The impact of calibration on the accuracy of harvester measurement of total harvest volume and assortment volume for Sitka spruce clearfells in Ireland

Tadhg Dooley[a], Traolach Layton[b] and Maarten Nieuwenhuis[c]

Abstract

Almost all timber in Ireland is felled using harvesters; the objective of the work reported here was to assess the impact of calibration on the accuracy of harvester wood volume measurement systems. The harvester used was a Timberjack 1270D with a 762C harvester head and a Timbermatic 300 control and measurement system. Harvester measurement was compared to weighbridge measurement (weight was converted into volume using volume-weight conversion factors) and to log volume, measured using standard calliper-and-tape log measurement.

The first part of the study dealt with the accuracy of the harvester system in measuring total and assortment volumes for whole stands, when compared to weighbridge results. Regular calibration resulted in a significant improvement in accuracy, reducing differences between the two estimates, from 12% to around 6%. However, this compares with accuracy levels of ± 2% of total site volume, which have been achieved in Finland on an annual basis.

The second part of the work comprised a more detailed analysis of the accuracy of the harvester system in measuring assortment volumes. Length measurement of four assortment categories was accurate after calibration, while the volume measurement was satisfactory for 5.50, 4.90 and 3.10 m lengths, but not for the 2.90 m category. Statistically significant differences in volume estimation were found for three assortment categories (4.90, 3.10 and 2.90 m). However, the differences between the harvester head and calliper-and-tape values were small (less than 30 mm and 0.007 m^3 in all cases), so the operational significance of these findings might be limited.

Keywords: Harvester, calibration, measurement accuracy, assortments.

Introduction

Almost all roundwood in Ireland is felled using mechanical harvesting systems. Modern harvesters come equipped with computerised measurement systems, which measure the stem during delimbing. Every time the stem is cross-cut, the machine measures the length assortment and the volume of the log (Rieppo 1993). If properly managed and maintained, these systems provide an accurate and cost-effective method of log measurement. They can provide precise results when installed, programmed and calibrated correctly. Accuracy levels of ± 2% of real volume have been achieved in Finland on an annual basis (Gingras 1995). There the measurements are used as a basis for optimising machine yield and assortment mix, payment of

[a] Forestry Services Limited, Dumdum, Co Tipperary, Ireland.

[b] Palfab Ltd.., Lissarda, Co Cork, Ireland.

[c] UCD School of Biology and Environmental Science, University College Dublin, Ireland (corresponding author: maarten.nieuwenhuis@ucd.ie).

contractors, payment of timber growers and the monitoring of operators (PTR 2000a). The data are also used in the mill to plan operations and select sawing patterns.

There are an estimated 64 harvesters and 144 forwarders operating in Ireland (Carlin 2005). About 50 harvesters have modern on-board computer systems (Fenton 2005).

The work reported here is part of a larger research project on sawmill production chain optimisation.

Background

Volume is one of the key measurements used to determine wood fibre quantity for stand production estimates, harvesting and timber sales. On the other hand weighbridge weight is used by virtually all boardmills and sawmills (Donnellan 2005) to estimate intake and for log stock control. Volume is obtained by applying a volume/weight ratio (Marshall and Murphy 2003), calculated by dividing the volume of a set number of sample logs by their weight. Purchases are paid for in euro per cubic metre overbark. When the logs from a specific sale arrive at the mill and are measured on the weighbridge, it is the first time in the sales process that the purchaser gets an accurate estimate of the actual total volume harvested and the distribution of this volume over the assortments.

On the other hand, almost all harvesting in developed countries is now mechanised, with single-grip harvesters predominant. All modern single-grip harvesters come equipped with computerised measuring systems. These measure the tree during delimbing; as it is fed through the harvesting head, a wheel measures the stem or log length and the delimbing knives or feed rollers measure the stem diameter at the same points. The log length and the diameter can be monitored using an in-cab display during operations. At every cross-cut the length assortment and volume of the log are recorded. Volume is measured using either sectional length and diameter readings or by using a single length and a top or mid diameter reading (Rieppo 1993).

A study carried out by Sondell et al. (2002) in Sweden on five harvesters and their computer systems, found that length and diameter sensing did not perform well, but that regular calibration of the measuring systems improved their performance.

