SIMULATION OF HARVESTING ASPARAGUS: MECHANICAL VS MANUAL

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Abstract

Asparagus harvesting methods and strategies have remained unchanged since inception in Washington. A bioeconomic model was developed to determine the profit optimizing frequency of harvesting for manual and mechanical harvesting techniques. The mechanical harvester is economically viable if the harvester cuts 72.3 percent and 73.55 percent of what a hand crew would cut for process and fresh utilization, respectively. The results indicate that decreasing the frequency of harvest increases profit for asparagus used in processing. This research is the first attempt to address the problem of asparagus harvesting with a bioeconomic model.

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1. Introduction

The timing of farming operations is crucial for agricultural producers attempting to earn the highest possible income. Several crop growth models had been developed to assist farmers in making better decisions introducing the timing of operations. Examples of agricultural crop growth models that have been developed include cotton (Gossym), corn, soybeans (Glycim), potatoes (2Dspud) (Comis, 2002), and peanuts (Hammer et al., 1995). Some of these models such as the Cotton Production Model (Comis, 2002), have been released and commercialized as decision tools in predicting the best timing in farming operations. Weed management models have been adopted in many areas around the world (Pannel et al., 2004; Kwon et al., 1998).

A crop growth model would benefit asparagus producers since cultural practices in one-year impact the crop size the following year. This is especially true with respect to the daily harvesting decisions that must be made and the level of carbohydrates (CHO) in the crown. In the literature there are only two models involving asparagus. The model of Lampert et al. (1980), and the more recent of Wilson et al. (2002) both addressed the overall biological cycle of asparagus. Neither of the two models predicts asparagus production on a daily basis. The Lampert et al. (1980) model only presented the total seasonal production. However, the results did not represent a commercial production situation (Dean, 1999). Wilson et al. (2002) described their model without reporting any actual prediction, either daily or seasonal. In this paper, the modeling of crop growth of asparagus is addressed with emphasis on production. The focus on production integrating economics aspects of the harvesting decisions results in a dynamic system model that can be used as a tool for making harvesting decisions on a daily and total seasonal yield basis.

Asparagus is generally harvested daily during the production season. The daily harvesting decision depends upon whether or not sufficient growth has occurred in the asparagus bed to justify the harvesting expense. The actual harvesting usually occurs only once each day starting in the early morning and ending in the early afternoon. The yield maximizing harvesting strategy would be to cut a spear as it reaches the desirable length, so multiple daily harvests would be needed in some periods to maximize yields. In the same manner, the energy used by the plant (crown) can be directed toward new spears rather than adding length to spears that are already at the required length for harvest.

The actual commercial practice in Washington State (USA) is to harvest asparagus daily. This system has been adopted since the first asparagus field was established. Increasing the number of harvests would mean multiple cuttings per day. This has not been done because of the perception that high temperatures during the afternoon affect efficiency of manual labor, the quality of the spears, and the schedule for receiving the asparagus at fresh packing and processing plants.

The adoption of a strategy with less frequent than daily harvests has not been considered profitable because of the loss in product harvested and the cost of manual harvesting. In fact, by not harvesting daily the quantity of asparagus trimmed (not payable) is greater because spears tend to be longer than the required length. This creates a waste of CHO reserve that could be used to produce a marketable or payable product. Furthermore, with the actual harvesting costs and pay structure on a per pound basis, there is an incentive on the producer and on the cutters to harvest as much quantity as possible.

With mechanical harvesting labor constraints are not binding. The frequency and timing of harvest could be flexible. However, research has not been carried out to study the impact on production. Although Lampert et al. (1980) addressed the issue of harvesting strategies, they only considered the length of the harvesting season and the possibility of skipping a harvesting season every n^{th} year. Stout et al. (1967) addressed this issue of different frequency of harvest from an economic base, but they did not relate the study to the biological response of plants with the different strategy. Because mechanical harvesting allows for more or less frequent harvesting than is possible with hand crews, the effect of a different harvesting frequency and timing needs to be addressed at a biological level. Currently a selective mechanical harvester, the Geiger – Lund asparagus harvester (Lund, 1985) is under development and a prototype has been used for field trials in Washington.

The objective of this paper is to present an asparagus growth model capable of predicting daily harvests to determine the impact on profits of different harvesting strategies involving frequencies of harvest with both mechanical and manual harvest techniques. Because a mechanical harvester cannot guarantee a recovery rate the same as manual labor the recovery rate that a mechanical harvester needs to have in order to be economically feasible was calculated.

This paper is organized in four sections. The growth model is described in the first section. The model is first described in detail in relation to the biology and agronomy, then by the economics. The biology and agronomy section includes 1) emergence and density dynamics; 2) spear growth, diameter, and weight; 3) CHO dynamics; and 4) production conditions. Three different scenarios are modeled in the following section. The scenarios consist of production simulation, comparison of harvesting schedules, and comparison of different harvesting strategies. The results of the three scenarios modeled are presented in the next section, while the conclusions are reported in the final section.

2. Model description

2.1. Overview

The asparagus growth model is a dynamic simulation model. The model integrates biological and agronomic characteristics of asparagus. The time frame used in the model is predicting productivity hourly. The model was built in GAUSS for Windows. It includes a number of parameters from recent publications and field trials conducted by Washington State University (USA) during the period 2001-2004 (Ball and Folwell, 2004, unpublished data).

The asparagus growth model is integrated with an economic model. The overall model is a decision support system to provide information and insights on hand versus machine harvesting, and to assist asparagus growers on the daily management practices during the production season. While other models attempted to include in the biological model the entire cycle of the asparagus field, this was deliberately not included in this model. The underlying reason of this decision was that growers do not want to reduce their CHO content below a minimum level, because that would negatively affect future yields. It was assumed that the harvest would stop when the minimum level of CHO is reached. Implicitly it was assumed that the plants are able to recover those CHO and have the optimal level restored by the beginning of the next harvesting season.

