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Field Capacity and Harvest Efficiency Evaluation of Traditional Small Box and Semi-Automated Bin Handling Systems for Wild Blueberries †

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Abstract: Mechanical harvesters with small box and semi-automated bin handling systems are increasingly being used for harvesting wild blueberries in Eastern Canada, and Northeastern, USA. However, their field capacity and performance have not been quantified and compared. Important measures of field capacity and efficiency for a traditional mechanical harvester were compared with a novel semi-automatic bin handling harvester. Data were obtained from on-farm field trials conducted at four sites in Nova Scotia, Canada in 2017 and 2018. Both harvesters had double head configurations, along with other similar engineering configurations: (i) 0.66 m picking reels; (ii) 16 picker bars per head and 65 teeth per bar; (iii) 1.72 m picking width; (iv) 21 rpm head speed; and (v) 0.31 ms^{-1} ground speed. Each harvester was operated for 120 min and data such as berry harvesting time and box handling time were recorded, with six replications during each year. Statistical methods were used to compare the harvest efficiency of the two mechanical harvesters. Harvest time efficiency was significantly higher for the semi-automatic bin handling technology than for the small box handling technology both in 2017 ($p < 0.001$), and 2018 ($p < 0.001$). Weed coverage did not have a significant effect of harvest time in either 2017 ($p = 0.694$) or 2018 ($p = 0.765$), though it did significantly affect yield in both 2017 ($p = 0.011$) and 2018 ($p = 0.045$). The findings provide useful insights for decision-makers contemplating the choice of harvesting technology to sustain profits from wild blueberry production.

Keywords: automation; efficiency; field capacity; mechanical harvester; mechanization; wild blueberry

1. Introduction

Wild blueberries are low growing plants with average height range from 0.10 to 0.16 m [1]. Wild blueberry production commonly follows a two-year cycle with vegetative growth occurring in the first year, followed by berry formation and harvest in the second year [2]. New shoots begin by developing from dormant buds on underground rhizomes [1] during the vegetative year. Plant stems continue to grow until tip-dieback in July and development of floral buds starts from August until October. Over winter, wild blueberry fields are covered with snow, and plants remain dormant until the floral buds develop in Spring [3]. Flowering starts in May of the fruit year and fruit development continues until harvest in mid to late August. The wild blueberry crop is then pruned by flail mower or burning in early Spring of the vegetative year or late in the fruit year after harvest. This is done to improve plant dominance by controlling grass and weed germination and to encourage more vigorous fruit producing stems to emerge in the subsequent year [1,4].

The principal challenges facing wild blueberry producers during harvesting are declining labour availability [5], short harvesting windows [6], high labour wages [7], high overall harvesting costs [8,9] and the over 43,000 ha of harvestable wild blueberry land each year [10]. Seasonal labour for wild blueberry production in Atlantic Canada continues to be in short supply. For wild blueberry production, the farm labour challenges are particularly critical during the short harvesting season, from mid-August through early-September as increased labor is needed to harvest the crop. Further, expansion in wild blueberry area under production, has prompted a need for more efficient berry harvesting systems. Investment in labour saving technologies has the potential to address constraints to further expanding crop hectarage [11] and enhancing worker productivity [12]. Further complicating this issue is the vast differences in harvestable yield between fields which can range from 1000 kg ha^{-1} to 8000 kg ha^{-1} [13,14]. As the harvestable yield increases the harvesting speed must decrease to maintain berry quality which subsequently, increases the total harvest time. Increased adoption of mechanical harvesters has the potential to reduce overall cost of production and save time compared with less efficient alternatives such as manual hand raking [4].

Doug Bragg Enterprises (DBE) are the only large-scale producer of wild blueberry harvesters in the world with over 1500 operational today [15]. Over the past few years, they have been designing and implementing a semi-automatic bin handling system for their harvesters which utilizes hydraulics to fill and offload blueberry storage bins. This new system was designed to replace their traditional small box handling system. A comparison of the primary components of each system can be observed in Table 1, and an image of each system can be observed in Figure 1.

Table 1. Comparison of major characteristics of harvesters with alternative handling systems.