Calibration involves checking, and if necessary correcting, harvester measurement by first measuring the volume of a log with the harvester and then using a tape and callipers. Provided measurement systems are set-up and calibrated according to design specifications, harvesters can provide accurate volume estimates. Requirements in Finland stipulate that harvester volume estimates must be ± 4% of the true stand volume. Accuracy levels of ± 2% of true stand volume have been obtained in practice (Gingras 1995). Studies on harvesting heads by the Forestry Commission in Britain reported similar accuracy levels to those recorded in Scandinavia (Forestry Commission 1995). In Ireland, a study carried out by PTR Ltd. in 2001 found volume accuracy levels of 6.7% for a clearfell site and 5.3% for a thinning site (PTR 2001a).

The aim of the research reported here was to further assess the accuracy of harvester head measurement systems under Irish forest conditions, focusing on the impact of calibration on measurement accuracy (Dooley 2005, Nieuwenhuis and Dooley, 2006). In order to achieve this aim, two studies were carried out.

First, an analysis was carried out of the accuracy of the harvester measurement system when dealing with the total harvest and assortment volumes from stands. Second, a detailed analysis of the accuracy of the calibrated harvester measurement system for different assortments was performed.

Materials and methods

Investigation sites

Harvest volumes and length assortment data were collected in five Sitka spruce (*Picea sitchensis* (Bong.) Carr.) stands, three in Co Cork and two in Co Limerick (Table 1), using a Timberjack 1270D with a 762C harvesting head and the Timbermatic 300 harvesting measuring and control system. Calibration checks and corrections were carried out at least twice at each of sites 2, 3, 4 and 5.

Measurement devices

Four measuring devices were used to calculate log length and volume:

1. the Pomo calliper,
2. loggers tape,
3. weighbridge measuring system and
4. the Timberjack On-Board-Computer-System (OBCS).

Calliper and tape diameter and length estimates were used to calibrate the harvester head. The calliper, loggers tape and the weighbridge measuring system were used to evaluate the accuracy of the harvester OBCS. The weighbridge measuring systems in the Palfab sawmill and the other mills to which the pallet and pulp wood was transported were used to assess the accuracy of the harvester OBCS

Table 1: Location and crop descriptions of the stands investigated.

Stand	*1*	*2*	*3*	*4*	*5*
County	*Limerick*	*Limerick*	*Cork*	*Cork*	*Cork*
Townland	*Park*	*Glennagowan*	*Cooragreenane*	*Coolen*	*Guagan Barra*
Forest	*Newcastlewest*	*Newcastlewest*	*Inchigeelagh*	*Inchigeelagh*	*Ballingeary*
Age yr	*44*	*41*	*43*	*43*	*42*
Thinned	*no*	*no*	*yes*	*yes*	*no*
Stems/ha	*1477*	*1408*	*846*	*626*	*1326*
Mean volume m	*0.41*	*0.40*	*0.50*	*0.64*	*0.47*
Mean dbh cm	*23*	*23*	*26*	*29*	*23*
Harvested area ha	*2.7*	*11.9*	*19.8*	*18.5*	*25.0*

for large volumes of timber, while the calliper and tape were used to assess the accuracy for individual logs.

The first part of the study dealt with total harvest and assortment volumes for four sites (1, 2, 3, and 4), comparing the harvester OBCS to the weighbridge measurement systems in the mills. It was carried out over a period of 14 months.

Weighbridge volumes were taken as the correct measurement and the harvester volumes were compared against these. Scheduled calibration checks (in addition to checks after repair work on the harvester head) were carried out once a month at every site, except for site 1 where no calibration checking was carried out; if necessary a full calibration of length and diameter was performed. The data from the harvester OBCS were collected on a daily basis via mobile internet connection to the sawmill. The weighbridge data were taken from the weighbridge computer systems when all the logs from the stand had arrived at the mills. The data were organised and analysed in each of four categories: total harvest volume, sawlog (5.50 and 4.90 m), boxwood (3.10 m) and pulpwood (2.90 m).

The second part of the study dealt with length and volume measurements of individual logs in four assortments (5.50, 4.90, 3.10 and 2.90 m) across three sites (3, 4 and 5). For this part of the study, the calliper-and-tape measurements were taken as the true or correct measurements, and the calibrated harvester OBCS measurements were compared against these. The data consisted of measurements on 375 logs in four assortments: 25 logs in the 5.50 m length assortment, 139 logs in the 4.90 m length assortment, 30 logs in the 3.10 m length assortment and 181 logs in the 2.90 m length assortment.

