Productivity Standards for Harvesters and Processors in Italy

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Abstract

The authors developed a general productivity model for the harvesters and processors currently used in Italy. The model consists of a set of mathematical relationships that can estimate the productivity of these machines under the whole range of specific work conditions faced in Italy. Such relationships can provide general directions to prospective users and can contribute to the development of scenario predictions. The original data pool contained more than 15,000 individual time-study records, each representing a single harvesting cycle (most often one tree). The records were extracted from 38 studies conducted with the same methods and by the same principal investigators between 1998 and 2008. Statistically significant models were developed for all cyclic work phases, such as moving, brushing, felling, and processing. Accessory time and delay time were added as percent factors, also estimated from the same studies. Model development aimed at achieving the best compromise solution between accuracy and easy use, avoiding the introduction of an excessively large number of input variables. Selected independent variables were tree volume, tree species, task type (harvesting or processing), machine power and type, density of residual stand and of harvest trees, stand type, and slope gradient. These models could predict a large proportion of the variability in the data and were successfully validated using reserved cycle records, extracted from the same data pool and not used for model development. Comparison with similar Nordic and German standards confirmed the sound structure of the Italian models while highlighting the need for specific productivity norms due to the different work conditions faced by Italian operators.

Originating from a purely Scandinavian background, the mechanized cut-to-length (CTL) system has gained worldwide acceptance, expanding far beyond the limits of boreal forestry. The advantages of harvesters and processors are so attractive that loggers all over the world have adopted the new technology, applying it to close-to-nature forestry (Suadicani and Fjeld 2001) and hardwood stands (Wang et al. 2005). Today, the use of these machines is no longer limited to gentle terrain (e.g., slope gradient $< 25\%$) and conifer forests, as demonstrated by their massive deployment in the Austrian (Stampfer 1999) and Swiss (Frutig et al. 2007) mountain forests. Harvesters and processors also are very popular in Mediterranean countries, such as Spain, Portugal (Spinelli et al. 2002), and Italy (Cielo and Zanuttini 2004), where they perform much of the harvesting in the industrial pine, eucalypt, and poplar plantations.

Such rapid expansion is helped by the remarkable flexibility of the mechanized CTL concept: cheap, general-purpose prime movers can be converted into effective CTL units by adding a harvester or processor head (Johansson 1995). In this respect, earthmoving machinery provides a good alternative to dedicated forestry units, offering a robust, multifunctional, and low-cost base (Wang and Haarlaa 2002). Its versatile character allows good economic results also when the harvester function is used for a relatively short proportion of the annual work time (Väätäinen et al. 2004), making it ideal for part-time users. For this reason, excavator-based CTL units are the first choice when the new technology is being introduced to a developing market, whereas mature markets prefer high-output dedicated units (Gellerstedt and Dahlin 1999).

Regardless of application details, mechanized CTL harvesting brings the industry to the forest, with strong effects on value recovery (Sondell et al. 2002) and labor productivity (Chiorescu and Grönlund 2001), hence the keen interest toward machine performance, whose correct evaluation is crucial when prospecting the introduction of

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CTL harvesting to a new environment (Spinelli and Magagnotti, in press). The performance of harvesters and processors has been documented by many studies, conducted over the past decade in almost all the places where these machines have been deployed. However, most of these studies offer limited help when making overall predictions because of their episodic character, which makes them representative of a specific case rather than of a general condition. In particular, single studies are heavily affected by the erratic variations of the human factor, which may cause meaningful differences in performance levels: different operators can possess very different abilities (Ovaskainen and Heikkilä 2007) so that overall productivity models should be based on very large samples where variation caused by the human factor can be leveled out by including several professional operators in the same general study (Nurminen et al. 2006). To date, very few such studies are available to the international scholar, and they all concern Nordic operations. Productivity standards have been developed in Sweden (Brunberg 1995, 1997), and a similar reference is now available for thinning in Finland (Sirén and Aaltio 2003).

No overall productivity reference is yet available for central and southern Europe, where the extrapolation of Nordic results might lead to significant errors since working conditions, operator training, and technological solutions are quite different and are likely to affect machine performance (Spinelli et al. 2009a). One typical example is the tree species: those harvested in central and southern Europe generally have heavy branching, which is known to decrease harvester productivity (Glöde 1999).