Handling System Components	Small Box Handling System	Semi-Automatic Bin Handling System
Tractor	Minimum 75-kilowatt (kW) farm tractor	
Harvester configuration	0.66 m picking head 16 picker bars per head 65 picker teeth per bar 0.86 m wide swath width per head Double head configuration (1.72 m effective picking width)	
Debris removal method	Blower fan	Blower fan with wind flow isolator
Box stacking and loading	Rear platform for manual stacking of boxes	Hydraulic rear handling system operated by tractor operator
Box loading/unloading	Manual labour	Loader tractor with forks
Empty box weight	1.36 kg	30 kg
Average weight of berry filled boxes	12 kg	136 kg

Figure 1. Image of semi-automated bin handling system (**left**) and small box handling system (**right**) on.

Doug Bragg Enterprises (DBE) Wild Blueberry Harvesters

The semi-automated bin handling system is pitched as being more efficient from both a cost and time savings perspective when compared with DBE's traditional small box handling system [15]. The semi-automated bin handling system eliminates the need for a second laborer to manually fill and change boxes and reduces the number of stoppages needed to load and offload boxes. This should all lead to improved field harvest efficiency in terms of area harvested per unit time. Akin to both systems is the harvesting mechanism in which, the reel of the picker head rotates common to the direction of the moving tractor. Comb type picking bars rake the berries from low growing plants and deposit them onto a side conveyer which move the berries toward the rear of the harvester. A blower fan removes debris at the end of the side conveyor. For the small box system, berries are collected by a laborer at this point. For the bin handling system, berries fall onto a rear conveyor which transport the berries to the large bins at the rear of the harvester. A process diagram for both systems can be seen in Figure 2.

Despite the potential efficiency improvements, the semi-automatic bin handling system comes at additional equipment cost compared with the small box handling system. That said, the increased cost associated with upgrading to the semi-automatic bin handling system may be offset by labour savings, and overall increased field harvest efficiency which could prove to justify the cost. Economics of the two handling systems were analyzed by Khan et al. 2020 [16]. The major takeaway from this work demonstrated a difference in net profit between the two systems of CAD\$674 ha^{-1} in 2017 under high yield conditions and CAD\$175 ha^{-1} under lower yielding conditions.

Performance of harvesters with the two handling systems have never previously been quantified and compared. Specifically, their performance in terms of harvest rate, field capacity and efficiency, have not been evaluated. Technical information on wild blueberry harvester field capacity is critical for optimizing production and management operations including scheduling field operations, optimizing farm labour use, and estimating berry harvesting cost and overall cost of production. Producers can enhance profit margins by adopting more efficient harvesting systems and the results of this study will be critical for growers when making this determination.

Studies have evaluated various mechanical harvesters for selected crops by quantifying and comparing several aspects of harvesting operations including harvest time and handling time [17,18], harvest rate [19,20], and field efficiency [21,22]. Harvest time and rate are important components of harvesting operations as producers often have limited time to harvest their crop. Field efficiency is also an important determinant of the performance of the harvester handling systems. In wild blueberries, this metric is often influenced by topography and fruit density as well as harvester handling parameters. Technical information on the components of total harvest time (especially when decomposed into harvest time and handling time) and harvest rate for wild blueberry mechanical harvesters are important and of interest to wild blueberry farmers and harvester manufacturers. This data has never been quantified and results can lay the groundwork for further harvester efficiency improvements in the long run while providing significant short-term benefits for growers.