Results

Part 1 - Total harvest and assortment volumes

Site 1 (no calibration) produced a total true harvested volume of 2,144 m^3 as calculated at the weighbridge, while the harvester OBCS estimated a total volume of 2,416 m^3, resulting in a difference of 272 m^3 or 12.69% (Table 2). The proportions of total volume in each assortment, as determined from the harvester and weighbridge data, differed by between 1 and 5%. However, the actual assortment volume differences, expressed as a percentage of the 'true' weighbridge volumes, were much larger and varied between -6.2 and 21.0%. Site 2 (calibrated) produced a difference between the total true harvested volume and the harvester OBCS total volume of 399 m^3 or 6.69%. The proportions of total volume in each assortment differed by between 0.1 and 1.4%, while the actual assortment volume differences ranged between 4.8 and 25.2%. Site 3 (calibrated) produced a difference of -403 m^3 (–5.52%) between the weighbridge volume and the harvester OBCS volume (Table 4). The proportions varied by between 0.2 and 1.6%, while the actual assortment volume differences ranged between -11.5 and 18.9%. Finally, site 4 (calibrated) produced a difference of -300 m^3 (–5.18%) in total volume, while the assortment proportions differed by between 0.3 and 2.3% (Table 5). The actual assortment volume differences ranged between -7.8 and 11.3%.

Table 2: Comparison of weighbridge and harvester volumes for site 1.

Assortment	Harvester volumes		Weighbridge volumes		Difference	
	m^3	% of total	m^3	% of total	m^3	%
Sawlog (5.5, 4.9 m)	1,397	57.83	1,155	53.87	242	20.98
Boxwood (3.1 m)	414	17.13	344	16.04	70	20.32
Pulpwood (2.9 m)	605	25.05	645	30.08	-40	-6.16
Total	2,416	100	2,144	100	272	12.69

Table 3: Comparison of weighbridge and harvester volumes for site 2.

Assortment	Harvester volumes		Weighbridge volumes		Difference	
	m^3	% of total	m^3	% of total	m^3	%
Sawlog (5.5, 4.9 m)	3,966	62.33	3,769	63.20	197	5.23
Boxwood (3.1 m)	599	9.42	479	8.03	120	25.16
Pulpwood (2.9 m)	1,798	28.25	1,716	28.77	82	4.77
Total	6,363	100	5,964	100	399	6.69

Table 4: Comparison of weighbridge and harvester volumes for site 3.

Assortment	Harvester volumes		Weighbridge volumes		Difference	
	m^3	% of total	m^3	% of total	m^3	%
Sawlog (5.5, 4.9 m)	4,951	71.76	5,257	71.99	-306	-5.82
Boxwood (3.1 m)	542	7.86	456	6.24	86	18.86
Pulpwood (2.9 m)	1,406	20.38	1,589	21.76	-183	-11.52
Total	6,899	100	7,302	100	-403	-5.52

Table 5: Comparison of weighbridge and harvester volumes for site 4.

Assortment	Harvester volumes		Weighbridge volumes		Difference	
	m^3	% of total	m^3	% of total	m^3	%
Sawlog (5.5, 4.9 m)	4,435	80.71	4,810	83.00	-375	-7.80
Boxwood (3.1 m)	351	6.39	348	6.01	3	0.86
Pulpwood (2.9 m)	709	12.90	637	10.99	72	11.30
Total	5,495	100	5,795	100	300	-5.18

A graphical representation illustrates the effect calibration had on the harvester OBCS measurement accuracy of assortment and total harvest volume (Figure 1). The differences between the harvester pulpwood volumes and the weighbridge pulpwood volumes fluctuate between the four sites; however the differences between the harvester and weighbridge volumes for the sawlog and boxwood categories appear to be moving towards the 0% error line. For total volume an immediate improvement is apparent when the results for the first site (where the harvester measurement system was not calibrated) are compared with the next 3 sites (where calibration was carried out).

Part 2 – Length and volume of logs by assortment classes

Before presenting the results of the statistical analysis of length and volume differences, the range of volume differences between the harvester OBCS and the calliper-and-tape volume measurements of the sawlog/boxwood and pulpwood assortment classes are presented. These illustrate the different error distributions of these product categories. The analysis of the differences for the combined sawlog/boxwood class revealed that 54% of the differences were within the ± 4% range (Figure 2), with just over 90% of the differences within the ± 8% range. For the pulpwood class, the analysis revealed that 24% of the differences were within the ± 4% range (Figure 3). The largest proportion of differences (over 19%) fell in the 6-8% range. The difference in the error distribution of the two product classes is very evident, showing a normal distribution pattern for the sawlog/boxwood class and a uniform distribution for the pulpwood class.

