RESEARCH ARTICLE

Effect of work schedule design on productivity of mechanised harvesting operations in Chile

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Abstract

Background: To improve production efficiency and harvesting economics some forest companies are looking at extended hours of use for forest machinery, which may include longer shift lengths, multiple shifts per day, and more harvesting days per week. A review of the literature provides mixed signals on the costs and benefits of extending work hours.

Methods: A long-term data base, which contained over 30 000 machine day records and was maintained by a Chilean forest company, was used to evaluate the effects of three types of extended work schedules (beyond a 9 hour work day) on the productivity of two types of harvesting operations; mechanised processing of *Pinus radiata* D. Don (radiata pine) stems into logs and mechanised harvesting of eucalypt (*Eucalyptus globulus* Labill and *E. nitens* H. Deane and Maiden) trees.

Results: Production increased as working hours increased. However, average hourly productivity fell by 9 to 30% as the working day length for equipment was extended from 9 to 18 hours. A range of factors, some interacting, were found to affect the level of decrease. These factors included type of work schedule, type of operation, season, tree species, and tree size.

Conclusions: Extending working hours beyond 9 hours per day did not result in equivalent increases in production for mechanized harvesting operations in Chile. Further research is needed on the overall economics of working extended hours.

Keywords: Forest operations, Human factors, Mechanised equipment, Productivity, Work shifts

Background

Worldwide, there is a trend towards mechanisation of forest harvesting operations, particularly as harvested tree size decreases. Productivity and cost improvement goals or labour-related issues (e.g. to improve worker safety or to overcome labour shortages) are generally the drivers for this trend.

Mechanised harvesting operations are capital intensive, with system purchase costs frequently exceeding a million US dollars. To reduce the impact of high equipment costs on a "per unit of production" basis and to increase overall profits, some logging companies are using extended working hours.

As noted by Mitchell (2008), a specific definition of extended working hours does not exist because there are so many options available for forest harvesting operations. These could range from single shifts longer than a traditional eight or nine hours per day, to multiple shifts per day with the shifts sometimes overlapping, to working six or seven days per week, to combinations of these.

Over the last three decades extended working hours – multiple shifts in particular – have been tried and failed in some parts of the world (e.g. New Zealand and south eastern USA) but in other parts (e.g. Scandinavia, Canada and parts of the north eastern USA) have been used for many years to increase production (Terlesk and Walker 1982, Mitchell 2008). In some countries, such as Australia (Nicholls et al. 2004), Sweden (Andersson 1999), Brazil (A. Santiago, Vice President of Forestry, International Paper of Brazil Ltd, personal communication 2007), Uruguay, Chile (Cordero et al. 2006) and the south eastern USA (Celone 2007), there is renewed interest in extended shift and multiple shift forest operations. Meeting the growing

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demand for improved monetary returns, increasing production efficiency and reducing obsolescence of forestry equipment are reasons given for this renewed interest (Nicholls 2003, Lebel et al. 2010).

Murphy and Vanderberg (2007) and Mitchell (2008) have looked at the economics of the use of extended working hours in forest harvesting operations. They note that, while there is a potential for a reduction in logging costs resulting from increased daily production, the size of the production increase is sometimes insufficient for logging cost reductions to be realised. They also note that the impact of extended hours on other tangible and intangible costs such as value recovery losses and human factors (such employee turnover rates, accident risk, and opportunity for employees to participate in social affairs and domestic activities) needs to be considered.

Extensive and meticulous studies were carried out by Vernon (1921, 1940) on the impacts of multiple shifts on munitions workers in UK factories during World War 1. He found that hourly productivity during night shifts was 0 to 17% less than during day shifts, depending on the gender of the worker, the season and the task carried out. LaJeunesse (1999) reported a 4% drop in productivity for 1920's U.S. cotton industry workers, working the night shift versus the day shift. Kerin and Carbone (2003) report an average drop in productivity of 5% for night shifts across all major US industries based on surveys of employees and managers from over 1000 companies. Studies of forest harvesting operations in Canada, south-eastern USA, Australia and New Zealand report a 4 to 40% drop in hourly productivity for night shifts versus day shifts (Maxwell 1982, Terlesk and Walker 1982, Nicholls et al. 2004, Mitchell 2008).

