs similarly as merely using the mean value of the measured output as predictor. A zero or a negative value represents an impractical model.

TABLE I

MEASURES OF AGREEMENT BETWEEN MEASURED AND PREDICTED OUTPUTS [14]

Measure	Equation [a]
Bias	$Bias = \frac{1}{N}\sum_{i=1}^{N}(Y_i - \hat{Y}_i)$
Correlation coefficient	$R = \frac{\sum\left[\left(Y_i-\bar{Y}\right)\left(\hat{Y}_i-\bar{\hat{Y}}\right)\right]}{\sqrt{\sum(Y_i-\bar{Y})^2\sum(\hat{Y}_i-\bar{\hat{Y}})^2}}$
Modeling efficiency	$EF = 1-\frac{\sum(Y_i-\hat{Y}_i)^2}{\sum(Y_i-\bar{Y})^2}$

[a]i =data point; N = data size; Y_i = measured variable at data point i; $\hat{Y}_i$ = predicted variable at data point i; $\bar{Y}$ = mean of measured variable; $\bar{\hat{Y}}$ = mean of predicted variable.

C. Sensitivity Analyses

Sensitivity analysis was performed in order to increase the understanding of the relationships that exists in the system between input and output variables, to identify the input variables that cause significant effect in the output variables, and to enhance communication of recommendations for horticultural intervention and behavioral adjustments. Local sensitivity analysis is aimed at understanding the effect of a single input variable and involves taking the partial derivatives of output variables with respect to the input variable of interest. For complex equations, the local sensitivity can be estimated computationally by varying the variable of interest while keeping the other variables fixed. Global sensitivity analysis on the other hand is aimed at understanding the changes in the output variables as each input variable varies within their defined ranges, and is useful for identifying input variables that cause significant effects in the outputs.

A local sensitivity study investigating the effects of six basic orchard characteristic variables and three harvester/operator characteristic variables on harvesting time and rate was conducted. Each variable was separately varied over five levels (Table II) to observe the response of various output variables. Four outputs – t_{TH}, R_{AC}, R_{TC}, and R_{FR} – were observed. The levels of input variables chosen were based on practical ranges. For S_R, a minimum of 4.2 m (lower is desirable for higher tree density and yield per unit ground area) is required for the current prototypes of the harvester. In the Results and Discussions section, the local sensitivity analysis results for closely related input variables have been paired and represented as interactions for enhanced visualization and space efficiency.

TABLE II
LEVELS OF ORCHARD AND HARVESTER/OPERATOR CHARACTERISTIC VARIABLES USED FOR STUDY

Orchard Characteristic Variables					Harvester/Operator Characteristic Variables			
Tree Spacing S_T (m)	Row Spacing S_R (m)	No. of Trees N_T	No. of Rows N_R	No. of Branches N_{TB}	*Fruit Load per Tree* W_{TF} (kg)	Forward Speed v_H (km/h)	Impactor Positioning Time t_{IP} (s)	Shaking Time per Point t_{PS} (s)
0.8	3.0	20	10	2	15	0.60	2	2
1.5	3.5	40	20	4	20	0.95	4	4
2.2	4.0	60	30	6	25	1.30	6	6
2.9	4.5	80	40	8	30	1.65	8	8
3.6	5.0	100	50	10	35	2.00	10	10

A global sensitivity of variation in input variables on the output variables was also analyzed using results from a 3^9 complete factorial simulation experiment (with three levels of input variables: low, medium, high; 19,683 combinations in total). Multiple regression analyses of all the input variables were done, yielding analysis of variance (ANOVA) tables. The ratios of the sum of squared errors from the ANOVA tables corresponding to each input variable and the associated total sum of squared errors were calculated as the corresponding sensitivity indices. Sensitivity index, with a maximum value of 1, is the measure of how sensitive an output variable is to the corresponding input variable. This value as a percentage (i.e. multiplied by 100) represents the percentage contribution of the input variable to explaining variability in the output variable, a measure of its importance.