The asparagus growth model represents a single field of one hectare. The harvest frequency and/or the harvest schedule can be chosen, as well as the density of plants per hectare, and the total energy reservoir per plant in percentage of CHO on root dry weight. This implies that the model is flexible in adapting to different production situations. For example, some fields may have a greater production potential because of the greater CHO reserve (Wilson et al., 1999) and a higher number of plants or crowns than others (McCormick and Thomsen, 1990).

The model does not consider the inter-year impacts on production. It was assumed that the selective mechanical harvester does not influence the spear emergence. Bouwkamp and McCully (1975) concluded that the nonselective mechanical harvesting did not interfere with spear emergence, therefore the same assumption was made for selective mechanical harvest. The model considers a full production field that can produce 6,160 kg/ha per year which is typical for Washington (USA).

2.2. Biology and agronomy

2.2.1. Emergence and density dynamics

The first spear emergence was predetermined in the model. This approach is similar to the model of Lampert et al. (1980). In the literature researchers have tried to predict the first spear emergence of an asparagus field using degree days. Although Dufault (1996) suggests that soil temperatures should be used to predict the first emergence, researchers prefer the use the ambient air temperature. Base temperatures adopted ranged from 4.4C (LeCompte and Blumenfield, 1958; Bouwkamp and McCully, 1975) to 7.1C (Wilson et al., 1999). Results using the Wilson et al. (2002) method on first spear emergence were not consistent with the commercial practices in the state of Washington (USA). Therefore, the predetermined date of April 5th for first emergence was adopted.

In relation to the number of spears that emerged, both models from Wilson et al. (2002) and Lampert et al. (1980) assumed that each plant of asparagus carries a certain amount of spears that are growing simultaneously. The spears emerge throughout the growing season. Although the results from Lampert (25.6 spears per plant) agreed with a previous work by Ellison and Scheer (1959), they do not reflect the dynamics of asparagus field in high density plantings. For example, McCormick and Thomsen (1990) reported that the number of spears per plant ranges from 9.5 to 5.7 for density of 19 thousand to 44 thousand crowns per hectare, respectively. Therefore, to determine the number of spears emerged in each period (hour) the following transcendental emergence function was adopted:

$$E_t = \alpha T_t^{\theta} \exp(\beta T_t) \tag{1}$$

where, E_t is the number of spears emerged in the period t, T_t is the average temperature in the period t, α, θ, and β are parameters of the function and their values are reported in Table 1. The value of the parameters were determined using the results of field trials conducted in Prosser, Washington (USA) (Dean, 1999).

The two components of the density dynamics are spears emerged and spears harvested. There might be other environmental factors affecting the number of spears in a field. For example, wind, insects, and temporary lack of moisture might influence spears emergence, but those factors were not included in the model. The model accounts for harvested and marketable spears. The marketable spears are in percentage of the total spears in the field. After emergence, the dynamics of the number of spears is only affected by the harvest. Spears are harvested once their length is above the minimum length required in the fresh or processed market. Spear number dynamics is then ruled by the following equations:

$$N_{a,t} = N_{a-1,t-1} - H_{a,t} \quad \text{for a} \geq 1, \quad \text{if} \quad L_{a,t} \geq RL^h , \tag{2}$$

where, $N_{a,t}$ is the number of spears of class a at time t, (note that $N_{0,t-1}=E_{t-1}$), $H_{a,t}$ is the number of spears of class a harvested in period t, $L_{a,t}$ is the length of the spears of class a at time t, RL^h is the required length (RL^f is the required length for the fresh market, and RL^p is the required length for the process market). Recall that $H_{a,t}$ is positive if the spears' length of class a at time t are greater than the required length (RL^h) for harvest. The class indicates age and is expressed in hours of life since emergence. For example $N_{61,t}$ indicates the number of spears of sixty-one hours of age at time t. The values of the parameters RL^f, and RL^p are reported in Table 1.

2.2.2. Spear growth, diameter, and weight

The asparagus growth model utilizes the spear growth model developed by Wilson et. al. (1999). Equation 3 reports the growth function for a spear of class a in the period t:

$$L_{a,t} = (L_{a-1,t-1} + U)\exp(c(T_t - Tb)) - U \tag{3}$$

where $L_{a,t}$ is the length of a spear of class a at time t, $L_{a-1,t-1}$ is the length of a spears of class a-1 at time t-1, U is the underground part of the spears before its emergence from the ground, T_t is the average temperature for period t, Tb is the base temperature above which there is asparagus growth, and c is the response of elongation rates of the temperature (T_t) above the base temperature (Tb). The length for spears just emerged, class 0, ($L_{0,t}$) was fixed. The values of the parameters U, c, Tb, and $L_{0,t}$ are reported in Table 1.

Spear diameter is highly influenced by CHO reserve in the roots (Tiedjens, 1924; Norton, 1913; Ellison and Scheer, 1959). Therefore it was decided to adopt the Michaelis-Menten functional form used by Lampert et al. (1980) to account for the change in diameter over the season. Equation 4 represents the relationship between spear diameter and CHO reserve in the root. Equation 5 represents the dynamics of spear diameter as the spear becomes older.

$$D_{1,t} = \frac{D_{\max}(CL_{t-1} - C_{\min})}{D_k + CL_{t-1} + C_{\min}} \tag{4}$$

$$D_{a,t} = D_{a-1,t-1}; \quad \text{for } a \geq 2 \tag{5}$$

where, $D_{1,t}$ is the diameter of spears of class 1 at time t, D_{max} is the maximum spear diameter, CL_{t-1} is the CHO level per plant at time t-1 (when the spear emerged), C_{min} is the minimum level of CHO level for spear production, and D_k is a Michaelis-Menten control parameter. The values of the parameters D_{max}, C_{min}, D_k, and the initial value of CHO level per plant (CL_0) are presented in Table 1. The Michaelis-Menten control parameter used by Lampert et al. (1980) has been adjusted to obtain diameter values more representative of the commercial production conditions in Washington.