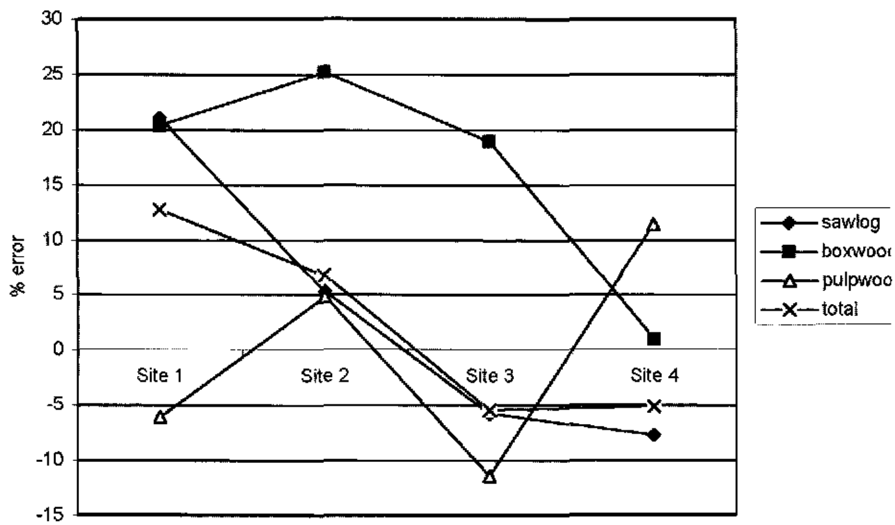

Figure 1: Percent error in the measurement of assortment volumes and total harvest volume for the four sites. No calibration took place at site 1, whereas regular calibration was carried out at sites 2, 3 and 4.

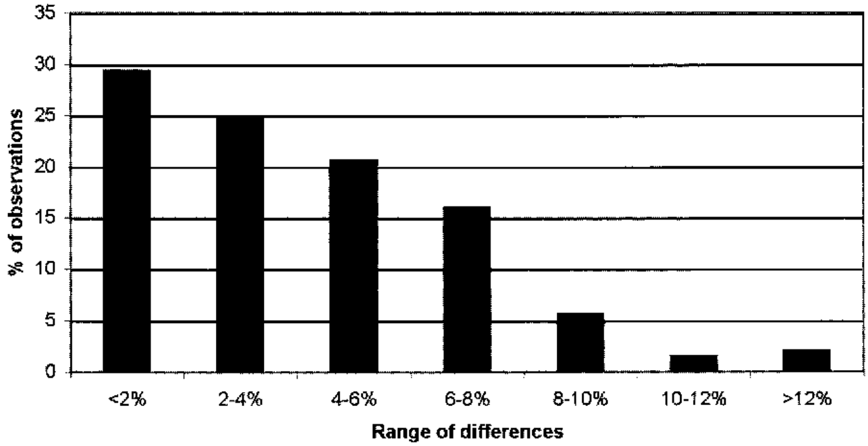

Figure 2: Frequency distribution (in %) of the range of differences in sawlog/boxwood volume measurements, between the harvester OBCS and the calliper-and-tape system.

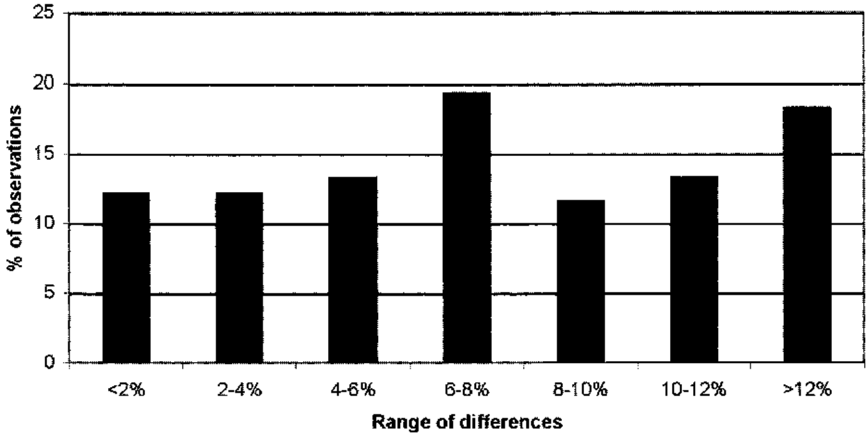

Figure 3: Frequency distribution (in %) of the range of differences in pulpwood volume measurements, between the harvester OBCS and the calliper-and-tape system.