III. RESULTS AND DISCUSSIONS

A. Model Performance

Model outputs were compared with measured field data. Fig. 2 shows a plot of the measured versus predicted outputs of the model, indicating very close predictions for all the outputs. The plots clearly distinguish between data points pertaining to the two orchards and the effect of their parametric differences are seen in the ranges of output variables. A summary of calculated values of the model performance measures are shown in Table III. On average, the model under-estimated t_{TH} (positive bias) but over-predicted all harvesting rate measures (negative bias). However, the correlation coefficient shows near perfect agreement between measured and predicted values. Modeling efficiency, which compares the model's performance against using the mean of the measured output as predictor, indicates an outstanding performance of the model.

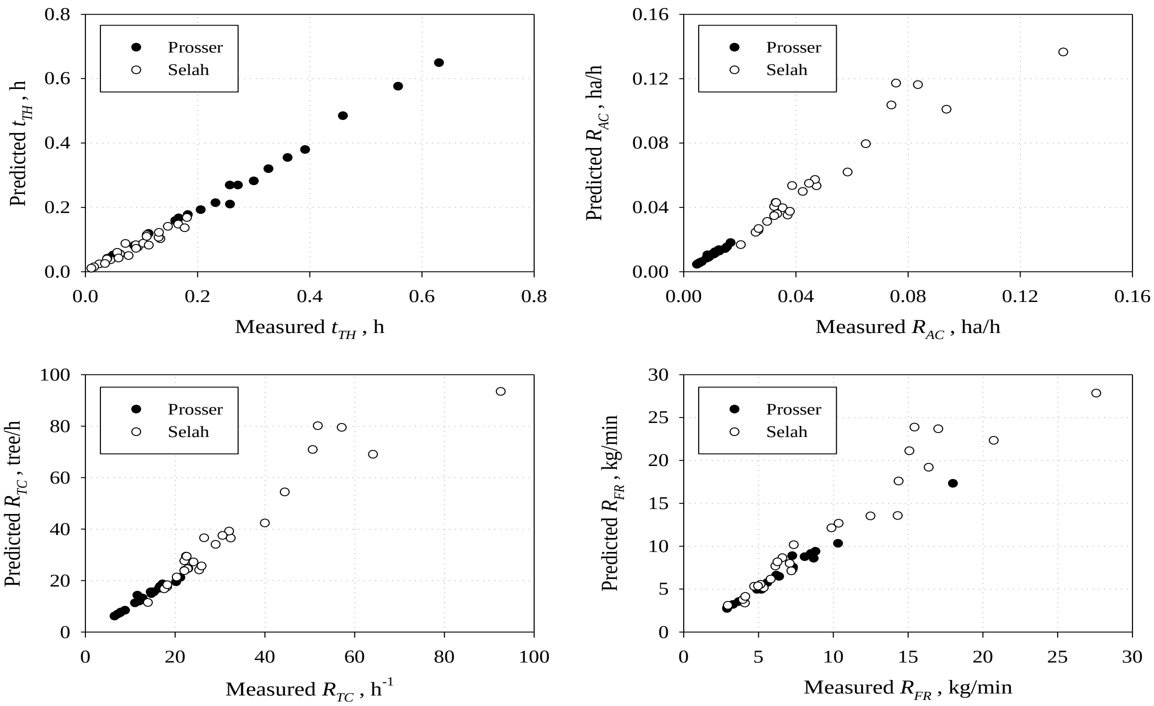

Fig. 2. Correlation between measured and predicted total harvest time, (t_{TH}; $R^2 = 0.990$), rate of area coverage (R_{AC} ; $R^2 = 0.951$), rate of tree coverage (R_{TC}; $R^2 = 0.939$) and rate of fruit removal (R_{FR}; $R^2 = 0.929$).

TABLE III
MODEL PERFORMANCE MEASURES

Measure	Total Harvest Time	Area Coverage Rate	Tree Coverage Rate	Fruit Removal Rate
Bias [a]	0.0073	-0.0047	-3.3108	-1.0174
Correlation Coefficient	0.9950	0.9751	0.9689	0.9640
Modeling Efficiency	0.9861	0.8577	0.8209	0.8350

[a]Units for Bias: h for total harvest time; ha/h for area coverage rate; trees/h for tree coverage rate, and kg/min for fruit removal rate.