The weight of each spear was calculated using a weight function as in Lampert et al. (1980). In the model each spear is harvested only if its length is greater than RL^h. Therefore, the model, in calculating the product harvested, considered only the portion of spear of the payable length. On the other hand, the remaining portion of the spear (called trimmed part) consumed CHO, and this consumption was considered in the use of CHO. In addition, the underground portion of the spear (the portion from the root to the ground) was accounted for in the CHO use. The model also considered that as the spear length reached a certain height (L_{max}) it did not have any commercial value because of low quality. If a spear continues to grow over L_{max} it starts to develop open braeks (crooked) that make it unmarketable. The value of the limiting length (L_{max}) is reported in Table 1. Equation 6, 7, and 8 describe the payable product and the effective weight of the asparagus for the CHO balance, respectively.

$$PW_{a,t} = \left(RL^h\right)\left(\frac{D_{a,t}}{2}\right)^2 \pi\left(f\right)\left(d\right); \quad \text{if } RL^h < L_{a,t} < L_{\max} \tag{6}$$

$$PW_{a,t} = 0 \quad \text{if} \quad L_{a,t} < RL^h \quad \text{or} \quad L_{a,t} > L_{\max} \tag{7}$$

$$W_{a,t} = \left(U + L_{a,t}\right)\left(\frac{D_{a,t}}{2}\right)^2 \pi(f)(d) \tag{8}$$

where, $PW_{a,t}$ is the payable weight of a spear, RL^h is the required length, $D_{a,t}$ is the diameter of the spear of class a at time t, f is the correction factor for the approximation of spear volume to cylinder volume, and d is the density of the spear. The values of the parameters used in equations 6, 7 and 8 are reported in Table 1.

2.2.3. CHO reserve dynamics

Asparagus yields depend on the CHO reserve. Recent research had focused on using the CHO root content as an indicator for crop management purposes (Wilson et al., 2002). The idea underlying this asparagus decision support system was to ensure a high level of CHO during the harvest. In the model when plants reach the minimum CHO level the production cycle is interrupted, or the harvest is stopped for the year.

The initial and the minimum optimal level of CHO content during the production period were defined using values from Drost (personal communication, 2003) and assuming an average dry weight of 600 g per plant (Wilson et al., 2002). In the model the consumption in CHO was adopted from Wilson et al. (2002). For computational purposes two CHO variables were defined, CL_t the CHO level at time t, and CR_t the CHO reserve at time t. In this way the model was able to account also for the consumption of CHO for spears not yet harvested. Equations 9 and 10 represent those two variables.

$$CL_t = CR_t - \frac{\sum_a N_{a,t} W_{a,t}}{bset}(dw), \text{ and} \tag{9}$$

$$CR_t = CR_{t-1} - \frac{\sum_a H_{a,t} W_{a,t}}{bset}(dw) \tag{10}$$

where, bset is the biosynthetic efficiency of transforming CHO in asparagus dry matter, and dw is the dry weight content of asparagus. Values of these last two parameters are presented in Table 1.

2.2.4. Production conditions

The model was developed for an asparagus field (1-hectare) with a crown density of 42,000 crowns per hectare in full production, and the row spacing assumed was 1.37 m. The field was assumed to be cultivated according the accepted practices in Washington (USA). The production level of an asparagus field for this area is commonly 6,160 kg/ha/yr.

The asparagus production can be for the fresh or process market. These two different markets have different grading requirements in terms of length. The fresh market prefers all green spears of 22.86 cm length. On the other hand, the processing market requires spears of 19.05 cm length. Growers in both markets are allowed to bring in asparagus with some white (underground portion) for a maximum of 2.54 cm length. In the model, it was assumed that the product for both markets was a green spear. The reason of this assumption was because those are the harvesting practices commonly adopted (Holmes, personal communications, 2003). The asparagus growth model was used to predict daily production for those two markets. It was assumed that the asparagus field responded in the same manner for those two different cutting heights and production was driven by temperature and by CHO reserve.

It was assumed a starting CHO reserve value of 450 mg/g of dry roots. No mortality of the planted crowns was assumed. The first emergence was assumed to be April 5th at 1 am. The weather data utilized were from a weather station located in the main asparagus production area of Washington (USA) (Matthews Corner). The hourly temperature was used to model the biodynamics of the asparagus field.

2.3. Economics

The asparagus growth model was integrated with an economic model to calculate the profits generated by the harvesting patterns simulated. The profit function for manual and mechanical harvests used are:

$$\Pi_{man} = P_y \sum_{a,t} \left(H_{a,t} PW_{a,t} \right) phm - \sum_t HC_t^{man} - OC^{man} - CF - CV \quad (11)$$

$$\Pi_{mec} = P_y \sum_{a,t} \left(H_{a,t} PW_{a,t} \right) phm - \sum_t HC_t^{mec} - OC^{mec} - CF - CV \quad (12)$$

where $\prod_{man}$ and $\prod_{mec}$ are the season profit per hectare for the manual and mechanical harvests, respectively, P_y is the price of asparagus (P_f indicates fresh asparagus, and P_p processed asparagus), $H_{a,t}$ is the number of spears of class a harvested at time t, $PW_{a,t}$ is the payable weight of the spear of class a harvested at time t, phm represents the percent of harvested spears that are marketable, HC_t^{man} is the harvesting cost at time t with the manual harvest, OC^{man} represents other costs involved in the manual harvest(housing for labor, and management costs), OC^{mec} indicates the other costs for mechanical harvest (financial costs and maintenance costs), CF represents the fixed costs (except management fees, amortized establishment costs, and land rent), and CV represents the variable costs except the harvest. The values of the parameter P_f, P_p, phm, CF, CV, OC^{m}, and OC^{mh} used in the simulation model are reported in Table 1.