Vernon (1921, 1940) showed that the hourly production by U.K. munitions workers, working 11 hours per day for a six day week, was up to 37% lower than when working 8 hours per day. The size of the decrease was related to the task being undertaken. Nevison (1992), cited in Dawson et al. (2004), reports a 20% reduction in performance by white-collar workers when 60 or more weekly hours are worked. Hanna et al. (2005) found that hourly productivity of U.S. construction workers declined as the length of the working week increased beyond 40 hours; hourly productivity being 93% and 79% for 50-hour and 60-hour weeks, respectively. Studies of delimber operators working eight-hour day shifts in eastern Canada showed that productivity starts to decrease much earlier than eight hours; hourly productivity in the post-lunch phase was approximately 11% lower than in the pre-lunch phase (Golsse 1991, 1992). Lebel et al. (2010) show the same trend for harvester operators working 12-hour night shifts in eastern Canada; the second half of the shift being less productive than the first half of the shift. Contrary to Golsse's findings, however, they report hourly productivity

of day shift harvester operators being higher in the second half of the shift than the first half of the shift.

Kirk (1998) noted that studies worldwide have linked poorly designed work schedules, with mental and physical fatigue, low productivity and low value recovery. Sullman and Kirk (1998) reported that harvester operators processing logs experienced mental workloads that were similar to simulated air traffic control work during busy periods and simulated flying of an F-16 jet. Gellerstedt (1997) describes a system for assessing the workload in different work-shift schedules. He reports that job-rotation will help sustain high levels of production. He also notes that experience in Sweden with the work-load assessment system has led some crews to increase the rated workload by 20% for hours worked between 6 pm and 6 am.

Some extended work schedule studies have used very small samples of operators (fewer than five); there is wide variability in the time of day at which humans perform their best. Others have been based on studies of short duration (less than a few weeks) where the action of being observed may positively or negatively influence the performance of the observee ("observer" effect). Vernon (1921) noted that, when investigating output from alternative work schedules, it was best to study as large a group of workers as possible over as long a period as possible to remove physical and psychical factors for individual workers. He also commented on the use of indirect observations (e.g. taking measurements from machines being used by the workers) to supplement direct observations.

In this paper, we report on the effects of extended working hours on the productivity of two types of harvesting operations undertaken by a Chilean forest company. Results are based on long-term data of many operators that have been collected by an indirect method.

Methods
Study location and company information

Extending more than 4700 km from north to south, Chile has a wide range of climatic conditions: more than 12 major eco-regions that include deserts, montane forests, high-altitude grasslands, and temperate rainforests among others. Chile is a leader in forestry in South America. The forest sector accounts for 3.2% of national GDP and US $4.9 billion in exports each year. The country has about 2.3 million ha of productive forest plantations.

Forestal Mininco is one of the largest forest companies in Chile. Its plantation forests are mainly located between the VII and IX regions to the south of Santiago and are predominantly of three species; radiata pine (*Pinus radiata,* D. Don), Tasmanian blue gum (*Eucalyptus globulus,* Labill), and shining gum (*Eucalyptus nitens,* H. Deane and Maiden). The climate in this area is temperate with average

monthly temperatures ranging from 7 to 19°C and average monthly rainfall ranging from 20 mm to 244 mm.

Average annual harvest volumes for all Forestal Mininco's plantations over the past five years have been 8.6 million m^3, including 1.5 million m^3 of thinnings. Forestal Mininco typically has 14 harvesting crews working in pine plantations and 10 harvesting crews working in eucalypt plantations. About 54% of the pine harvest and 22% of the eucalypt harvest comes from steep terrain. This study relates to ground-based harvesting operations in all three species on non- steep terrain in forests located mainly in regions VIII and IX. Steep terrain operations have been excluded since they are limited to nine-hour days for safety reasons.