Hence, there is a need for developing overall productivity references that may be used for general predictions or integrated into system simulation models, thus expanding their scope and increasing their reliability. In fact, a number of existing spreadsheet models for harvesting simulation already include the CTL option (Holtzscher and Lanford 1997, Spinelli et al. 2009b), but their extended application is constrained by the limits of the original data.

The goal of this study was to develop a general productivity model for the harvesters and processors currently used in Italy, where mechanized CTL harvesting was introduced more than 10 years ago and is now spreading to a large variety of operations (Spinelli et al., submitted for publication). Here, the conditions encountered by CTL units are very different from those found in the Nordic countries and include mountain forests, hardwoods, close-to-nature forestry, and industrial poplar plantations. This study aims at calculating a set of mathematical relationships that can estimate the productivity of CTL units under the whole range of specific work conditions faced in Italy. Such relationships can provide general directions to prospective users and can contribute to the development of scenario predictions. Furthermore, the comparison between these eventual standards and those developed for northern Europe can help gauge the differences between the Nordic and the southern European working environment, thus addressing the main issues for future technical developments. Finally, the information obtained from the models can easily be extended to countries in which work conditions are similar to those in Italy, at least until specific local models become available.

Materials and Methods

The authors compiled the raw data from 38 complete time studies, conducted between 1998 and 2008 by the researchers of the Italian National Council for Research. A general description of the studies is shown in Table 1, which reports both site characteristics and machine type. All of the time studies were set up and carried out by the same principal investigators and with the same methods. Productive time was separated from delay time (Björheden et al. 1995) and split into functional elements, expected to react to different variables (Bergstrand 1991).

Delay-free time per tree was subdivided into five basic elements: move (at roadside or within the stand), brush (occurring only if operating within the stand), grab (if processing at the deck) or fell (if harvesting within the stand), and process (delimbing and bucking). Move activity within the stand is inherently different from that at the road, so the two cases were recorded and analyzed separately. Grabbing a stem from a pile is also different than felling a standing tree, justifying separate evaluation. On the other hand, processing was considered to be similar in character whether conducted in the stand or at the landing, so the data were combined for analysis, and an indicator variable was used to check for differences between the two cases, as suggested for harvesting work studies (Olsen et al. 1998).

The merchantable overbark volume processed during each cycle was also recorded and associated to the observation data. All time-motion data were recorded with Husky Hunter handheld field computers running Siwork3 time-study software (Kofman 1995).

Clear-cuts are most heavily represented in the database, but the proportion of partial cuts is still meaningful (28%). The stronger representation of clear-cuts is the logical consequence of their higher profitability, which entails a better investment capability and therefore favors the application of mechanized harvesting. Besides, the Italian mechanized firms are still comparatively few and can often choose their work, generally opting for the most profitable opportunities.

Almost 60 percent of the studies concern general-purpose prime movers, such as tracked or wheeled excavators, flexible-legs excavators (so-called spiders), and farm tractors. In Italy, most loggers are relatively new to mechanized CTL harvesting and are afraid of the strong commitment required by the purchase of a dedicated harvester. Besides, the superior agility of such units might be unnecessary if they are to be deployed in flatland row plantations or by the roadside under a yarder.

Some studies investigated the harvesting (felling, delimbing, and crosscutting) of standing trees, while others focused on the processing (delimbing and crosscutting) of previously felled trees windrowed or piled at roadside or on the cutover.

The database represents 19 different professional operators, generally experienced and proficient. Each operator, however, was a potential source of individual variability, which must be taken into account when evaluating the results (Gellerstedt 2002). No attempt was made to normalize individual performances by means of productivity ratings (Scott 1973), recognizing that all kinds of normalization or corrections can introduce new sources of errors and uncontrolled variation in the data (Gullberg 1995). All operators worked single shifts with occasional overtime so

Table 1.—General description of the time studies.