To evaluate the impact on profits of different harvesting schedules of both mechanical and manual harvesting, assumptions were made to calculate the cost of manual harvest with a different harvesting schedule. The common practice is to offer a set price charge per pound to harvest, with some possible monetary augmentation paid to guarantee minimum wages. It was assumed that labor for harvest is paid an average of US$8.00 per hour. The cost of manual harvest was assumed to be a function of the time spent for walking, cutting and picking up spears, and the number of spears ready for harvest that are present in the field. If the costs of manual harvest were lower or equal the potential revenue from harvesting, then there is no harvest. Harvest only occurred if the potential revenue from harvesting was greater than harvesting costs. Equation 13 reports the cost function for manual harvest and equation 14 the harvesting constraint imposed (revenue from harvesting must be greater than harvesting costs).

$$HC_t^{man} = r\left(w + pt\sum_a H_{a,t}\right) \tag{13}$$

$$HC_t^{man}\begin{cases} > 0 & \text{if} \quad P_y\left(\sum_a H_{a,t}PW_{a,t}\right)phm > HC_t^{man} \\ = 0 & \text{otherwise} \end{cases} \tag{14}$$

where, HC_t^{man} is the cost of manual harvest at time t, r is the wage per hour, w is the walking time spent in harvesting 1 ha of asparagus, pt is the picking time, and H_t is the number of harvested spears. The values of the parameters r, w, pt adopted in the simulation are reported in Table 1.

The cost for the Geiger Lund selective asparagus mechanical harvester (Lund, 1985) was also included in the economic model to calculate the economic impact in the adoption of mechanical harvesting, and to determine the feasible percentage of product recovery in order to be profitable. The cost of the harvester was included in the model using equation 15.

$$HC_t^{mec} = MHC \tag{15}$$

where, HC_t^{mec} is the cost of mechanical harvest per period t, and MHC is the constant cost of mechanical harvest per period t. The term MHC includes costs per harvest or cutting including labor and fuel costs. HC_t^{mec} is subject to the constraint expressed in equation 13. The value for the parameter MHC is reported in Table 1

3. Scenarios modeled

Three scenario situations were modeled. In each case a hectare of asparagus in “normal production conditions” was assumed. Historical hourly weather data from 1989 to 2003were used to simulate daily production.

3.1. Scenario 1: production simulation

Scenario 1 simulated the production of a hectare of asparagus to show the outcome of the simulation model for 15 years. This scenario was chosen to highlight the profit performances of the machine harvester and its percentage of recovery needed to be as profitable as the traditional manual harvest. It was assumed that harvest happened each day at 8 a.m. if there were spears longer than the required length (RL^h) and the revenue from harvesting were greater than harvesting costs (constraint expressed in equation 14). If those two constraints did not hold, then harvest would take place the following day. Detailed results were obtained for each year: 1) yield (kg/ha); 2) number of harvests; 3) profit for the mechanical harvester and the manual harvest (US$/ha); 4) unit costs for both the mechanical harvester and the manual harvest (US$/kg); and 5) the percentage of recovery needed to break-even or equate the profit performances of the manual harvest (that was the control sample in the simulation).

The break-even percentage of recovery (rec) was calculated using the following equation:

$$rec = 1 - \left(\frac{\dfrac{\Pi_{man} - \Pi_{mec}}{P_y}}{\sum_{a,t} PW_{a,t}} \right) \tag{16}$$

where, the rec indicates the percentage of recovery, Π_{man} is the profit obtained with manual harvest, Π_{mec} is the profit obtained with the mechanical harvester, P_y is the price of the asparagus for the process (P_p) and the fresh (P_f) markets have different prices, the term $\sum_{a,t} PW_{a,t}$ indicates the total yield. It is necessary to calculate the rate of recovery needed for the mechanical harvester because it does not have a full recovery rate compared to a hand crew.

3.2. Scenario 2: comparison of harvesting schedules

Scenario 2 modeled the profit performances with different harvesting schedules. Because of the lack of information in the literature for different asparagus harvesting strategies, the model was used to determine the outcomes in changing the harvesting timing. The following harvesting intervals were chosen: 12, 16, 20, 24 (control), 28, 32, 36, 40, 44, and 48 hours. Although those harvesting intervals may be difficult to follow because the timing can be in the middle of the night, no information is available on the outcomes of different harvesting timing. The results are presented in terms of profit and unit costs for both the manual and the mechanical harvest. Other simulated results include the yield, the number of harvests, the recovery rate needed for the mechanical harvester to break-even with manual harvesting at the control frequency (24 hours).

The recovery rate necessary for the mechanical harvester to break-even with the manual harvest at the control frequency, $rec_{control}$, was calculated as:

$$rec_{control} = 1 - \left(\frac{\dfrac{\Pi_{man}^{control} - \Pi_{mec}}{P_y}}{\sum_{a,t} PW_{a,t}} \right) \tag{17}$$

where, $rec_{control}$ is the recovery rate needed for the mechanical harvester to equate the profit performance of the manual harvest at the control frequency, $\Pi_{man}^{control}$ is the profit of the control frequency with manual harvest. This recovery rate referred to the control frequency was calculated to compare the profit results of the mechanical harvester to the traditional strategy.