B. *Effects of Tree and Row Spacing*

The surface plots in Fig. 3 show the main effects of each characteristic variable along its axis and the interaction between them over the surface. With all other input variables set to their mid-range values, a 0.5-m increase in S_T which increased the total area to be harvested increased t_{TH} by ~6 min and R_{AC} by ~92 m^2/h, but decreased R_{TC} by ~0.8 trees/h and R_{FR} by ~320 g/min. Without further analysis, these changes appear to be insignificant, but that will be revealed by the results from the global sensitivity analysis. Increasing S_R by 0.5 m, which also increased the total area to be harvested, with other variables fixed at their mid-range values, increased R_{AC} by ~50 m^2/h but had no effect on t_{TH}, R_{TC}, and R_{FR}. Increasing tree and row spacing for a fixed area will reduce the total number of trees to be harvested as well as the total harvesting time, but may not affect harvesting rate. However, the actual number of trees to be harvested will depend on the shape of the ground area. For instance, assume a 1 ha orchard having tree spacing of 2 m, row spacing of 4 m, orchard length parallel to row, and orchard width perpendicular to row. Total number of trees for various length x width dimensions will be as follows: 1250 trees for 100 m x 100 m; 1200 trees for 200 m x 50 m; and 1250 trees for 50 m x 200 m. Effects of number of trees and number of rows are discussed in the next sub-section.

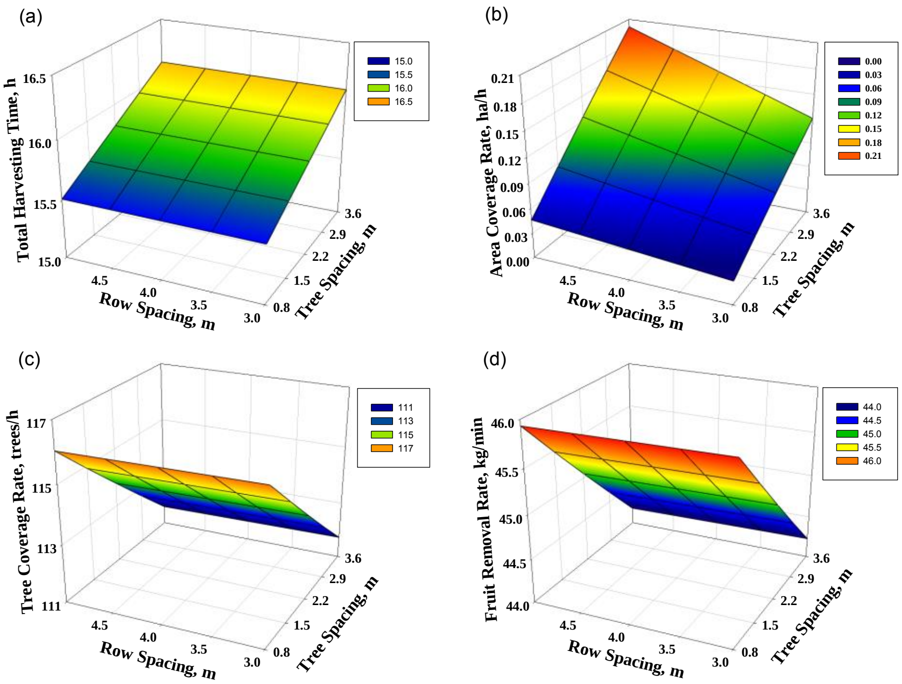

Fig. 3. Surface plot showing interaction of tree spacing and row spacing on total harvest time and harvest rate.

C. Effects of Number of Trees and Rows

Increasing N_T and N_R both increased t_{TH} (Fig. 4). Having either more trees per row or more rows while keeping other input variables fixed increased the number of trees to be harvested as expected, thereby increasing the harvesting time. For instance, an increase of 1 tree per row increases total harvesting time by ~16 min while increasing number of rows by 1 increases harvesting time by ~32 min. However, neither N_T nor N_R affects any measure of harvesting rate. It means that varying the size of the orchard by changing the number of trees per row or number of rows does not affect harvesting rate in any way. Also, the extra time spent to turn around from one row to another has no effect on harvesting rate. Thus, it is reasonable and fair to compare harvesting rate between orchards of different sizes.