Site no.	Stand type	Species[a]	Age (y)	Density (trees/ha)[b]	DBH (cm)[c]	Treatment	Removal (m^3/ha)	Base type/model	Head model	Work task
1	Plantation	Ash-alder	9	800	13	Thinning	23	Excav. 13 t	Keto 100	Harvest
2	Plantation	Spruce	40	320	22	Thinning	64	JD1270 C	JD758 B	Process
3	Plantation	Spruce	42	365	23	Thinning	100	JD1270 C	JD758 B	Process
4	Plantation	Austrian pine	43	949	17	Thinning	81	Spider 9 t	Woody 50	Harvest
5	Plantation	Austrian pine	45	678	21	Thinning	68	Spider 9 t	Woody 50	Harvest
6	Coppice	Beech	45	2,020	13	Thinning	153	Excav. 5 t	Arbro 400	Process
7	Coppice	Beech	45	2,020	13	Thinning	153	JD1470 C	JD290 H	Process
8	Plantation	Douglas-fir	39	820	20	Thinning	61	Spider 11 t	Woody 50	Harvest
9	Plantation	Fir	65	474	26	Thinning	53	JD1070 B	JD745	Harvest
10	Plantation	Spruce	35	1,135	18	Thinning	76	Spider 9 t	Woody 50	Harvest
11	Coppice	Ash	45	325	16	Clear-cut	35	Spider 9 t	Woody 50	Process
12	Plantation	Austrian pine	46	708	22	Clear-cut	175	Spider 9 t	Woody 50	Harvest
13	Coppice	Chestnut	55	1,213	19	Clear-cut	261	JD1270 B	JD762 B	Process
14	Coppice	Chestnut	20	1,600	15	Clear-cut	143	Excav. 18 t	Lako 55	Process
15	Coppice	Chestnut	30	2,722	10	Clear-cut	67	Excav. 15 t	Kesla 25 H	Process
16	Plantation	Fir	43	494	27	Clear-cut	208	JD1070 B	JD745	Harvest
17	Coppice	Oak	30	1,650	15	Clear-cut	234	Excav. 15 t	Kesla 25 H	Process
18	Plantation	Poplar	23	364	42	Clear-cut	520	Excav, 25 t	JD762 B	Process
19	Plantation	Poplar	5	1,158	12	Clear-cut	148	Farm tractor	Arbro 400	Harvest
20	Plantation	Poplar	11	333	35	Clear-cut	236	JD870 B	JD746	Harvest
21	Plantation	Poplar	15	625	26	Clear-cut	302	JD870 B	JD746	Harvest
22	Plantation	Poplar	12	238	29	Clear-cut	186	Excav. 15 t	Patu 560	Process
23	Plantation	Poplar	11	278	29	Clear-cut	233	Excav. 15 t	Patu 560	Process
24	Plantation	Poplar	14	278	33	Clear-cut	216	Excav, 25 t	JD762 B	Process
25	Plantation	Poplar	11	238	32	Clear-cut	218	Excav, 25 t	JD762 B	Process
26	Plantation	Radiata pine	28	1,150	21	Clear-cut	263	Excav. 30 t	AFM 80	Process
27	Plantation	Sequoia	36	1,100	27	Clear-cut	388	Excav. 13 t	JD743	Harvest
28	Plantation	Spruce	70	300	39	Clear-cut	230	JD1270 C	JD758 B	Harvest
29	Plantation	Spruce	45	494	26	Clear-cut	136	JD1270 C	JD758 B	Process
30	Forest	Spruce	150	199	41	Clear-cut	283	Excav. 20 t	Woody 60	Process
31	Plantation	Spruce	45	504	25	Clear-cut	169	Spider 9 t	Woody 50	Harvest
32	Forest	Spruce	53	84	24	Clear-cut	25	JD1270 C	JD758 B	Harvest
33	Plantation	White pine	21	1,710	18	Clear-cut	344	JD1270 B	JD762 B	Harvest
34	Plantation	White pine	22	1,570	24	Clear-cut	460	JD1270 B	JD762 B	Harvest
35	Plantation	White pine	23	950	25	Clear-cut	331	JD1270 B	JD762 B	Harvest
36	Plantation	White pine	33	680	31	Clear-cut	669	JD1270 B	JD762 B	Harvest
37	Plantation	White pine	22	1,333	25	Clear-cut	440	Farm tractor	Keto 50	Harvest
38	Forest	Mix fir-beech	120	73	41	Selection	125	Excav. 15 t	Patu 560	Process

[a] Ash = *Fraxinus ornus* L.; alder = *Alnus cordata* (Loisel.) Desf.; spruce = *Picea abies* L. (Karst.); Austrian pine = *Pinus nigra* J. F. Arnold; beech = *Fagus sylvatica* L.; Douglas-fir = *Pseudotsuga menziesii* Mirbel.; fir = *Abies alba* Mill.; chestnut = *Castanea sativa* Mill.; oak = *Quercus cerris* L.; poplar = *Populus ×euroamericana* (different hybrids); radiata pine = *Pinus radiata* D. Don.; sequoia = *Sequoia sempervirens* (D. Don.) Endl.; white pine = *Pinus strobus* L.