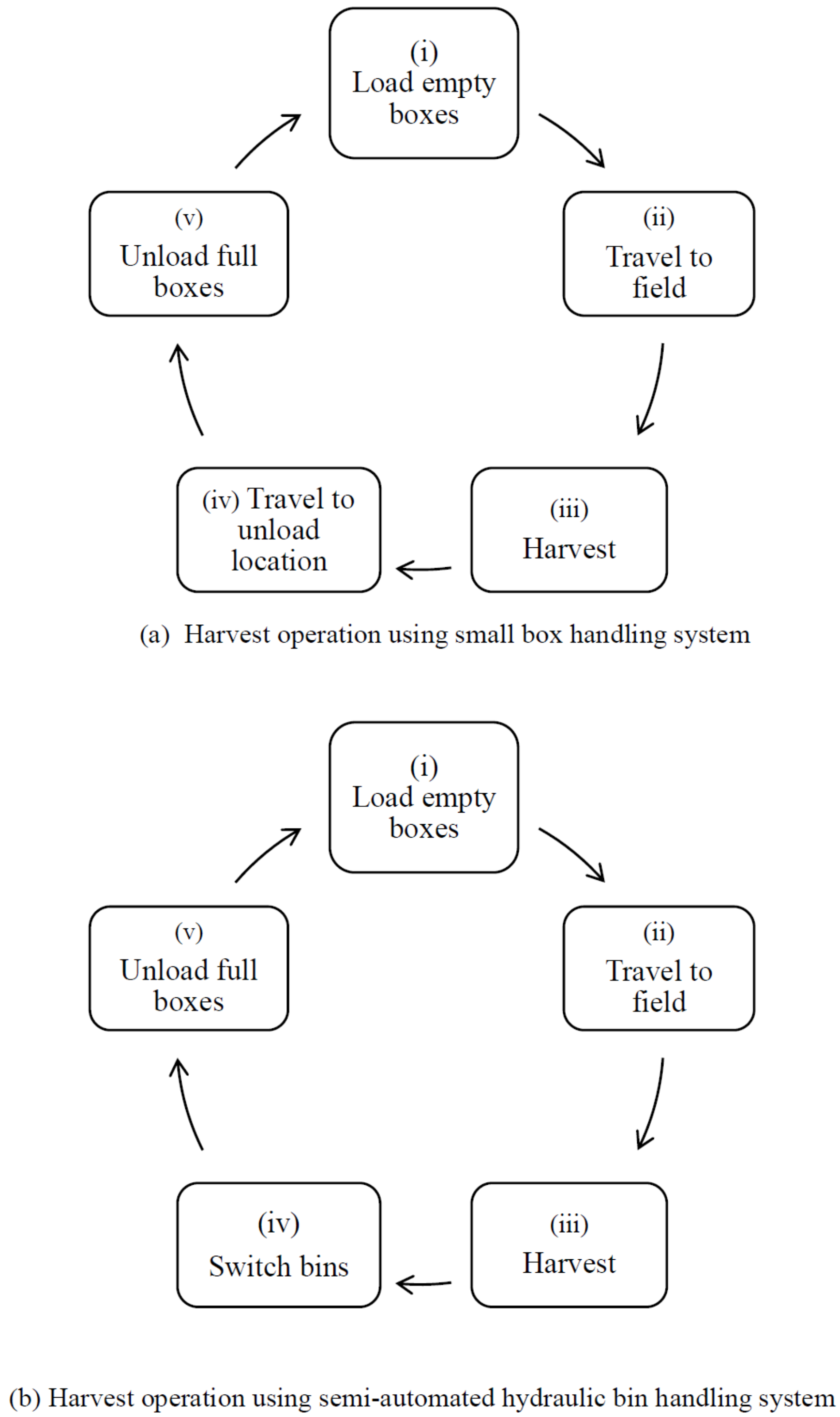

Figure 2. Process diagram for the small box handling system (**a**) and the large bin handling system (**b**).

The objective of this study was to quantify and compare the harvest efficiency of wild blueberry mechanical harvesters with both the small box handling system and the semi-automated bin handling system under actual harvesting conditions. The first objective was to quantify, decompose, and compare machine harvest time and berry handling times of mechanical harvesters with the two box handling systems. Handling time was explicitly decomposed into box loading time and unloading time. The second objective was to quantify and compare harvest rate of the small box handling system with similar parameters for the semi-automatic bin handling system. This novel study to assess wild blueberry harvester efficiency will have the ultimate benefit of providing growers with the tools necessary to make an informed decision on whether to upgrade their harvesters. It will also lay the groundwork for further innovation of wild blueberry harvesters by providing critical harvesting and handling data.

2. Materials and Methods

2.1. Study Fields

Field harvesting trials were conducted during 2017 and 2018. In 2017, field trials were conducted on a five-hectare fruit field in central Nova Scotia, Canada (45°42′65.59″ N, −63°49′66.56″ W, 5-hectare field) near Debert (Figure 3). In-field investigation into harvesting operations allowed for compiling data that reflects actual cropping conditions. The field trials were conducted on 27 and 28 August 2017. The harvesters fitted with the small box handling and semi-automatic bin handling systems were operated by different harvester operators with similar skill and experience.

Figure 3. Boundary map for Debert field.

In 2018, field experiments were conducted in two wild blueberry fields in Portapique (45°40′88.79″ N, −63°72′35.65″ W, 2-hectare section of field) and Antigonish (45°55′71.51″ N, −61°72′61.77″ W, 2-hectare section of field), Nova Scotia (Figure 4). Field harvesting trials were carried out on 19 and 20 August 2018 in Portapique and 23 and 24 August 2018 in Antigonish.