3.3. Scenario 3: comparison of harvesting strategies

Scenario 3 represented a production situation where the asparagus producer intends to purchase an asparagus harvester. The model simulates the profits generated by a predetermined scheduled harvest where the grower needs to harvest a certain area. It was assumed that the harvest can only take place during the daylight, between the 5.00 a.m. to 9.00 p.m. The estimated harvester capacity is 1.32 ha/h (at the speed of 3.22 km/h). Thus, different asparagus areas were assumed to be harvested by the same machine. Because of the capacity and the timing constraints different harvesting schedule were developed for the following areas: 10.60, 15.89, 21.19, 26.49, 31.79, 37.09, and 42.39 ha. The profit of each harvesting strategy was then calculated. For comparison purposes, profit performances of manual harvest were calculated. In addition to profit, the yield (kg/ha), the number of harvests, and break-even recovery rates with respect to manual harvest and control strategy with manual harvest were calculated.

4. Results and discussion

4.1. Scenario 1: production simulation

The production simulation was performed for asparagus being harvested for both the processed and the fresh market. The results are reported in Tables 2 and 3 for the processed and fresh market respectively. In terms of yield and number of harvests there were differences. The process asparagus yielded a lower production per hectare (6,115.24 kg) and required a higher number of harvests (57.73) than the fresh market asparagus (6,352.28 kg/ha and 51.60 harvests).

Process asparagus required a shorter length to be harvested, but a higher number of spears were harvested. As described previously, each time a spear is harvested the underground portion was not accounted as payable product, but it was in the CHO balance. Therefore, the higher the number of spears harvested the lower the production because of the higher quantity of underground portion.

The average season in terms of the number of harvests simulated was shorter for the fresh asparagus because spears were bigger and consumed more CHO than the ones for the process market. The years with the shorter harvesting seasons for process and fresh markets had 50 and 45 harvests, respectively. The reason was that the ambient temperature in the harvesting season was higher, so spears emerged and grew faster than in other years. The variability in term of number of harvests was almost the same for both markets.

The average unit cost of the machine harvester per kg of asparagus harvested in the simulation period 1989-2003 was lower than the one for manual harvesting. Values for the process market were 0.644 and 0.314 US$/kg for the manual and mechanical harvesting respectively. The values for the fresh market were 0.541 and 0.280 US$/kg for the manual and mechanical harvesting respectively. A difference in unit costs for the process and manual harvest costs was evident. Asparagus spears for the fresh market were longer than the ones for the process market, therefore the manual labor, in terms of unit cost was lower than for process market. For example, spears of asparagus for the process market are shorter and lighter than the ones for the fresh market, so more picking and walking time is required, generating the high unit costs.

The profit results showed that the machine harvester could be more profitable than manual harvest if the full recovery of asparagus was possible. However, this was not the case from the preliminary trials with the Geiger-Lund harvester machine in Washington (USA). Therefore, the breakeven recovery rate with profit from the manual harvest was calculated. The average rate of recovery needed by the harvester machine to have the same profit performances as the manual harvest was 72.30 percent and 73.55 percent for process and fresh market respectively. These results were consistent with all the years of the simulation and their variability was low.

4.2. Scenario 2: comparison of harvesting schedules

The average aggregate results of the simulation model with different harvesting schedules were reported in Table 4 for the process market and in Table 5 for the fresh market. The common frequency of harvest adopted by growers is to harvest asparagus every 24 hours. The schedule of harvesting every 24 hours resulted in the highest profits for only the fresh product. Examining the profits for manual harvesting, profit performance at 24 hours was less than for the 28, and 32 hours schedules in the process market, although the values were not statistically different. These results indicated that changing harvesting schedules could increase profits per hectare for the process product. This could also be integrated as implying that the harvesting decision for this particular product should not be made automatically each morning.

The frequency of harvest impacted the quantity of asparagus harvested. The more frequent the asparagus harvest, there would be less trimmed product that consumed CHO as well the payable product. Therefore, intensifying the frequency of harvest would maximize the potential yield production of the asparagus field. On the other hand, by relaxing the harvest frequency, the quantity of wasted product, as well the spears that passed the maximum length were greater. For example, the yield for the 48 hours strategy was 4,916.81 kg/ha. It was lower than the yield for the 12-hour strategy of 6,390.34 kg/ha (Table 4). A reason why the profit is not higher using more frequent harvesting strategies is that the increased revenue generated by the higher production does not compensate the higher harvesting costs. In the same way, the increased profit generated by less frequent harvesting strategies for process product indicated that the savings in harvesting costs by harvesting less frequently are greater than the loss in revenue due to the lower production. For the fresh product this condition does not hold, because the profit maximizing harvesting strategies is at the 24 hour interval.

Only for the processed product will harvesting less frequently with manual harvest increase the profits per hectare. The highest profit with manual harvest was achieved by harvesting every 28 hours. At this frequency of harvest the simulated profit was the highest recorded (2,163.11 US$/ha). A manual harvest every 32 hours also resulted in higher profits than the harvest every 24 hours, but lower than the harvest every 28 hours. In the 15 years of simulation, the values of those three strategies were not statistically different.

The same pattern of profits was observed for the mechanical harvest. In fact, decreasing the frequency of harvest did not increase profits per hectare. The highest profit recorded for the mechanical harvest considering a recovery rate of 100% was at the 32 hours frequency of harvesting. The unit cost of mechanical harvesting kept decreasing by decreasing the frequency of harvest with the lowest value of US$0.18/kg of asparagus. An indicator of the best frequency to adopt would be to consider the break-even percentage to obtain the same profit as the 24 hours frequency. The break-even percentage of recovery respect to the 24-hour schedule for the 28, 32, 36, and 40 hour frequency were statistically different than the traditional harvesting method. Changing frequency of harvest reduces the break-even recovery rate for the mechanical harvester to be economically feasible.