[b] Density is the initial density before cut.

[c] DBH = diameter at breast height.

that fatigue was unlikely to significantly affect performance (Nicholls et al. 2004).

The overall data set contains 15,148 cycle observations corresponding to 15,366 trees. Multitree handling (i.e., handling more than one tree per cycle) was observed on rare occasions, exclusively when processing felled trees from a deck. Tree volume ranged from 0.010 to 7 m^3, with an average value of 0.346 m^3. Total study volume amounts to 5,239 m^3, and study time to 329 hours of net work, excluding all delays. Average productivity is 46 trees or 15.9 m^3 per net hour, excluding all delays.

We used regression analysis of the time-study data to develop a set of equations capable of predicting cycle time (and therefore productivity) as a function of statistically significant independent variables. Documented validation is a prerequisite of production models derived from time-study data (Howard 1992), and it was conducted according to the same procedure recently used by Adebayo et al. (2007) for a similar modeling study. The data set was partitioned at random into two subsets: the first subset, containing 70 percent of the observation number, was used to calculate appropriate productivity relationships through regression analysis; the second subset, with the remaining 30 percent of the observations (reserved data), was used to validate the regressions obtained above. To this purpose, the time consumption equations were used to predict the reserved data, then the predicted cycle times were correlated with the observed cycle times, and the resulting r^2 (validated r^2) was used as a measure for the predictive capacity of the equations. Furthermore, two-sample t tests were used to test the differences between predicted and observed cycle times.

Table 2 shows a regression matrix for the independent variables used in conducting the regression analysis of each time element. Transformations of the independent variables were chosen on the basis of theoretical as well as empirical considerations. For example, move time per tree was

Table 2.—Regression analysis matrix.

Independent variables	Dependent variables[a]					
	Move (at deck)	Move (in stand)	Brush (in stand)	Grab (at deck)	Fell (in stand)	Process
Continuous						
Tree vol. (m^3)	**		NS	**	**	**
Carrier power (kW)	NS	**	NS	**	**	**
Head size, max. cut diam. (cm)				NS	NS	NS
Gradient (%)	NS	**	NS	NS	**	**
Removals (trees/ha)		*	NS		NS	NS
Residuals (trees/ha)		**	NS		NS	NS
Discrete						
Carrier type	NS	**	NS	**	**	**
Head type (roller, stroke)				NS	NS	**
Work task (process, harvest)	[b]	[b]	[b]	[b]	[b]	NS
Operation (clear-fell, thinning)		NS	NS		NS	NS
Stand (coppice, forest, plantation)[c]		NS	**		NS	NS
Species (seven species or combinations)	NS	NS	NS	NS	NS	**

[a] * = significant ($P < 0.05$); ** = highly significant ($P < 0.01$); NS = not significant in addition to other factors.
[b] Activities at the deck (process) were analyzed separately from those in the woods (harvest).
[c] Only processing at the deck was observed in coppice stands.

expected to be related to distance between trees to be removed; therefore, the inverse of trees removed per hectare was used when developing the regression model.

If machine power limits throughput, as it probably does for at least some portion of each of the time elements, time to complete a given task is related to power available in the following fashion: power = work/time or time = work/power. If more power is available, say, by increasing the size of the machine's engine, time for a given task should decrease. There are likely to be diminishing returns as power is increased, however, so the transformation of power included in the regression models for time was power$^{-0.5}$ rather than power^{-1}.

Grab and fell are piece-handling activities, so time per tree would be expected to increase somewhat as tree volume increased but at a linear or smaller rate until tree size approached the machine capacity. Processing is a length-handling activity, so time per tree should increase less than linearly with tree volume, again until the machine was overly taxed. The transformations of tree volume selected for the regression model were based on these theoretical considerations as well as the empirical trends.

Results

Table 3 reports the average time consumption per tree, as extracted from the entire data pool. Data are subdivided by basic element and refer to a very similar average tree volume: 0.341 and 0.350 m^3, respectively, for processing at the deck and harvesting within the stand.

Table 3.—Mean values and standard deviations for the time elements and for the total net cycle time.