Figure 4. Boundary maps for Portapique (**left**) and Antigonish (**right**) fields.

For each of the fields studied in both years, recommended agronomic and management practices were implemented over the past decade, including herbicides, fungicides, insecticides, induced pollination, and mechanical pruning. That said, berry production throughout the Maritimes was affected by frost damage in 2018 [8] resulting in significant reduction in harvestable fruit compared with 2017. During each of the harvesting dates, conditions were similarly sunny and dry. Weather conditions for each of the harvest sites and dates can be observed in Table 2.

Table 2. Weather data for each of the sites and harvest dates used in this study.

Fields	**Debert**		**Portapique**		**Antigonish**	
Sampling dates	27 August 2017	28 August 2017	19 August 2018	20 August 2018	23 August 2018	24 August 2018
Minimum temperature, °C	8.3	5.6	15.0	12.0	18.0	13.0
Maximum temperature, °C	20.4	22.8	23.0	24.0	27.0	25.0
Mean temperature, °C	14.4	14.2	19.0	18.0	22.5	19.0
Rain, mm	0.0	0.0	0.3	0.0	0.1	0.0

2.2. Description of Mechanical Harvesters

In this study, a mechanical harvester with small box handling system was operated with a 100 kW tractor while an 82 kW tractor was used for the semi-automatic bin handling system. A 48 kW loader tractor was also used in both years for loading and unloading the large bins. The two harvester systems were fitted with double-head harvester configurations with a 1.72 m effective picking width. Both harvester heads had a similar configuration of 0.66 m (diameter) picking reel, 16 picker bars and 65 tooth configurations (Table 1). Both harvesters were operated at a ground speed of 0.31 m s^{-1} and head speed of 21 rpm.

2.3. Analyzed Parameters

The two primary methods used for comparing the two harvesting systems were harvest time and harvest rate. Harvest time was defined as the time in which the harvester is actively harvesting fruit over a two-hour period. The component of time in which the harvester was not harvesting fruit during the two-hour period was defined as handling time. Handling time for the small box system is the time to travel to the unloading location on the edge of the field, the time to return to the picking location and the period in which boxes are being loaded and unloaded from the harvester. Handling time for the semi-automated bin system is the period in which bins are being loaded and unloaded only as full bins are dropped in field and picked up by a second tractor with this system.

Harvest rate was defined in hours per hectare [23] and is represented by Equation (1) [24]:

$$HR = \frac{2.78}{S * W * FE} \tag{1}$$

where HR is the harvest rate (h ha^{-1}), S is the average speed of the operating harvester (m s^{-1}), W is the working width of the harvesters picking heads (m) and FE is the field efficiency (unitless). The constant 2.78 was determined by dividing the number of square meters in a hectare by the number of seconds in an hour [24]. Field efficiency was calculated by dividing the total harvesting time by the total time (harvesting plus handling). In each of the analyses, speed was maintained at a constant 0.31 m s^{-1} and a working width of 1.72 m was used on both harvesters.

2.4. Experimental Design

Data collected from 2017 and 2018 had to be analyzed separately due to the significant difference in harvestable yield resulting from the late frost event of 2018 [8] and the usage of multiple fields in 2018. Multiple fields had to be used in 2018 due to limitations in equipment accessibility and an inability to test both systems in the same field.

A Completely Randomized Design (CRD) was used to compare the difference in harvest time and rate between the small box handling system and the semi-automated bin handling system. Each harvester was operated for two hours, with six replications during each year. Total harvest time and handling time during harvesting were measured manually using a stopwatch. Berries harvested during each replication were weighed using an electronic industrial weighing scale (M1, Western Scale Co. Ltd., Port Coquitlam, BC, Canada) at a privately-owned wild blueberry receiving shed in Debert, Nova Scotia. During each replication, conditions were visually classified as either weedy or non-weedy. Weedy conditions were determined to be areas of more than 25% weed coverage and occurred primarily towards the outer extents of the three fields. All three fields saw similar weed profiles with narrowleaf goldenrod (*Euthamia graminifolia* L. Nutt.) being the predominant weed towards the outer extents of the fields and hair fescue (*Festuca filiformis*) and tickle grass (*Agrostis scabra*) being scattered throughout the inner portions.