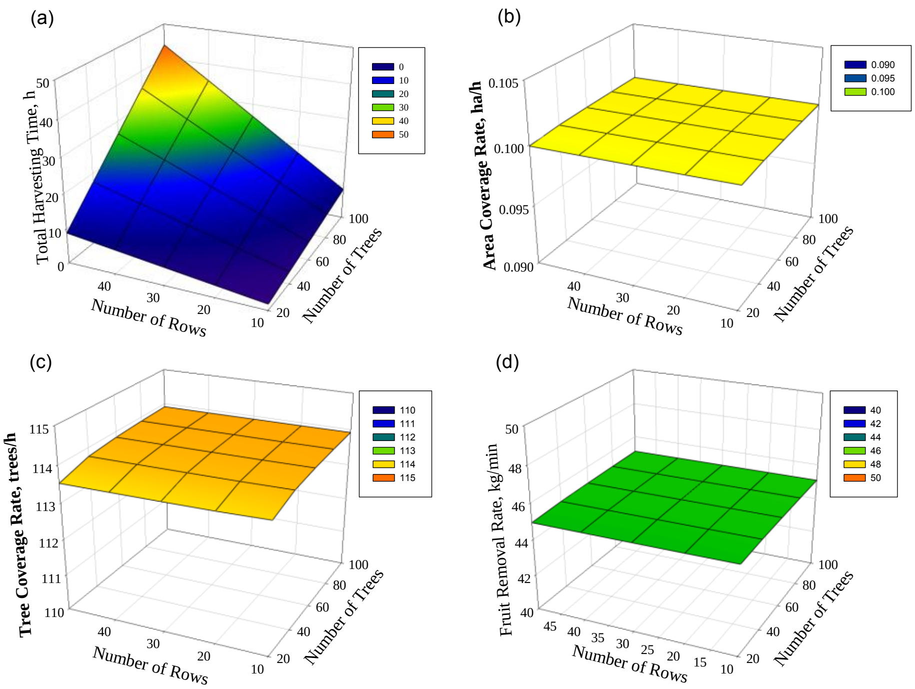

Fig. 4. Surface plot showing interaction of number of trees and rows on total harvest time and harvesting rate.

D. Effects of Number of Branches and Fruit Load

N_{TB} remarkably affects t_{TH}, R_{AC}, R_{TC}, and R_{FR} (Fig. 5). Increasing N_{TB} increases t_{TH} and decreases R_{AC}, R_{TC}, and R_{FR}. This observation suggests that for different orchards with trees trained to have different number of scaffold branches per tree, more time will be spent harvesting the orchard with the more number of branches per tree. This higher total harvest time means lower rates of area coverage, tree coverage, and fruit removal. For example, maintaining the other input variables at their mid-range values, an increase by 1 branch per side of a tree increased harvesting time by ~2.6 h but decreased harvesting rate by the function $aN_{TB}^{-0.95}$, where: a = 0.55 for R_{AC}; a = 626 for R_{TC}; and a = 247.7 for R_{FR}. Increasing from 1 branch to 2 branches per side changed tree coverage rate from 321 to 168 trees/h, a 50% reduction. Varying W_{TF} only affects R_{FR}, but has no effect on t_{TH}, R_{AC}, and R_{TC}. For instance, an increase of 1 kg fruit per tree increases the rate of fruit removal by 1.8 kg/min. This may partly be due to the assumption that a constant η_{FR} is achieved by a constant t_{PS}. In the case where the absolute amount of fruit removed is dependent on the shaking time, i.e. longer duration is required for more fruit, significant interaction between N_{TB} and t_{PS} may exist for R_{AC} and R_{TC}.