Work phase	Mean (SD)	
	At deck	In stand
Move	7.3 (25.4)	19.7 (47.9)
Brush	0.0 (0.0)	2.5 (18.8)
Grab/fell	21.3 (24.3)	28.4 (30.6)
Process	70.9 (101.1)	63.6 (68.6)
Total	99.5 (117.4)	114.2 (109.9)

Regression analysis of 70 percent of the original data pool allowed estimating six equations, capable of predicting the time consumption for each individual work phase, namely, move time at deck, move time in the stand, brushing time, felling time, time for grabbing a tree from a deck, and processing time. Table 4 defines the dummy (indicator) variables found to be significant for one or more of the time elements.

Move time at deck when processing prefelled trees was not significantly related to tree volume and was highly variable. This can be expected because when processing trees from a deck, the machine can reach many stems from the same position. Therefore, most of the observations will have zero move time associated with them. Move time also depends on a number of factors that could not be included in the model, such as decking layout and operator ability to organize the work in the most effective way. The predictive equation is reported below (n = 5,693, predicted r^2 = 0.008). It includes tree volume because the full crane reach can be used only with smaller trees, whereas larger trees must be handled at a closer distance. This, as well as the fact that more small trees can be piled per length of deck, theoretically justifies more frequent moving when processing larger trees and the consequently longer moving time per tree:

$$\text{Move at deck}, 10^{-2}\,\text{min tree}^{-1} = 5.6 + 4.26\,\text{tree volume}, \text{m}^3 \quad (1)$$

Move time within the stand while harvesting increased with slope and the number of residual trees per hectare and decreased with the number of removed trees per hectare and with the power of the prime mover. Time per tree was substantially longer for spider- or tractor-based harvesters, which are somewhat awkward compared with dedicated harvesters and excavator base units. The predictive equation shows a weak correlation (n = 5,643, predicted r^2 = 0.091) although stronger than for Equation 1. Nevertheless, the

Table 4.—Definitions of dummy (indicator) variables.

Variable	Definition
Chestnut or poplar	1 if species is chestnut or poplar, 0 for other species
Excavator	1 for excavator-based machines, 0 for other types (dedicated, spider, or farm tractor)
Forest	1 for naturally regenerated forests, 0 for plantations
Nonspider	1 for any base other than a spider (dedicated, excavator, or farm tractor), 0 for spider
Other hardwood	1 if species is a hardwood other than chestnut or poplar, 0 for chestnut, poplar, or conifer
Spider	1 for spider-based machines, 0 for other types (dedicated, excavator, or farm tractor)
Stroker	1 for heads utilizing short-stroke advance mechanisms, 0 for other types (roller or track advance mechanisms)
Tractor	1 for farm tractor-based machines, 0 for other types (dedicated, excavator, or spider)

terms in the equation are highly significant, and the relationship is logical, so it was decided to retain the regression, as follows:

$$\begin{aligned}&\text{Move within stand, } 10^{-2}\text{min tree}^{-1}\\&= 7.5 + (12{,}412 + 771 \text{ Slope gradient, } \%\\&\quad + 46{,}706 \text{ Spider dummy}\\&\quad + 63{,}153 \text{ Farm tractor dummy})\\&\quad \div (\text{Removals, tree ha}^{-1}\\&\quad \times (\text{Machine power, kW})^{0.5})\\&\quad + 0.204 \times \text{Residuals, tree ha}^{-1}\\&\quad \div (\text{Machine power, kW})^{0.5}\end{aligned} \tag{2}$$

Brush time is the time needed to clean the undergrowth from around removal trees and applies only to harvest (vs. processing), which involves access to the stand. No brush time is needed when processing trees from a deck. Brush time per tree was greater under forest conditions than in plantations, the latter generally presenting much sparser undergrowth. This element also had inherently high variability, as brushing is performed only when necessary, and therefore more than 95 percent of the observations had zero brushing time associated with them (n = 5,641, predicted $r^2 = 0.020$). The predictive equation is as follows:

$$\text{Brush, } 10^{-2} \text{ min tree}^{-1} = 1.8 + 9.2 \text{ Forest dummy} \tag{3}$$

Grab time from a deck increased with tree size and decreased with machine power. Spider-based machines took roughly twice as long as others of the same power to grab a tree. The coefficient of determination is much higher than in the previous equations because of a much more stable work routine. Residuals show a generally good fit (n = 5,693, predicted $r^2 = 0.162$) across the range of tree volume, which confirms the overall reliability of the equation reported below:

$$\begin{aligned}&\text{Grab, } 10^{-2}\text{ min tree}^{-1}\\&= 15.2 + 153.1 \text{ tree volume, m}^3\\&\quad \div (\text{Machine power, kW})^{0.5}\\&\quad + \text{Spider dummy} \times (13.9 + 274.9 \text{ tree volume, m}^3\\&\quad \div (\text{Machine power, kW})^{0.5})\end{aligned} \tag{4}$$