In harvesting for the fresh market, the average aggregated results from the simulation model indicated that the best strategy for both manual and mechanical harvesting is the actual practice. The 24 hours interval had the highest profits. By decreasing the frequency of harvest, the quantity of trimmed product and the spears that exceed the maximum length increased. On the other hand, even though the unit costs for both mechanical and manual harvest decreased by decreasing the frequency of harvest, the cost saving associated with it was not enough to compensate the loss of product by harvesting less frequently. The percentage of recovery needed for the mechanical harvester to equate the profit performance of the manual harvest at the traditional harvesting frequency (24 hours) were not statistically different at the 24, 28, and 32 hour frequencies.

For fresh product using the same parameters in the cost function shown in equation 13 results in a unit cost rate lower than the one actually paid by growers. The reason is that spears for the fresh market have a higher weight than the ones for the process market because they are longer. If manual labor is paid to harvest fresh product the same wage rate as the labor for the processed product, it is paid a lower unit rate.

The results presented above indicated that more research is needed to address the frequency of harvest for the processed product despite a long tradition in the 24 hours frequency. Our results show that the best strategy for the fresh product is actually the one used. Nevertheless, decreasing the frequency of harvest could improve the economic potential of the mechanical harvester because of the lower breakeven recovery rate needed for both process and fresh products.

4.3. Scenario 3: comparison of harvesting strategies

The traditional management strategy for a grower who would buy a mechanical harvester would be to purchase enough machines to ensure his/her asparagus fields can be harvested each day. From the preliminary trials (Ball and Folwell, 2004) this area is 21.19 hectares. In comparing different management strategies we showed that the optimal area to be assigned to a mechanical harvester machine might be different than the traditional area that would be assigned for the process market (Table 6) but not for the fresh market (Table 7).

For the process market product the profit maximizing strategy for manual harvesting was to allocate for a crew an area of 26.49 ha instead of the 21.19 ha usually reserved. The reason was that by decreasing the frequency of harvest the savings in cost expenses were higher than the losses due to a lower production. With the 26.49 ha allocated, the increase in profit for manual harvest was only US$16.00, but the increase in the case of mechanical harvest was US$109. Although those values are not statistically different, changing frequency of harvest may increase slightly the profit level for growers. The percentage of recovery to obtain the same profit level as the traditional management choice was lowest at the 31.79 ha per mechanical harvester. The breakeven percentages of recovery for mechanical harvester respect to the traditional method were not statistically different for the traditional (21.19 ha), 26.49 and 31.79 ha of capacity. The last two harvesting capacity for mechanical harvester had a lower percentage of recovery necessary to equate the profit level of the traditional method.

Results for the fresh market product were similar to the previous section. The traditional harvesting method, that assigns an area for one harvest per day, had the highest profit performances for both the manual and mechanical harvesting. By increasing or decreasing the frequency of harvest for the fresh product, profits decreased. The percent of recovery to equate the profit performance at the traditional managerial choice was at 26.49 ha (72.95 percent), but it was not statistically different than the traditional harvest.

Decreasing the frequency of harvest might be the better choice only for the process product with either manual or mechanical harvest. The results for the fresh product do not justify a change in management strategy even in the case of adoption of mechanical harvesting.

5. Conclusions

This article represents the first attempt to simulate the daily production of asparagus. The bioeconomic model was used to simulate the production and the profit levels of mechanical and manual harvesting. The percentage of recovery rate needed for the mechanical harvester to break-even profit performances of the manual harvest was calculated for each year in the period 1989-2003. The average break-even rate of the harvester was 72.30 percent and 73.55 percent for process and fresh product respectively.

Different frequencies of harvest and different management strategies were compared using the bioeconomic model. The control strategy used was the classical daily harvest, frequency of 24 hours, with manual harvesting. The results showed a potential benefit in decreasing the frequency of harvest in the case of mechanical harvest for the process market. The recovery rate to breakeven the control frequency with manual harvest was statistically lower at the 32 and 36 hour intervals. Those values were statistically different than the traditional frequency. The mechanical harvest for the fresh market did not show similar results, decreasing the frequency of harvesting did not show any statistical difference with respect to the traditional strategy.

Similar results were obtained using different management strategies, although without any statistical difference with respect to the traditional strategy. For processed product a harvester capacity of 31.79 ha lowered the breakeven recovery rates of mechanical harvest to 69.28 percent from the 72.34 percent of the traditional strategy.

Further issues that still need to be addressed are: identify the optimal harvesting frequency and management strategy, investigate with a sensitivity analysis for price of the product and wage rate, model the risk and the uncertainty in the decision making process of the asparagus grower regarding harvest decisions. Also, some weather variables that were not included might be inserted to improve the level of prediction in daily quantity harvested.

The results presented were originated from a simulation model. Therefore more field development is necessary to establish the best harvesting schedule and management strategy. Those results could be used to address the problem of adopting mechanical harvest of asparagus. Because of the lack of field research in addressing the frequency of harvest and the managerial choice connected with it, this paper represents the only work that addressed those issues.

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Tables

Table 1. Parameter’s values for the equations.