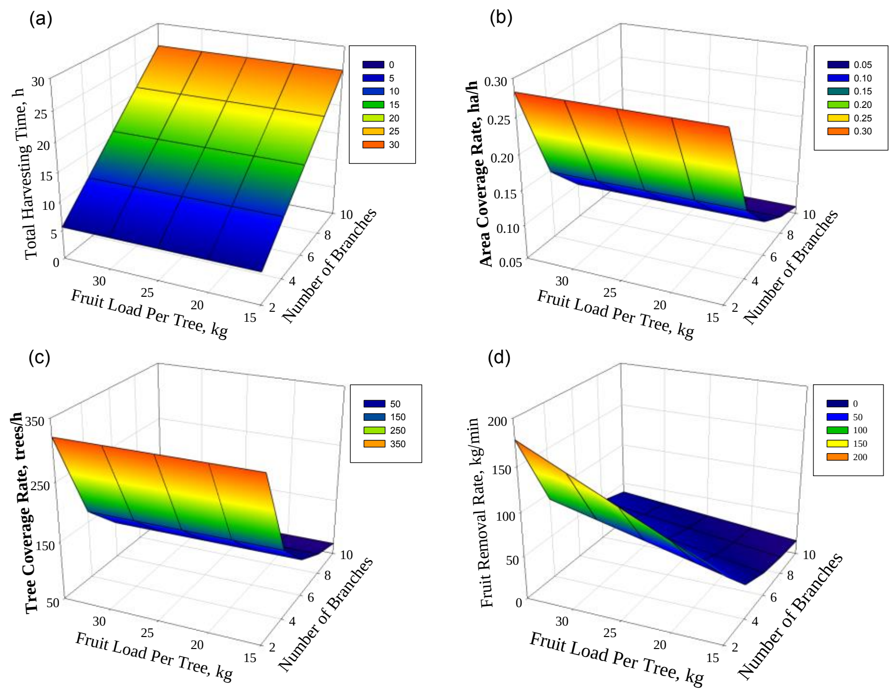

Fig. 5. Surface plot showing interaction of number of branches and fruit load on total harvest time and harvesting rate.

E. Effect of Harvester Travel Speed

Increasing forward travel speed of the harvester caused a reduction in t_{TH} due to reduced time to travel from tree to tree and reduced turnaround time and it increased R_{AC}, R_{TC}, and R_{FR} slightly (Fig. 6). Over the entire travel speed range from 0.6 - 2.0 km/h, t_{TH} reduced by ~46 min, increasing R_{AC} by ~47 m^2/h, R_{TC} by ~5 trees/h, and R_{FR} by ~2 kg/min. However, the gains for R_{AC}, R_{TC}, and R_{FR} are very small due to significantly longer duration the system took in positioning the harvester by the next tree compared to the time gained by faster forward speed. This implies that for different operators of the harvesting system, given that orchard condition remains the same and other operator characteristic variables are held constant, an operator who normally runs the harvester in open field at a faster travel speed will not spend any less time harvesting an orchard even though a skilled operator may be more efficient at positioning the machine.

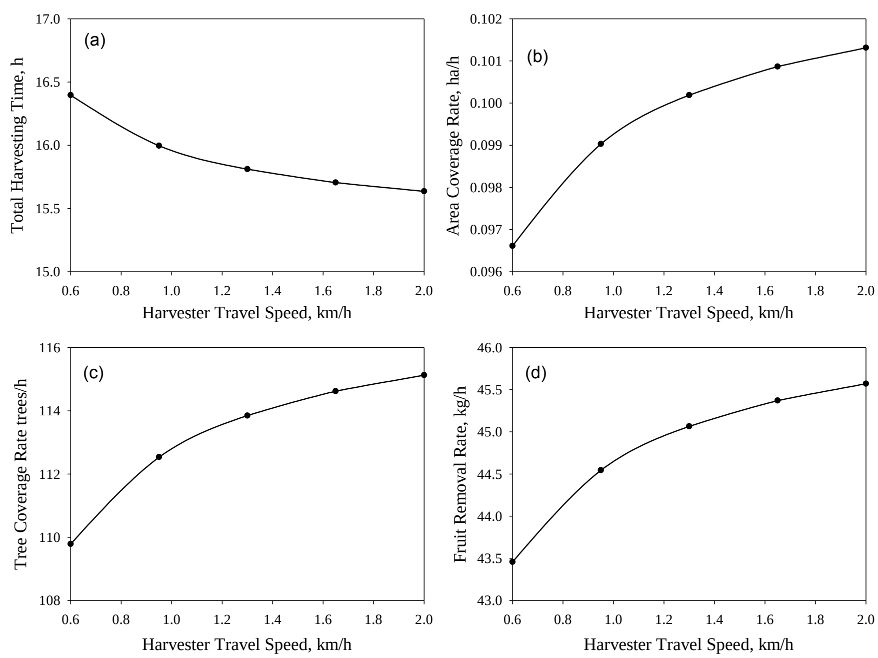

Fig. 6. Effect of harvester travel speed on total harvest time and harvesting rate.