Fell time within the stand increased almost linearly across the observed ranges of tree volume for most machines. Time decreased with machine power and increased with gradient for all but the spider-based harvesters, which seem insensitive to slope gradient during the felling operation, within the limits explored by the study. Time consumption was greater for the excavator-, tractor-, and spider-based machines compared with the dedicated harvesters. Residuals are a bit low at the upper end of the volume range, although the magnitudes are miniscule compared with the mean felling time per tree. The equation below is highly significant (n = 5,122, predicted r^2 = 0.472) and explained almost half the variability recorded for felling time:

$$\begin{aligned}&\text{Fell, } 10^{-2}\text{min tree}^{-1}\\&= 3.8 + 156.5 \text{ tree volume, m}^3\\&\quad \div (\text{Machine power, kW})^{0.5}\\&\quad + 1.18 \text{ Nonspider dummy} \times \text{Slope gradient, } \%\\&\quad + 6.5 \text{ Excavator dummy}\\&\quad + 24.8 \text{ Farm tractor dummy}\\&\quad + \text{Spider dummy}(25.5 + 188.5 \times \text{tree volume, m}^3\\&\quad \div (\text{Machine power, kW})^{0.5})\end{aligned} \tag{5}$$

Process (delimbing and bucking) time per tree increased with tree volume, number of logs, and gradient, while it decreased with machine power. Stroke processors (vs. roller or track-type heads) and tractor-based machines required more time than other types. There was no significant difference between the processing times recorded for roadside work and for work within the stand, other factors being equal. The mean residuals plot evenly distributed around the fitted values across the range of tree volume, indicating that the linear term is appropriate. There is more scatter of the means at the upper volumes, although this is due to there being only 45 observations of trees larger than 3 m^3 compared with 8,300 smaller. A further explanation can be the branching, which is very variable on large trees and may combine with overall tree size in making processing particularly difficult. Processing of chestnut and poplar required less time than for conifers, other factors being equal. This is logical because poplar clones are selected for straight stems and are usually pruned, whereas chestnut is always in the form of coppice sprouts, generally slender and with few branches. Other hardwoods—generally branchy and badly formed—took more time to process than did the conifers. The regression shown below is highly significant (n = 11,324, predicted r^2

= 0.670) and explained two-thirds of the variability recorded for processing time:

$$\begin{aligned}
&\text{Process, } 10^{-2}\,\text{min tree}^{-1}\\
&\quad = 22.7 + 1.433\,\text{tree volume, m}^3\\
&\qquad \times \text{Slope gradient, \%}\\
&\quad + (1{,}115 + 446\,\text{Stroker dummy}\\
&\qquad + 2{,}244\,\text{Farm tractor dummy}\\
&\qquad - 362\,\text{Chestnut or Poplar dummy}\\
&\qquad + 1{,}118\,\text{Other Hardwood dummy})\\
&\quad \times \text{tree volume, m}^3/(\text{Machine power, kW})^{0.5} \qquad (6)
\end{aligned}$$

The validity of all the equations was checked by comparing the predictions and the actual values for the second subset, specifically reserved for the purpose. Table 5 reports the actual and predicted values, the percent error for the estimates, the results of the paired t test conducted between the two groups of data (actual and predicted), and the coefficients of variation for the respective regressions (actual vs. predicted). Where the paired t test indicated that the difference between the two groups was not significant, the prediction was accepted as valid. The limit for significance was assumed to be the usual $P < 0.05$. The coefficient of variation was taken instead as a measure for the reliability of individual predictions conducted at cycle level. The trend was considered valid whenever the coefficient of variation for the actual versus predicted was of the same magnitude as the coefficient of variation recorded for the predictive equations. Four equations out of six appear to be validated, whereas correction factors should be applied to the predictions obtained from Equation 2 (Move in stand) and Equation 5 (Fell). The predicted and actual time elements were summed to obtain total cycle time. The predicted value for total cycle time is valid for processing at a deck, whereas it should be corrected for harvesting. In any case, the error is limited and represents, respectively, −2 and −3.5 percent. In general, the predictive equations tend to slightly underestimate time consumption for the reserved data set, presumably because of random variation, including that which might be explained by factors that were not included in the data collection. In the case of felling, for instance, tree position and tree lean may have played significant roles, but appropriate estimators were not included in the original record, and therefore it was not possible to capture and represent the effects of these variables.