Analysis of assortment length and volume differences

For all four assortments, the mean length measurements by the harvester OBCS were greater than the corresponding tape measurement means. Differences between mean tape and harvester length measurements were 0.02 m or less for the 4.90, 3.10, and 2.90 m assortment classes, with a 0.13 m difference for the 5.50 m assortment class. The variances associated with all means were very small, except for the tape measurement of the 5.50 m assortment. The low mean value and the large variation associated with these tape measurements were caused by a number of logs with actual (i.e. tape) lengths more than 20% below the target value of 5.50 m. A statistical analysis was carried out on the (normally distributed) length differences for the three longest assortment classes. A summary of the results is presented in Table 6. There was no significant difference in length measurements for the 5.50 m assortment class, while for the 4.90 and 3.10 m classes significant differences were found.

The mean volume measurements by the calliper-and-tape system were greater than the corresponding harvester OBCS measurement means for all four assortments. Differences between mean calliper-and-tape and harvester volume measurements were 0.007 m^3 or less for all assortments. The variances associated with all means were very small, except for the variances of the mean calliper-and-tape and harvester OBCS measurements at the 5.50 m assortment class. A statistical analysis was carried out on the volume differences for the three longest assortment classes and a summary of the results is presented in Table 7. There was no significant difference between the volume measurements for the 5.50 m assortment class, while for the 4.90 and 3.10 m classes significant differences were found.

Table 6: Statistical comparisons of length measurements for the sawlog and boxwood assortments.

Length	*Sample size*	*Harvester*		*Tape*		*t critical*	*t*
		Mean	*Variance*	*Mean*	*Variance*		
m		*m*					
5.50	*25*	*5.52*	*0.00020*	*5.39*	*0.12033*	*2.06390*	*1.94456*
4.90	*139*	*4.93*	*0.00020*	*4.91*	*0.00365*	*1.97731*	*2.36213**
3.10	*30*	*3.10*	*0.00004*	*3.09*	*0.00057*	*2.04523*	*2.64149**

**significant at the 95% confidence level*

Table 7: Statistical comparisons of volume measurements for the sawlog and boxwood assortments.

Length	*Sample size*	*Harvester*		*Tape*		*t critical*	*t*
		Mean	*Variance*	*Mean*	*Variance*		
m		*m*					
5.50	*25*	*0.373*	*0.0285*	*0.380*	*0.0296*	*2.06390*	*0.96935*
4.90	*139*	*0.217*	*0.0088*	*0.224*	*0.0098*	*1.97731*	*6.10368**
3.10	*30*	*0.077*	*0.0003*	*0.079*	*0.0003*	*2.04523*	*3.25579**

**significant at 95% confidence level*

Discussion

Part 1 - Total harvest and assortment volumes

The purpose of the first part of this study was to investigate the accuracy of the harvester OBCS measurement system compared to the weighbridge measurement system when dealing with total harvest and assortment volumes. The weighbridge measurement system is the predominant method of calculating stand volumes in Ireland (Donnellan 2005); therefore it was decided to evaluate the accuracy of the harvester OBCS measurement system against the weighbridge system. The weighbridge results for the sawlog and boxwood assortment categories are based on sale proposal specific weight/volume conversion factors and, as a result, should be very accurate. It is not certain if this was the case for the pulpwood results.

It was found that the accuracy of the harvester improved greatly after calibration. From a 12.71% difference between the harvester volume and the weighbridge volume at the first site (where no calibration was carried out) the accuracy improved to a 6.69% difference at the second site, and differences of –5.52% and –5.18%, respectively, between the harvester and weighbridge volumes at sites 3 and 4. These total volume differences of around ± 5% were very similar to results of a study carryout by PTR in 2001 where differences between the harvester and weighbridge volumes of 6.7% for a clearfell site and 5.3% for a thinning site were recorded (PTR 2001a). However, none of these harvester volume estimates are as accurate as those regularly achieved in Finland (± 2%) for total site volumes, which are used for contract purposes (Gingras 1995). A possible explanation for this high level of accuracy is that stems tend to be cleaner, with less and smaller branches, making it easier for the harvester head to delimb the stem, causing less measurement errors. The time of year during which harvesting takes place and its effect on the cohesion between bark and the underlying wood is another factor that may have an impact on length measurement accuracy in particular. If bark gets detached from the wood, the harvesting head wheel that is used for length measurement will measure the length of bark going through the harvesting head, not the length of the log. During the winter period in Finland bark is strongly attached, facilitating accurate length measurement. In addition, in Finland harvester measurement for timber sale purposes has been used for several years, while the studies reported here are among the first carried out in Ireland, reflecting the recent introduction and application of this technology in Irish forest operations.