Harvesting operations and work hours

Tree length harvesting systems are used in clearfall radiata pine plantations. Trees are felled with a feller-buncher, extracted to roadside landings with grapple or cable skidders, delimbed and processed into logs with a dangle-head processor on an excavator base. Logs are then sorted and stacked with a loading grapple on an excavator base, and loaded onto a truck with a truck mounted hydraulic crane. The size of the equipment used depends on the size of tree within the stands in which harvesting is taking place. Forestal Mininco classifies pine stands into four average tree size classes labelled A through D, with A having the biggest trees and D the smallest; over 0.9 m^3, 0.65 to 0.89 m^3, 0.4 to 0.64 m^3, and under 0.4 m^3. Waratah 620 processors working over Komatsu PC200 excavators are typically used in Forest Classes C and D. Waratah 622 processors working over Komatsu PC200 excavators or Waratah 622B processors working over Komatsu PC220 excavators are typically used in Forest Classes A and B. The forest class also determines the number of products (different diameter and lengths) cut, ranging from 8 to 10 for Forest Class A to 3 or 4 for Forest Class D.

Cut-to-length harvesting systems are used in the eucalypt plantations. Trees are felled, debarked and processed into logs with a mechanised harvester. Then the logs are extracted to roadside with a forwarder. Eucalypt logs are then loaded onto trucks using excavators fitted with hydraulic grapples. Only one product is cut in eucalypt plantations. Forestal Mininco also classifies eucalypt stands based on average tree size. Only three size classes, labelled A through C, are used however; over 0.75 m^3, 0.5 to 0.74 m^3, and under 0.5 m^3. Typical equipment used in the eucalypt plantations includes Valmet 380 harvesters in forest classes A and B, and Valmet 370 harvesters in forest class C.

Both the processors in pine plantations and the harvesters in eucalypt plantations are fitted with halogen or xenon lighting systems which produce 30 lux or greater of illuminance in the boom working area for night operation.

With respect to harvesting operations, Forestal Mininco classifies the working year into two seasons; summer and winter. Summers tend to be hot and dry, while winters are cooler and wetter.

The average area harvested before equipment has to be moved to another stand is 64 ha (range = 12 to 221 ha) so the average time between equipment moves is about 2 months.

Forestal Mininco's logging contractors usually work 30 days per month. Four types of work schedules are used in both pine and eucalypt plantations. These include:

- Single shift of 9 work hours – this typically starts at 8 am and finishes at 6 pm (9 hours of work with one hour for lunch)
- Single shift of 12 work hours – this typically starts at 8 am and finishes at 9 pm (12 hours of work with one hour for lunch)
- Double shift of 16 work hours – the first crew typically starts at 6 am and finishes at 3 pm (8 hours of work with one hour for lunch) and the second crew starts at 3 pm and finishes at 12 am (8 hours of work with one hour for lunch)
- Double shift of 18 work hours – the first crew typically starts at 5 am and finishes at 3 pm (9 hours of work with one hour for lunch) and the second crew starts at 3 pm and finishes at 1 am (9 hours of work with one hour for lunch).

For each shift there is a single operator per machine. The operator works for about four hours then takes a "lunch" break (~1 hour). For shifts longer than 9 hours the operator takes additional short rest and food breaks (~10 minutes).

All harvesting contractors working for Forestal Mininco have a separate contractor who maintains and services their equipment on-site each night. Both harvesting and maintenance contractors agree that equipment will be mechanically available to carry out harvest operations for a minimum of 85% of the scheduled work shift.

The equipment limiting production in the pine operations tends to be the processor. In the eucalypt operations it is usually the harvester.

Data collection, storage and analysis

In 2006 Forestal Mininco contracted a consultant to develop a system to increase the productivity of the harvesting equipment used in their forests. The system has been named M3, short for cubic metres. Each day every machine operator records tree count data on an M3 form. For processors and harvesters, the data are obtained from the machines' computers. Mechanical downtime that occurs within scheduled shifts is also recorded for each machine. At the end of the work shift

the contractor's supervisor reviews the information and then sends this information to Forestal Mininco's intranet. Average tree size for the stand is combined with tree counts to obtain productivity per shift hour (m^3 hr^{-1}). Productivity information is available, via the intranet, to company and contractor personnel.