Parameter	Equation number	Value	Source
RL^f	2,3,7	22.86 cm	Washington Asparagus Commission (2004)
RL^p	2,3,7	19.05 cm	Washington Asparagus Commission (2004)
$L_{0,t}$	4	1.27 cm	Folwell (2003) (unpublished data)
α	1	0.000025	Curve fitting from Dean (1999)
θ	1	5	Curve fitting from Dean (1999)
β	1	0.21	Curve fitting from Dean (1999)
U	4	12 cm	Wilson et al. (1999)
C	4	0.02232	Wilson et al. (1999)
Tb	4	7.1C	Wilson et al. (1999)
D_{max}	5	2.8 cm	Lampert et al. (1980)
C_{min}	5	168.5	Scott et al. (1939)
D_k	5	55	Tiziano Cembali
CL_0	5	270	Drost (2003) (personal communication)
L_{max}	7	34.29 cm	Holmes (2004) (personal communication)
F	7, 8	0.75	Value fitting data
D	7, 8	0.95	Hooper and Folwell (1999)
bset	9, 10	0.7	Penning de Vries et al. (1974)
dw	9, 10	9%	Wilson et al. (2002)
P^f	11	US$0.99/kg	Schreiber (2004) (personal communication)
P^f	11	US$1.19/kg	Seneca (2004) (personal communication)
pmh	11	50%	Value fitting field data
CF	11	US$157.16/acre	Ball et al. (2002)
CV	11	US$338.97/acre	Ball et al. (2002)
r	12	US$8.00/h	Ball et al. (2002)
w	12	0.73h	Calculated value
pt	12	2.24 sec	Calculated value
OC^m	12	US$165.00/acre	Holmes (2004) (personal communications)
MHC	13	US$9.39/acre	Ball and Folwell (2004)
OC^{mh}	13	US$12322.41/harvester	Ball and Folwell (2004)

Table 2. Aggregate results of the daily harvest per year of processed product.

Year	Yield (kg/ha)	Number of harvests (#)	Profit for harvester machine ($/ha)	Profit for manual harvest ($/ha)	Unit costs of mechanical harvester (US$/kg)	Unit costs of manual harvest (US$/kg)	Break even percentage of recovery (rec) (%)
1989	6103.09	55	4181.91	2143.19	0.304	0.638	71.94
1990	6193.56	63	4103.96	2093.17	0.330	0.655	72.73
1991	6244.68	64	4141.61	2123.89	0.331	0.654	72.86
1992	6023.00	50	4202.59	2165.39	0.289	0.627	71.59
1993	6080.91	55	4155.50	2123.80	0.306	0.640	71.93
1994	6079.97	53	4200.80	2141.55	0.298	0.637	71.55
1995	6115.51	55	4196.70	2156.15	0.304	0.637	71.97
1996	5972.01	62	3863.41	1941.62	0.338	0.660	72.97
1997	6087.95	54	4187.09	2160.67	0.301	0.634	72.04
1998	6123.22	56	4182.66	2138.55	0.307	0.641	71.96
1999	6158.87	62	4085.87	2094.27	0.328	0.651	72.84
2000	6163.42	59	4160.90	2135.65	0.317	0.645	72.40
2001	6050.74	56	4096.38	2084.17	0.311	0.644	72.07
2002	6183.40	62	4115.07	2119.24	0.327	0.649	72.89
2003	6148.33	60	4119.74	2126.85	0.321	0.645	72.77
Average	6115.24	57.73	4132.95	2116.54	0.314	0.644	72.30
Min	5972.01	50.00	3863.41	1941.62	0.289	0.627	71.55
Max	6244.68	64.00	4202.59	2165.39	0.338	0.660	72.97

Table 3. Aggregate results of the daily harvest per year of fresh product.

Year	Yield (kg/ha)	Number of harvests (#)	Profit for harvester machine ($/ha)	Profit for manual harvest ($/ha)	Unit costs of mechanical harvester (US$/kg)	Unit costs of manual harvest (US$/kg)	Break even percentage of recovery (rec) (%)
1989	6241.10	49	3219.60	1550.13	0.275	0.543	72.92
1990	6619.10	57	3407.29	1687.27	0.288	0.548	73.69
1991	6640.50	56	3451.63	1720.86	0.283	0.544	73.61
1992	6172.55	45	3244.73	1611.21	0.263	0.528	73.21
1993	6054.79	47	3082.01	1481.39	0.276	0.541	73.23
1994	6229.76	48	3231.61	1564.04	0.272	0.540	72.90
1995	6327.60	47	3351.46	1673.96	0.264	0.529	73.16
1996	6271.90	57	3064.38	1470.58	0.304	0.558	74.27
1997	6295.74	49	3273.57	1608.84	0.273	0.537	73.23
1998	6406.27	50	3359.53	1642.07	0.272	0.540	72.86
1999	6423.73	58	3191.12	1566.48	0.300	0.553	74.39
2000	6521.53	53	3403.75	1706.48	0.278	0.538	73.65
2001	6034.92	47	3062.39	1505.14	0.277	0.535	73.87
2002	6591.39	57	3379.92	1690.78	0.289	0.545	74.05
2003	6453.25	54	3313.11	1665.75	0.284	0.539	74.15
Average	6352.28	51.60	3269.07	1609.67	0.280	0.541	73.55
Min	6034.92	45.00	3062.39	1470.58	0.2634	0.5280	72.86
Max	6640.50	58.00	3451.63	1720.86	0.3036	0.5578	74.39

Table 4. Average aggregate results of the harvests at different frequencies during the period 1989-2003 for processed product.

Frequency of harvest (h)	Yield (kg/ha)	Number of harvest (#)	Profit for harvester machine with 100% recovery rate ($/ha)	Profit for manual harvest ($/ha)	Unit costs of mechanical harvest (US$/kg)	Unit costs of manual harvest (US$/kg)	Breakeven percentage of recovery respect to the 24h schedule of manual harvest (reccontrol) (%)
12	6,388.15 a†	98.80	2,923.40	1,695.89 g††	0.54	0.73	89.74 a†††
16	6,324.46 ab	86.93	3,413.67	1,826.17 ef	0.46	0.71	83.13 b
20	6,213.97 bc	69.80	3,854.17	2,002.49 c	0.37	0.67	76.87 c
24	6,115.24 cd	57.73	4,132.95	2,116.54 ab	0.31	0.64	72.67 d
28	5,998.78 d	48.87	4,283.13	2,165.10 a	0.27	0.63	70.04 f
32	5,814.14 e	42.20	4,280.32	2,137.26 a	0.24	0.61	69.14 f
36	5,573.55 f	36.73	4,169.22	2,060.67 bc	0.22	0.60	69.53 f
40	5,355.92 g	32.53	4,046.36	1,968.28 cd	0.21	0.59	70.29ef
44	5,180.71 h	29.40	3,942.20	1,898.19 de	0.19	0.59	71.02 e
48	4,927.18 I	26.53	3,733.33	1,762.92 fg	0.18	0.58	73.17 d

† Average yield followed by same lower case letter are not significantly different at P≤0.05 according to LSD test.
†† Average breakeven percentage of recovery followed by same lower case letter are not significantly different at P≤0.05 according to LSD test.
††† Average profit for manual harvest followed by same lower case letter are not significantly different at P≤0.05 according to LSD test.