The proportions of total volume in each of the harvester OBCS measured assortments compared to each of the weighbridge measured assortments were very similar, especially for the three sites where the harvester was calibrated. No difference between harvester versus weighbridge assortment proportions was greater than 2.3%. This is an important finding, as the processing industry needs to know the proportion of each assortment cut, allowing for production planning based on production data, customer orders and yard inventories (Nieuwenhuis 2002, Nieuwenhuis et al. 1999).

Even though the differences between the actual harvester and weighbridge assortment volumes were greatest at the site that was not calibrated (Site 1), large differences were also found between the harvester and weighbridge assortment volumes for the calibrated sites: sawlog volume estimates differed by between -7.80% and 20.98%; boxwood differed by between 0.86% and 25.16%; and pulpwood by between -11.52% and 11.30%. A reason for these differences could be that the calibration of the harvester was not carried out evenly for the full range of diameters encountered in each stand, e.g. volumes at small diameters were overestimated and volumes at large diameters under estimated, or vice versa. A study carried out by Sondell et al. (2002) showed that such errors can occur as a result of this type of inadequate calibration, even when the total volume estimate might be accurate. In addition, not all logs that have been measured by the harvester OBCS measurement system may have reached the mill. The data collected during the study did not include information on harvested timber left on site. A study by PTR on harvest volume residue found that up to 2.36% of the total volume can be left on site, while the loss of bark can affect total volume by an additional 2% (PTR 2001b).

Part 2 – Length and volume of logs by assortment classes

The purpose of the second part of the study was to investigate the accuracy of the measurements by the harvester OBCS for different assortment categories. It was found that the length category with the least accurate harvester length measurements was the 5.50 m category, with only 76% of the logs within the ± 0.05 m range. This maybe is not surprising, as even a small error in measurement per unit length can become substantial as a result of the long length of the 5.50 m category. The length as determined by the harvester was within ± 0.05 m of the true length for over 90% of the logs in each of the other three assortments (4.90 m category 92% of logs, 3.10 m category 96% of logs, the 2.90 m category, 91% logs). These three assortment categories meet the standard target in Sweden of 90% of the logs falling within 5 cm of the specified assortment length (Sondell et al. 2002).

In the analysis of volume accuracy, the proportion of logs within the ± 4% range was the critical factor. Requirements in Finland stipulate that volume estimates must be within ± 4% of the true volume (PTR 1997). It was found that the volume category with the least accurate harvester OBCS volume measurements was the 2.90 m category with only 24% of the logs within the ± 4% range. A reason for this low accuracy level could be that this length assortment is predominately cut from the top part of the stem which has the most branches and can be extremely rough (Joyce and OCarroll 2002). The volume accuracy of the sawlog/boxwood category, as determined by the harvester volume measurements, achieved 54% of the logs within ± 4% of the calliper-and-tape measurements. When the range is extended to ± 8%, almost 90% of the logs cut by the harvester in the sawlog/boxwood categories were within this wider range. This range is of interest because it is more representative of the level of harvester volume measurement accuracy that is being achieved in Irish forests (PTR 2000a). This sawlog/boxwood result was satisfactory but can probably be further improved by more regular calibration (PTR 2000b). However, for the logs cut by the harvester in the 2.90 m assortment, less than 60% are within the ± 8% range. It is not clear if more calibration will improve this result, as the roughness of the higher portion of the stems might make measurements with the current technology inherently unreliable and inaccurate.