Data collection on processors working in pine plantations began in 2007 for the M3 system. Data collection on harvesters working in eucalypt plantations started in 2009. Over 22,000 data points have been collected on processors and over 9,000 collected on harvesters. Each data point represents one productivity value for one machine for one day. Data stored in the M3 system can be sorted and averages determined by species, forest class, season, work schedule and equipment type. Tables 1 and 2 provide summaries of the distribution of data points used in our analyses for the processors and harvesters, respectively.

Pairwise comparisons of average productivity for the four shift lengths were carried out using a t-test, along with the Welch-Satterthwaite formula for calculating degrees of freedom. Means were considered to be significantly different if they exceeded a p-value of 0.05.

In Chile, approximately 75% of daily costs for mechanised harvesting operations are related to equipment costs and 25% are related to labour costs. Fixed costs for depreciation, insurance, and interest account for about half of equipment related daily costs. A small spreadsheet model was developed that allowed us to estimate the combined effects of changes in daily production and spreading fixed costs over greater numbers of scheduled hours for the 9-hour, 12-hour, 16-hour, and 18-hour work schedule designs described above. The 9-hour work schedule was set as the base case against which other costs were compared in relative terms.

Table 1 Distribution of data points by season, forest class and work schedule that were used in the analyses for processors working in radiata pine plantations

Category	Sub-category	Number of days	Total days (%)
Season	Winter	7628	33
	Summer	15339	67
Forest Class*	A	9186	40
	B	4984	22
	C	3842	17
	D	4955	22
Working hours	9	14987	65
per day	12	4799	21
	16	2563	11
	18	618	3
Total		22967	100

* Forest class refers to the average tree size in the stand; A = > 0.9 m^3, B = 0.65 to 0.89 m^3, C = 0.4 to 0.64 m^3, D = < 0.4 m^3.

Table 2 Distribution of data points by season, forest class, species and work schedule that were used in the analyses for harvesters working in eucalypt plantations

Category	Sub-category	Number of days	Total days (%)
Season	Winter	4479	47
	Summer	4951	53
Forest Class*	A	308	3
	B	5337	57
	C	3785	40
Species	E. globulus	1676	28
	E. nitens	6743	72
Working hours	9	117	1
per day	12	6916	73
	16	1200	13
	18	1197	13
Total		9430	100

* Forest class refers to the average tree size in the stand; A = > 0.75 m^3, B = 0.5 to 0.74 m^3, C = < 0.5 m^3.

Results

Daily production levels averaged for all seasons, all forest classes, and all species are shown in Figure 1 for each work schedule length and for each machine type. Increasing the number of hours worked per day generally resulted in greater daily production for both types of operations; processors in radiata pine plantations and harvesters in eucalypt plantations. The exception was for processors where extending the working hours from 16 to 18 resulted in no increase in daily production.
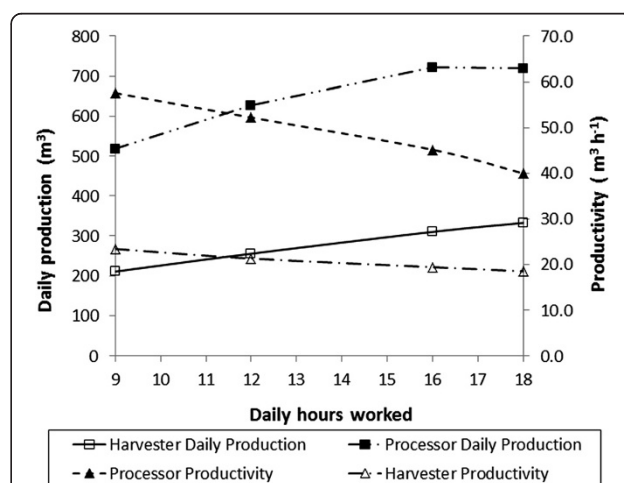

Figure 1 Effect of daily hours worked on daily production and average hourly productivity for mechanised processors operating in radiata pine plantations and harvesters operating in eucalypt plantations. Production and productivity are the averages for all seasons, all forest classes, and all species for each machine type.