All statistical analyses were performed using Minitab 19 (Minitab Inc., New York, NY, USA) using two-sample *t*-tests. All data was checked for normality and constant variance prior to analysis.

3. Results and Discussion

3.1. Comparison of 2017 and 2018 Data

Using a two-sample t-test it was determined that the mean harvest times in 2017 and 2018 were significantly different for both the small box handling system ($p = 0.015$) and the semi-automated bin handling system ($p < 0.001$; Table 3).

Table 3. Mean harvesting times for a 2.00 h period for both the small box handling system and the semi-automated bin handling system for 2017 and 2018.

Year and Harvester Handling System	Mean Harvesting Time (h)
2017 Small Box	1.45 ± 0.04
2018 Small Box	1.51 ± 0.03
2017 Semi-Automated Bin	1.77 ± 0.04
2018 Semi-Automated Bin	1.96 ± 0.02

All data was determined to be normally distributed and constant variance was not violated in any of the samples when using a residuals plot. The observed difference can most likely be attributed to the significant difference in terms of yield between 2017 and 2018 ($p < 0.001$) which resulted in more time between needing to offload full boxes and bins. As a result, data was analyzed separately for the 2017 and 2018 harvesting seasons.

3.2. Berry Harvest Time and Handling Time

In comparing within year and between handling systems, it was determined that there was a significant difference in terms of harvest time for the small box and semi automated systems in 2017 ($p < 0.001$) and 2018 ($p < 0.001$). In both cases, the semi-automated bin handling system outperformed the small box handling system. This result is encouraging, as it suggests that significantly more time can be dedicated to harvesting when using the semi-automated bin system compared with the significantly greater handling time of the small box system. In 2017 the semi-automated bin handling system resulted in a 55% reduction in total handling time while in 2018 this number improved to a 68% reduction in total handling time. All of this means that harvester operators can harvest more land in less time and generate greater profit through reduced fuel consumption and labor costs. Additionally, the short harvesting window of the wild blueberry crop means that on larger operations, growers may not have time to harvest all of their crop before spoilage occurs. Use of the semi-automated bin handling system could help to alleviate much of this pressure.

In comparing within year and between handling systems, it was determined that there was a significant difference in terms of handling time for 2017 ($p < 0.001$) and 2018 ($p < 0.001$). In both cases, handling time was significantly lower for the semi-automated bin handling system. A full breakdown of handling time for both systems can be observed in Table 4.

Table 4. Breakdown of total handling time for 2017 and 2018.

Handling Component	Small Box Handling (h)	Semi-Automated Bin Handling Time (h)
2017		
Total Handling Time	0.56 ± 0.04	0.25 ± 0.04
Loading Bin/Box Time	0.17 ± 0.01	0.10 ± 0.01
Unloading Bin/Box Time	0.39 ± 0.04	0.15 ± 0.03
2018		
Total Handling Time	0.49 ± 0.04	0.16 ± 0.03
Loading Bin/Box Time	0.15 ± 0.01	0.05 ± 0.01
Unloading Bin/Box Time	0.34 ± 0.04	0.11 ± 0.03

It should be noted that while time spent clearing debris from the harvester is included in handling time, this component never exceeded the time required to load and unload boxes. Clearing debris was always performed in parallel with loading and unloading and therefore it does not appear in Table 4.

3.3. Effect of Weed Coverage on Berry Harvest and Handling Time

Weed coverage, when classified as either high or low, did not have a significant impact on harvest time in either 2017 ($p = 0.694$) or 2018 ($p = 0.765$). Likewise, handling time was not significantly impacted by weed coverage in 2017 ($p = 0.778$) or 2018 ($p = 0.976$). These results are somewhat surprising as operators observed more weeds and debris making their way into the bins and boxes when harvesting in high weed conditions. Additionally, operators observed more weeds binding up in the teeth and housing of the harvester head which had to be periodically cleaned out. However, the results suggest that the time spent dealing with the additional weeds did not result in reduced efficiency when compared with low weed conditions. This is likely since the period spent loading and unloading bins and boxes is typically much longer than the period spent cleaning debris from the harvester. As these two tasks are typically performed in parallel, the additional weed build up did not result in a significant difference in handling time. That said, the weeds do create an additional task for the operator which in some instances could impact efficiency. It is equally important to note that harvest speed was maintained at a consistent 0.31 m s^{-1} regardless of weed coverage meaning that, harvest time shouldn't be significantly different provided berry yield is the same. However, when comparing berry yield by weed coverage, it was determined that significantly more berries were harvested under low weed conditions than high weed conditions both in 2017 (p = 0.011) and in 2018 (p = 0.045). Therefore, it is reasonable to suggest that the additional weed debris which collected in bins and boxes while harvesting in high weed conditions accounted for the reduction in harvestable yield when it came to the rate at which bins and boxes were filled. Therefore, while harvest time and handling time are not impacted by weed coverage, harvested berry yield is. It has also been noted that berry yield and picking efficiency is impacted by weed buildup in the harvesting teeth [25]. This factor could potentially be impacting the berry yields observed under high weed treatments.