In the comparisons of length, it was found that for all four assortments the mean length measurements by the harvester were greater than the corresponding tape measurement means. In contrast, the mean volume measurements by the calliper-and-tape method were greater than the corresponding harvester measurement means for all four assortments. The only logical explanation for these contradictory results is that the diameter measurements by the harvester produced smaller values than the calliper measurements. As it was not possible to record the individual harvester diameter measurement values used in the volume calculations, it was not feasible to check this hypothesis. When the differences between the harvester and calliper-and-tape length and volume measurements for the three sawlog and boxwood assortment categories were statistically analysed, the lengths and volumes differences for two categories were found to be significant (i.e. 4.90 and 3.10 m). However, the actual differences between the harvester and calliper-and-tape means for these assortment categories were extremely small (less than 3 cm and 0.007 m^3 all cases). From an operational perspective, these statistically significant but small differences may not have an important impact, and may indicate that the measurement system of the harvester was performing consistently and accurately.

Conclusions

Regular calibration improved the measurement accuracy of the harvester measurement system for the total harvest and assortment volumes on the four sites. However, even with calibration, several large differences were found between site assortment volumes as obtained at the weighbridge and as measured by the OBCS. A more detailed log-by-log analysis showed that length estimates obtained by the harvester measurement system were compatible with the results obtained with the tape measurement system for each of the four assortment categories. Volume estimates obtained by the harvester measurement system for the sawlog/boxwood category were relatively accurate; however volume estimates for the pulpwood category were unacceptable. If harvester measurement systems are to be used successfully, a major training initiative will be required to give contractors a proper appreciation of the importance of frequent and regular checking and calibration procedures.

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References

Forestry Commission. 1995. *Technical Development Branch Report* Nos. 2/95, 7/95 and 9/95. HMSO, London.

Carlin, M. 2005. *IT applications in Irish roundwood harvesting*. COFORD information technology (IT) workshop 2005. COFORD, Dublin.

Donnellan, M. 2005. Personal communication. Coillte, Kilkenny.

Dooley, T. 2005. *The Effect of Calibration on the Accuracy of Harvester Measurements*. M Agr. Sc. thesis, University College Dublin.

Fenton, M. 2005. Personal communication on 15/02/2005. Coillte, Kilkenny.

Gingras, J-F. 1995. *Recent Developments in Chip Cleaning and Cut-To-Length Harvesting Technologies in Finland*. Forest Engineering Research Institute of Canada (FERIC) Eastern Division, Internal Report IR-1995-06-01.

Joyce, P.M. and OCarroll, N. 2002. *Sitka spruce in Ireland*. COFORD, Dublin.

Marshall, H. and Murphy, G. 2003. Factors Affecting the Accuracy of Weighbridge Systems. *International Journal of Forest Engineering* 14(1): 67-78.

Nieuwenhuis, M. 2002. The development and validation of pre-harvest inventory methodologies for timber procurement in Ireland. *Silva Fennica* 36(2): 535-547.

Nieuwenhuis, M. and Dooley, T. 2006. The Effect of Calibration on the Accuracy of Harvester Measurements. *International Journal of Forest Engineering* 17(2): 25-33.

Nieuwenhuis, M., Malone, L., McHugh, F. and Layton, T. 1999. Development and evaluation of a pre-harvest inventory and cross-cutting simulation procedure to maximise value recovery. *Irish Forestry* 56(1): 12-28.

PTR. 1997. *A Feasibility Study to Develop an Impartial and Integrated System of Timber Volume Measurement Suitable for the Irish Timber Industry (Phase II – Stage 2). International Timber Measurement Practice & Administration. Current & Potential Significance to the Irish Forest Industry.* Purser Tarleton Russell Ltd., Dublin.

PTR. 2000a. *Harvester Head Measurement Study – Final Report (Phase III)*. Purser Tarleton Russell Ltd., Dublin.

PTR. 2000b. *Study of the Potential for Harvester Head Measurement to Provide Coillte with Timber Volume Data for Invoicing Purposes*. Purser Tarleton Russell Ltd., Dublin.

PTR. 2001a. *Study of the Potential for Harvester Head Measurement to Provide Coillte with Timber Volume Data for Invoicing Purposes*. Purser Tarleton Russell Ltd., Dublin.

PTR. 2001b. *Harvest Volume Residue Assessment*. Purser Tarleton Russell Ltd., Dublin.

Rieppo, K. 1993. *Finnish Forest Machinery and Harvester Control Measurement (FERIC)*. Conference proceedings: Forest Harvesting and Mensuration Technology. Institute of Engineers of Ireland, Dublin.

Sondell, J., Möller, J. J. and Arlinger, J. 2002. *Third-generation merchandising computers*. Skogforsk Results No. 2.