Average hourly productivity levels were determined for each machine type by dividing average daily production levels for all seasons, all forest classes, and all species by the work schedule length. Figure 1 shows that increasing the number of hours worked per day resulted in a drop in average hourly productivity for both processors and harvesters; the rate of production decreases as the working day length is increased. However, the magnitude of the drop in productivity differs between processors and harvesters. Mechanised operations are man–machine systems. The effect of long hours on the machine operator, resulting in physical and mental fatigue, undoubtedly contributes to the drop in productivity. However, longer working days also result in more opportunities for mechanical problems, fewer hours available for equipment maintenance outside of normal working hours, more passing of responsibility onto the next operator to fix any problems, and greater lost time. Summaries of equipment downtime records show that average downtime for processors was about 7% of the total

scheduled hours for all four work schedules. For harvesters, the average downtime was about 10% of the total scheduled hours for three of the four work schedules; average downtime for the 12 hour work schedule was somewhat higher at 17%.

Table 3 shows the effect of work schedule design with season and tree size on the productivity for processors. Table 4 shows the corresponding data for harvesters. Drops in average hourly productivity, ranging between 0% and 34%, were observed. Most drops in hourly productivity were significantly different from zero at the $p = 0.05$ level.

Season effects both processor and harvester productivity for slightly different reasons. Productivity of the processors is generally lower during the summer season than the winter season, despite having more natural light. The hot weather (35° to 37°C) produces more mechanical problems through overheating of equipment and the need to frequently clean air filters due to roadside processing next to dusty roads. Hot weather is also

Table 3 Effect of daily hours worked on average hourly productivity for mechanised processors operating in radiata pine plantations

Category	Sub-category	Hours worked per day	Average ** productivity (m^3 hr^{-1})	Standard error productivity (m^3 hr^{-1})	Change in productivity relative to 9-hour work day (%)
Season	Winter	9	58 a	0.2	0
		12	53 b	0.3	−9
		16	47 c	0.4	−19
		18	41 d	0.7	−29
	Summer	9	57 a	0.3	0
		12	50 b	0.4	−12
		16	41 c	0.6	−28
		18	37 d	1.2	−34
Forest Class*	A	9	72 a	0.2	0
		12	65 b	0.3	−12
		16	59 c	0.5	−23
		18	56 d	1.2	−28
	B	9	55 a	0.2	0
		12	51 b	0.4	−7
		16	47 c	0.5	−13
		18	45 d	0.9	−18
	C	9	41 a	0.2	0
		12	40 a	0.3	−1
		16	37 b	0.4	−7
		18	34 c	0.5	−12
	D	9	29 a	0.2	0
		12	28 a	0.3	−1
		16	27 b	0.3	−3
		18	25 c	0.6	−7

* Forest class refers to the average tree size in the stand; A = > 0.9 m^3, B = 0.65 to 0.89 m^3, C = 0.4 to 0.64 m^3, D = < 0.4 m^3.
** Shift lengths within each sub-category with letter codes that differ from letter codes of other shift lengths are significantly different at the $p = 0.05$ level.

Table 4 Effect of daily hours worked on average hourly productivity for mechanised harvesters operating in eucalypt plantations

Category	Sub-category	Hours worked per day	Average ** Productivity ($m^3\ hr^{-1}$)	Standard error productivity ($m^3\ hr^{-1}$)	Change in productivity relative to 9-hour work day (%)
Season	Winter	9	24.5 a	0.8	0
		12	22.9 b	0.1	−7
		16	20.3 c	0.1	−17
		18	20.1 c	0.1	−18
	Summer	9	22.3 a	0.8	0
		12	19.4 b	0.1	−13
		16	18.2 c	0.2	−19
		18	17.3 d	0.1	−23
Forest Class*	A	9	25.0 a	1.8	0
		12	25.0 a	0.3	0
		16	20.0 b	0.5	−20
		18	18.0 c	0.5	−28
	B	9	24.0 a	0.7	0
		12	24.0 a	0.1	0
		16	21.3 b	0.1	−11
		18	19.3 c	0.1	−19
	C	9	22.3 a	0.9	0
		12	17.4 b	0.1	−22
		16	16.4 c	0.2	−26
		18	16.4 c	0.3	−26
Species	*E. globulus*	9	23.0 a	1.8	0
		12	16.3 b	0.1	−29
		16	15.5 b	0.4	−33
		18	15.5 b	0.8	−33
	E. nitens	9	23.4 a	0.6	0
		12	22.7 a	0.1	−3
		16	19.8 b	0.1	−16
		18	18.6 c	0.1	−21