Table 5. Average aggregate results of the harvests at different frequencies during the period 1989-2003 for fresh product.

Frequency of harvest (h)	Yield (kg/ha)	Number of harvest (#)	Profit for harvester machine with 100% recovery rate ($/ha)	Profit for manual harvest ($/ha)	Unit costs of mechanical harvest (US$/kg)	Unit costs of manual harvest (US$/kg)	Breakeven percentage of recovery respect to the 24h schedule of manual harvest (reccontrol) (%)
12	6,796.63 a†	86.87	2,308.11	1,338.04 de††	0.47	0.61	88.71 a†††
16	6,729.69 a	77.53	2,749.30	1,436.42 dc	0.40	0.59	81.96 b
20	6,586.77 ab	62.27	3,136.85	1,587.53 ab	0.33	0.56	75.61 d
24	6,352.28 b	51.60	3,269.07	1,609.67 a	0.28	0.54	72.63 de
28	6,043.40 c	43.73	3,229.62	1,551.94 bc	0.25	0.53	71.97 e
32	5,758.30 d	38.00	3,143.39	1,464.73 bcd	0.23	0.52	72.14 e
36	5,383.76 e	33.20	2,933.31	1,310.37 e	0.22	0.52	74.33 de
40	5,105.36 f	29.33	2,786.85	1,213.14 ef	0.20	0.51	75.92 cd
44	4,835.13 g	26.33	2,621.29	1,093.54 f	0.19	0.51	78.23 c
48	4,519.24 h	23.60	2,399.16	943.46 g	0.19	0.51	81.86 b

† Average yield followed by same lower case letter are not significantly different at P≤0.05 according to LSD test.
†† Average breakeven percentage of recovery followed by same lower case letter are not significantly different at P≤0.05 according to LSD test.
††† Average profit for manual harvest followed by same lower case letter are not significantly different at P≤0.05 according to LSD test.

Table 6. Average aggregate results of the harvests with different management strategies during the period 1989-2003 for processed product.

Area harvested (ha)	Yield (kg/ha)	Number of harvest (#)	Profit for harvester machine with 100% recovery rate ($/ha)	Profit for manual harvest ($/ha)	Unit costs of mechanical harvest (US$/kg)	Unit costs of manual harvest (US$/kg)	Breakeven percentage of recovery respect to the 21.19 ha strategy of manual harvest ($rec_{control}$) (%)
10.60	6,368.57 a†	102.93	2,803.94	1,625.53 d††	0.56	0.74	91.28 a†††
15.89	6,272.66 a	77.53	3,666.90	1,930.29 b	0.41	0.69	79.60 bc
21.19	6,114.83 b	57.73	4,132.45	2,117.05 a	0.31	0.64	72.67 d
26.49	5,868.55 c	45.33	4,243.29	2,134.65 a	0.26	0.62	69.96 d
31.79	5,554.88 d	36.60	4,150.05	2,050.49 a	0.22	0.60	69.71 d
37.09	5,244.00 e	30.73	3,971.48	1,918.40 b	0.20	0.59	70.87 c
42.39	4,951.26 f	26.40	3,765.07	1,783.51 c	0.18	0.58	72.80 b

† Average yield followed by same lower case letter are not significantly different at P≤0.05 according to LSD test.
†† Average breakeven percentage of recovery followed by same lower case letter are not significantly different at P≤0.05 according to LSD test.
††† Average profit for manual harvest followed by same lower case letter are not significantly different at P≤0.05 according to LSD test.

Table 7. Average aggregate results of the harvests with different management strategies during the period 1989-2003 for fresh product.

Area harvested (ha)	Yield (kg/ha)	Number of harvest (#)	Profit for harvester machine with 100% recovery rate ($/ha)	Profit for manual harvest ($/ha)	Unit costs of mechanical harvest (US$/kg)	Unit costs of manual harvest (US$/kg)	Breakeven percentage of recovery respect to the 21.19 ha strategy of manual harvest (reccontrol) (%)
10.60	6,771.03 a†	90.60	2,195.96	1,277.95 b††	0.48	0.62	90.34 a†††
15.89	6,654.07 a	69.20	2,964.76	1,521.05 a	0.36	0.57	78.47 bc
21.19	6,358.26 b	51.60	3,274.98	1,611.86 a	0.28	0.54	72.55 d
26.49	5,906.34 c	40.73	3,197.09	1,515.57 a	0.24	0.52	71.89 d
31.79	5,370.88 d	33.00	2,925.21	1,317.36 b	0.21	0.51	74.35 d
37.09	4,937.77 e	27.67	2,676.59	1,139.12 c	0.20	0.51	77.45c
42.39	4,544.52 f	23.67	2,422.55	961.74 d	0.19	0.51	81.34 b

† Average yield followed by same lower case letter are not significantly different at P≤0.05 according to LSD test.
†† Average breakeven percentage of recovery followed by same lower case letter are not significantly different at P≤0.05 according to LSD test.
††† Average profit for manual harvest followed by same lower case letter are not significantly different at P≤0.05 according to LSD test.

Figure 1. Actual versus simulated daily asparagus production for the Unit 15, 2001.