F. Effects of Impactor Positioning Time and Shaking Time

Increasing either t_{IP} or t_{PS} increased t_{TH} and decreased R_{AC}, R_{TC}, and R_{FR}. (Fig. 7). It was found that a 2-s increase in t_{IP} caused ~102 min increase in t_{TH} and a 2-s increase in t_{PS} increases t_{TH} by ~51 s when other variables were kept constant. The relationship between harvesting rate and impactor positioning time can be described by a log function, $-a\ln t_{IP}+b$, where: a = 0.066, b = 0.221 for R_{AC}; a = 75.3, b = 250 for R_{TC}; and a = 29.8, b = 99 for R_{FR}. On the other hand, the relationship between harvesting rate and shaking time per actuation point can be described by an exponential function, $a\exp(0.055t_{PS})$, where: a = 0.141 for R_{AC}; a = 159.8 for R_{TC}; and a = 63.2 for R_{FR}. Interaction between t_{IP} and t_{PS} results in the minimum values of R_{AC}, R_{TC}, and R_{FR} at maximum t_{IP} and t_{PS}. These results showed that greater harvest time will be spent with smaller rates of area coverage, tree coverage and fruit removal if: 1) operator is unskilled and takes more time to position impactor (or end effector) at actuation point on tree branch; or 2) pedicel-fruit retention force (PFRF) is high requiring more time to achieve high fruit removal efficiency.

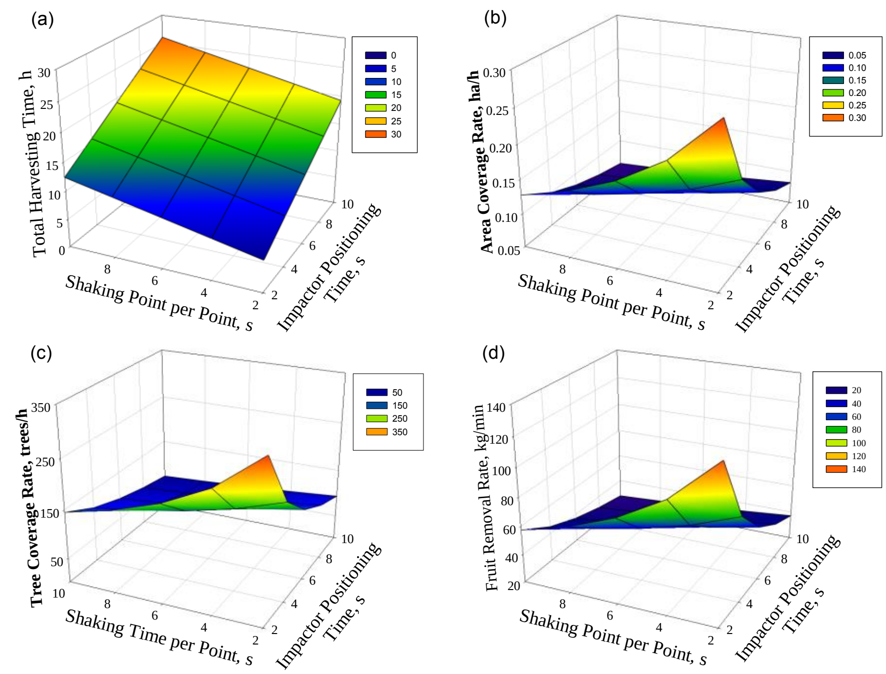

Fig. 7. Surface plots showing interaction of actuation point locating time and shaking time on total harvest time and harvest rate.