* Forest class refers to the average tree size in the stand: A = > 0.75 m^3, B = 0.5 to 0.74 m^3, C = < 0.5 m^3. No Forest Class A stands of *E. globulus* are included in this summary.
** Shift lengths within each sub-category with letter codes that differ from letter codes of other shift lengths are significantly different at the $p = 0.05$ level.

likely to create greater operator fatigue with a possible impact on productivity. Productivity of the harvesters is also generally lower during the summer season than the winter season. Hot weather contributes to more mechanical problems. In addition, debarking the eucalypt logs is much more difficult in summer than winter. In summer, trees have to be passed through the harvester head 4 or 5 times to debark the logs properly, in winter only 1 to 2 passes are required. Operator fatigue and mechanical problems are more exacerbated by extended working hours during the summer (up to 34% drop in average productivity for the total shift) than the winter (up to

29% drop in average productivity for the total shift) for both processor and harvester operations.

The impact of tree size on the productivity of harvesting equipment is well known and described in the literature (e.g., Bulley 1999, Jirousek et al. 2007). It is also strongly evident in Tables 3 and 4 which show productivity decreasing as tree size decreases for both processing operations and mechanised harvesting operations. What can also be seen for the processor operation is that productivity declines at a faster relative rate for big trees (up to 28% drop) than small trees (up to 7% drop) as the number of working hours per day is increased.

Big trees, being heavier produce more mechanical problems. Higher value and a wider range of products can be cut from Forest Class A and B stands than from Forest Class C and D stands. Assessing changes in quality and determining what products should be cut requires more attention on the part of the operator, possibly leading to more mental fatigue. Very strict control of length and diameter measuring systems also means that the processor has to be frequently calibrated; sometimes taking 1 to 2 hours. Unlike processor productivity, there is no clear trend for harvester productivity declining at a faster rate for big trees than small trees with longer working hours; the productivity drop for big trees (up to 26%) is similar to the productivity drop for small trees (up to 28%), but larger than the productivity drop for mid-size trees (up to 19%).

Harvester productivity was higher in the *E. nitens* stands than the *E. globulus* stand due mainly to less difficulty felling and debarking the trees (*E. globulus* tends to have thinner stems and 2 stems per tree). The drop in productivity with longer working hours tended to be greater for *E. globulus* than *E. nitens*.

The productivity data shown in Tables 3 and 4 are averages for the total working day. The impact of extending working days beyond 9 hours can be looked at in a different way by assuming that productivity for the first 9 hours is held constant and then calculating the marginal productivity required in the additional hours to achieve the average hourly productivity reported for the total shift. For example, if 180 m^3 is produced in a 9-hour day and 210 m^3 is produced in a 12-hour day, the productivity for the first 9 hours would be 20 m^3 per hour. The marginal productivity for the last 3 hours of the 12-hour day would be calculated to be 10 m^3 per hour (= [210−180]/3), which is a 50% drop in productivity for these 3 hours.

Marginal productivity levels are provided in Table 5. It can be seen that marginal productivity for processors that were operated for 12 hours per day was 37% lower than the average productivity for processors that were operated for 9 hours per day. Marginal productivity was 61% lower for processors operating 18 hours per day than the average productivity for processors operating 9 hours per day. Drops in marginal productivity were not as great for the harvesters as they were for the processors, but still they ranged between 36 and 42% of the 9 hour day productivity.

Access to the harvesting contractors' financial records was not available so costs were estimated. Changes in estimated costs due to changes in work schedules may, or may not, reflect changes to actual costs. Estimated costs per unit of production increased by approximately 30% for the processors and 15% for the harvesters when scheduled hours per day were increased from 9 to 18. Unit production costs were greater for all three work schedules above 9 hours per day. Lower hourly productivity associated with longer work schedules negated the reduction in hourly fixed costs.