3.4. Harvest Rate

Harvest rate was significantly improved for the semi-automated bin handling system both in 2017 ($p < 0.001$) and 2018 ($p < 0.001$) when compared with the small box handling system. Mean values for these harvesting rates can be observed in Table 5.

Table 5. Mean harvest rates for both harvester handling systems for 2017 and 2018.

Year and Harvester Handling System	Mean Harvesting Rate (h/ha)
2017 Small Box	7.22 ± 0.19
2018 Small Box	6.89 ± 0.18
2017 Semi-Automated Bin	5.89 ± 0.10
2018 Semi-Automated Bin	5.33 ± 0.04

These results make sense given that the significant differences observed in harvest time over the two-hour sample period. The significant reduction in harvest rate means that harvester operators can harvest more cropland in less time using the semi-automated bin handling system when compared with the small box handling system. As discussed, this is largely due to the reduced handling time with the semi-automated system.

Similar to harvest time, weed coverage did not have a significant impact on harvest rate in either 2017 (p = 0.754) or 2018 (p = 0.737) at a consistent harvesting speed of 0.31 m s^{-1}.

Comparing these findings with those in other cropping systems, we can see how a similar move towards enhanced mechanization has improved efficiencies. Zhang et al., 2016 developed a low-cost apple harvest-assist unit to replace ladders when picking [26]. Their units were able to improve harvest efficiency by 22% when compared with harvesting on a ladder. Across a variety of commodities, mechanized trunk shakers have proven to increase harvest efficiency by 15% over manual shaker techniques [27]. Use of a mechanized system in litchi harvesting improved efficiency by 1.55 kg min^{-1} over traditional hand harvesting, an improvement of 267% [28]. In highbush blueberries, efficiency improvements of up to 20 times have been seen when comparing mechanical harvesters to hand picking [29,30]. Comparing the results of our study to hand raking in wild blueberry yields a similar story, where a single hand raker averages 44 h ha^{-1} [5,31]. This means that a one double headed DBE wild blueberry harvester with a bin handling system can replace 8.25 laborers hand raking. There is the further benefit that harvester operators can also work longer hours, averaging a ten hour harvest day, whereas hand rakers typically average six [5]. If you factor in these increased hours, the DBE harvester can replace 13.83 laborers hand raking. For an industry which struggles to find enough laborers on a yearly basis, this labor savings is critical to the success of the crop moving forward.

4. Conclusions

Wild blueberry farmers are currently facing farm labour shortages and rising labour wages which have increased overall wild blueberry harvesting costs. Wild blueberry farmers in Atlantic Canada, Quebec and Maine are seeking alternatives to the traditional small box handling system, such as the semi-automated bin handling technology. In this study, field capacity and harvest performance were quantified and compared for wild blueberry mechanical harvesters with both the small box and semi-automatic bin handling systems with double-head harvester configurations. Harvest time, box handling time and harvest rate data were used to quantify and compare the harvest efficiency of the two harvest handling systems. For both 2017 and 2018, the semi-automatic bin handling system demonstrated statistically improved harvest time and harvest rate. The effect of weed coverage on these same parameters was not significant though the effect of weed coverage on yield was shown to have a significant effect. In conclusion, the semi-automated bin handling system was a significant improvement on the small box handling system from a harvesting efficiency standpoint. In 2017, the semi-automated bin handling system resulted in a 55% reduction in total handling time while in 2018 this number improved to a 68% reduction in total handling time. This reduction in handling time resulted in an 18.5% increase in overall harvest efficiency in 2017 and a 22.7% increase in 2018. In all, the findings of this research demonstrate the superiority of the bin handling system from a handling time and harvest efficiency standpoint.

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