G. Significance of Characteristic Variables

Global sensitivity analysis aims at understanding the interplay of independent variables that describe a system, deducing the contributions of these variables to variation in dependent output variable(s) as well as their significance, and ranking them by their importance (extent of contribution). The results of the global sensitivity analysis (Fig. 8) showed the contributions of various orchard and harvester/operator characteristic variables to variation in harvesting time and rate. Only the main effects are captured in this figure.

Tree spacing and row spacing only affected the area coverage rate (19.9% and 3.6% contributions, respectively) by defining the area occupied per unit tree. Number of trees and number of rows did not affect any of the three measures of harvesting rate. Number of branches in a tree highly affected all the output variables (contributions were 18.6% for total harvesting time; 29.4% for area coverage rate; 46.8% for tree coverage rate; and 37.5% for fruit removal rate). Fruit load in a tree only affected fruit removal rate (11.4% contribution) by determining how much fruit was released in a single shaking event assuming constant fruit removal efficiency at a fixed shaking time per actuation point. However, where pedicel-fruit retention force is higher and more time is required to achieve similar fruit removal efficiency, significant interaction between fruit load per tree and shaking time per actuation point may exist. Moreover, if fruit distribution is such that multiple actuation points are required per scaffold branch, then significant interaction between shaking time and number of shaking points per branch may also exist.

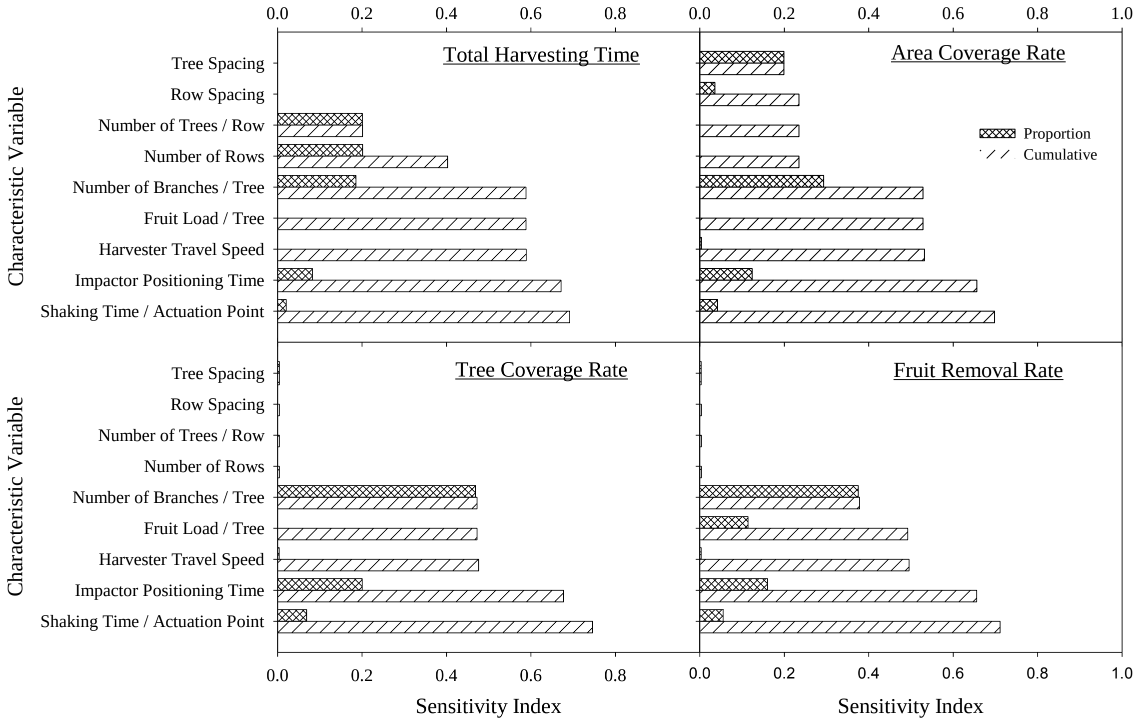

Fig. 8. Sensitivity index showing different orchard and harvester/operator characteristic variables to explaining variation in harvesting rate.