Discussion and conclusions

The objective of this study was to determine the effects of work schedule design on the productivity of mechanised harvesting operations. We found that working the machine for more hours per day lead to higher daily production. While one might expect this to happen, not all studies on extending work hours find this trend. For example, Vernon (1940) found the daily production was lower (up to −19% difference) for two studies and essentially the same (up to +1% difference) for another two studies when the working hours of UK factory munitions workers were 10 to 30% greater.

We also showed that daily production did not increase linearly with increases in hours worked; marginal productivity for shift lengths greater than 9 hours was lower than average productivity for 9-hour shifts. Doubling the number of hours worked resulted in average drops in marginal productivity of 61% and 42% for processors and harvesters, respectively. These drops in marginal

Table 5 Effect of daily hours worked on marginal hourly productivity for mechanised processors and harvesters operating beyond 9 hours per day

Equipment	Working hours per day	Average productivity (m^3 hr^{-1})	Additional work hours beyond 9 hours per day	Marginal productivity (m^3 hr^{-1})	Difference between marginal productivity and 9-hour productivity (%)
Processors	9	57.6	0	-	-
	12	52.2	3	36.1	−37
	16	45.1	7	29.1	−49
	18	39.9	9	22.3	−61
Harvesters	9	23.4	0	-	-
	12	21.3	3	15.0	−36
	16	19.4	7	14.3	−39
	18	18.5	9	13.6	−42

productivity are higher than those reported by Nichols et al. (2004) where doubling the hours worked for mechanised harvesting operations in Australia resulted in a 22% drop in marginal productivity. They are similar to those reported by Mitchell (2008) where almost doubling the hours worked for harvesting operations in the south-eastern USA resulted in a drop in marginal productivity of about 40%. However, our findings run counter to those of Rose (2007) who essentially found no drop in marginal productivity for the second shift of a large centralised processing yard in New Zealand, and those of H. Marshall (Interpine Forestry, Rotorua, New Zealand. personal communication, October 20, 2011) who found a 21% increase in marginal productivity for the second shift of a mill yard mechanised log processing operation in New Zealand. Since their findings do run counter to ours possible reasons for the difference are necessary. Both these New Zealand studies were of long duration (over 6 months in length) so the "observer" effect is not expected to have greatly influenced their findings. However, very good lighting outside of normal daylight hours was a feature of the operations they studied; this was considerably better than the illumination from the halogen or xenon lighting packages attached to the in-forest log processing and harvesting operations in this study. Additionally, the processing equipment in the operations they studied was in fixed locations and did not have to navigate amongst trees or across difficult terrain, unlike the harvesters in this study.

We found that season of the year had an impact on the productivity associated with working extended hours for both processors and harvesters; productivity impacts being greater for the summer season than the winter season. This finding differs from that of Vernon (1940) who found that impacts on U.K. factory munitions workers were greater in the winter season than the summer season. Harsher winters in the U.K. than in our study area in Chile may have accounted for this difference. Although we are unable to cite studies on the seasonal effects of extended hours on forest harvesting operations in regions such as Canada and Scandinavia we expect that, similar to Vernon's finding, impacts would be greater in winter than summer because of cold climates, snow and fewer hours of daylight.

Tree size and species were found to interact with the effects of extended working hours on processors and harvesters, respectively. Extending working hours had a larger effect on processor productivity for large trees than for small trees. Productivity impacts were also larger for harvesters working in *E. globulus* stands than in *E. nitens* stands. We know of no other studies that have reported these interactions.

Comparisons between the "9-hour single shift" and "12-hour single shift" operations allow assessment of the effects of more work hours per day, during daylight hours, on productivity. Extending the shift length by 3 hours resulted in a 9% drop in average hourly productivity for harvesters and a marginal productivity that was 36% lower than the 9-hour productivity. For processors, extending the shift length by 3 hours resulted in a 10% drop in average hourly productivity and a marginal productivity that was 37% lower than the 9-hour productivity. As was noted earlier downtime was relatively higher for the 12-hour shift than for the 9-hour shift and would have accounted for some of the drop in productivity.