Harvester forward travel speed did not significantly affect total harvesting time or any of the harvesting rate measures and can be considered not relevant to them. Impactor positioning time and shaking time per branch both affected all the output variables with the former contributing more in each case. Among all the significant variables, shaking time per actuation point contributed the least to variation in all the outputs (2.1% for total harvest time, 4.2% for area coverage rate, 6.9% for tree coverage rate, and 5.5% for fruit removal rate), with the exception of area coverage rate where row spacing contributed the least (3.6%).

Overall, the effect of orchard characteristics on harvesting time and rate achieved by the harvesting system is greater than the effect of harvester/operator characteristics. Orchard characteristics contributed a total of 58.9% while operator characteristics contributed only 10.4%. For harvesting rate, orchard condition contributed the following percentages to its variation: 52.8%, 47.3%, and 49.2% respectively to area coverage rate, tree coverage rate, and fruit removal rate. On the other hand, operator effect contributed the following percentages to the variation in the data: 17.0%, 27.3%, and 21.9% respectively to area coverage rate, tree coverage rate, and fruit removal rate. The number of branches per tree is the most important variable affecting total harvesting time and harvesting rate, which underscores the importance of tree training to optimize performance of the mechanical harvesting system. Of all harvester/operator characteristic variables, impactor positioning time contributed the most to variation in total harvesting time (8.3% contribution) and harvesting rate (12.4% for area coverage rate, 20.1% for tree coverage rate and 16.1% for fruit removal rate). An implication is that if the trees being harvested are so densely foliaged such that visibility of appropriate target branches by the operator is very difficult, the extra time spent trying to locate appropriate actuation points will very much increase the total harvesting time while decreasing harvesting rate significantly.

IV. CONCLUSION

A model (set of algebraic equations) was developed to simulate mechanical sweet cherry harvesting with a mirrored-pair harvest system. The model was validated using data from two field tests with modeling efficiency of 82% to 99%. Local and global sensitivity analyses were conducted varying six orchard characteristic variables (tree spacing (S_T), row spacing (S_R), number of trees per row (N_T), number of rows (N_R), number of branches per tree (N_{TB}), and fruit load per tree (W_{TF})) and three harvester/operator characteristic variables (harvester speed (v_H), time to position impactor on actuation point (t_{IP}), and shaking time per actuation point (t_{PS})) in order to understand the effects of these variables on total harvest time and harvesting rate. Harvesting rate was evaluated by three measures: area coverage rate, tree coverage rate, and fruit removal rate. Total harvesting time was found to be affected by N_T (20% contribution), N_R (20%), N_{TB} (19%), t_{IP} (8%), and t_{PS} (2%). Area coverage rate was affected by S_T (20%), S_R (4%), N_{TB} (29%), t_{IP} (12%), and t_{PS} (4%). Tree coverage rate was affected by N_{TB} (47%), t_{IP} (20%), and t_{PS} (7%). Also, fruit removal rate was affected by N_{TB} (38%), W_{TF} (11%), t_{IP} (16%), and t_{PS} (6%). The number of branches per tree stood out as the variable causing the most variation in harvesting rate. The results can be used to optimize orchard characteristics and adjust operator behaviors for improved performance in mechanical sweet cherry harvesting.

NOMENCLATURE

k – maneuver correction factor
N_R – number of rows
N_T – number of trees per row
N_{TB} – number of scaffold branches per tree
PFRF – pedicel-fruit retention force
R_{AC} – time rate of area coverage (ha/h)
R_{FR} – time rate of fruit removal by weight (kg/min)
R_{TC} – time rate of tree coverage (trees/h)
S_R – row spacing (m)
S_T – inter-row tree spacing (m)
t_{BS} – shaking time per branch (s)
t_{IP} – end effector/impactor positioning time (s)
t_{PS} – shaking time per point (s)
t_{TA} – turnaround time (s)
t_{TH} – total harvest time (h)
t_{TS} – shaking time per tree (s)
t_{TT} – tree-to-tree drive time (s)
v_H – harvester speed (km/h)
W_{TF} – total weight of fruit per tree (kg)
η_{FR} – average fruit removal efficiency (%)

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