Much research on the effects of shift work has been carried out in the health-care industry (e.g. de Cordova et al. 2012) and other industries (e.g. Amendola et al. 2011) where 24 hours per day and 7 days per week work is the norm. Comment is often made on the effect of circadian rhythm on productivity, error rates and accident risk of workers; human productivity is generally at its lowest and error rates and accident risk at their highest between midnight and 6 am, peaking in the early hours of the morning (2 to 4 am) (Folkard and Tucker 2003). Only the "double shift – 18 hours" work schedules included in our study crossed into the low circadian rhythm time zone. However, both double shift work schedules do include some evening work in them. Comparisons of the "single 9-hour day shift" and the "double 18-hour shift" allow assessment of the effects on productivity of an evening shift of the same duration as a day shift. Our study showed marginal productivity for the evening shift was 42% to 61% lower than 9-hour productivity for harvesters and processors respectively.

Gingras (2004) comments that with proper equipment selection (i.e., a good lighting package), maintenance scheduling (i.e., during the day shift where possible), and production planning (e.g. allocating the most difficult terrain for the day shift) the differences between the productivity of day and night work shifts can be minimised for Canadian forest harvesting operations. Our analyses indicated that extended shift or multi-shift work schedules would not lead to sufficient production to reduce production costs below those of 9-hour single shift operations. This finding runs counter to economic analyses by Mitchell (2008) where the productivity of night shift south-eastern USA harvesting operations would need to fall by 43%, compared with day shift operations, before production costs for double shift operations were higher than single shift operations. Drops in productivity of this magnitude were found for the "double shift –18 hour" work schedule operated by Forestal Mininco. Neither Mitchell's nor our analyses took into account the impacts on value recovery and accident rates as did the analyses by Murphy and Vanderberg (2007).

As noted above, Forestal Mininco's harvester and processor operators, although they do have rest breaks, work on the same machine for the entire shift.

Experience in Scandinavia and research by Gellerstedt (1997) would indicate that operator work load can be decreased and productivity levels increased by rotating jobs with other workers. Tyson (1997) reports a 50% increase in hourly production and improved value recovery when an operation went from running two extended continuous shifts to one incorporating more frequent shorter shifts with regular breaks. High performance rosters involve work enlargement, cross-training and increased responsibility taken by each crew member. Gellerstedt (1997) notes that, because people differ from each other, individual crew members must have the opportunity to adjust their work load and working hours to suit their situation. These might include having the harvester or processor operator swap jobs after three hours with the extraction machine operator or carrying out some light or heavy manual work. These might also include selecting the day or evening shift that suits them best in a multi-shift operation. Managing the human factor as well as managing machine utilisation is more likely to lead to improved harvesting economics.

The research reported in this paper has some limitations:

- It relates to forest operations in one region of South America that has a comparatively mild climate.
- It relates to two types of harvesting operations; processors working in radiata pine plantations and harvesters working in eucalypt plantations.
- It excludes late night shifts which span the time of day when humans are at the lowest point of their circadian rhythm (2 to 4 am).
- It inadequately explains why mechanical downtime, as a percentage of the shift length, should be higher for harvesters working 12-hour shifts than for harvesters working single or multi-shifts of shorter duration.
- It inadequately explains why production on the second shift with a new operator should be so much lower than production of the first shift with the same number of hours worked.

Consequently, further research on the effects of extended hours on productivity is needed in a wider range of forest types, climates, work schedules, and equipment types (e.g. extraction machines). Further research is also needed on the overall economics of working extended hours.

Despite these limitations, our research has shown that, for mechanised harvesting operations in Chile, working extended hours led to greater production but the relationship was not linear. Hourly productivity declined as the length of the working day increased beyond 9 hours. Long-term data sets, like those stored in Forestal Mininco's M3 system, provided an opportunity to identify these trends. They also allowed us to identify interactions between the length of the work shift and other factors, such as season and tree size. Understanding the effects of extended work hours and different work schedules on productivity of mechanised operations will allow harvest planners to better manage log supply, labour force requirements, and harvesting economics.

Competing interests

Authors' contributions

PP participated in the collection, preliminary analysis and interpretation of the data and assisted with the drafting and revision of the manuscript. GM participated in further analysis and interpretation of the data and drafted and revised the manuscript. Both authors read and approved the final manuscript.

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