The equations presented above allow estimating cyclic net time, which can be transformed into scheduled time consumption by adding appropriate estimates for accessory time and delay time. In the cases observed, accessory time consisted mostly of tasks such as slash piling, log stacking, and log sorting, which are also known to have a significant impact on productivity (Gingras 1996). These tasks are not cyclic and occur every so often after harvesting or processing a certain number of trees. Therefore, inaccurate results can derive from attaching the time consumption for a specific occurrence to one specific observation; for instance, the amount of slash handled during slash piling generally belongs to a number of previous cycles and not just to the cycle during which the action occurs. The allocation of this time to the respective cycles is laborious and does not necessarily produce reliable results so that many researchers simply calculate a constant time consumption per cycle and add it to the sum of cyclic time (e.g., Nurminen et al. 2006). As an alternative, one can develop percent coefficients that relate the duration of accessory time to the duration of cumulative cyclic time in order to reflect the indirect effect of tree size and shape on accessory time, on the assumption that bigger trees are likely to produce more slash and that the redistribution of slash piling time should be proportional to the amount of slash handled (e.g., Spinelli et al 2009a). That was the approach followed in this study, where 2 percent coefficients were developed, equal to 14.7 percent (SD = 34.3) and 29.6 percent (SD = 81.8), respectively, for harvesting in the stand and processing at the deck. The development of different coefficients for the two different work types was justified by a t test, demonstrating that the two work types actually presented a significantly different incidence of accessory time ($t = 14.5$, $P < 0.0001$, df = 15,138).

Delay time can be added to productive time using appropriate coefficients in order to reflect actual scheduled time, which is the time to be paid for. This practice is common in Nordic studies (Kuitto et al. 1994), and specific coefficients have recently been developed for harvesters and processors operating in Italy (Spinelli and Visser 2008). Such coefficients represent a percent incidence and are applied to the sum of productive and accessory time to calculate the duration of delay time. Different coefficients were developed for harvesting work in natural forests,

Table 5.—Results of the validation tests.

Eq. no.[a]	Element	Actual	Predicted	Δ %[b]	t test P	r^2 val.[c]	r^2 pred.[c]
1	Move (at deck)	7.5	7.1	−5.3	0.559	0.009	0.008
2	Move (in stand)	19.6	14.4	**−26.5**	<0.0001	0.098	0.091
3	Brush	1.2	1.1	−8.3	0.458	0.051	0.020
4	Grab	22.0	21.2	−3.6	0.158	0.121	0.162
5	Fell	29.2	26.8	**−8.2**	<0.0001	0.401	0.472
6	Process	67.6	68.2	0.9	0.701	0.685	0.670
—	Total at deck	99.7	97.8	−1.9	0.068	0.684	—
—	Total in stand	114.5	110.5	**−3.5**	0.002	0.558	—

[a] Equation number as reported in the text.
[b] Bold values represent significant differences between actual and predicted values ($P < 0.05$) to be adopted as correction factors.
[c] r^2 val. and r^2 pred. are the coefficients of determination for the regression of actual versus predicted values and of the original predictive equations (1 through 6), respectively.

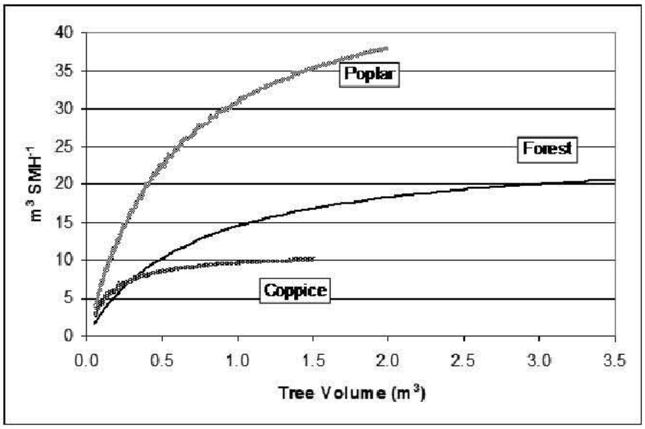

Figure 1.—Predicted overall productivity in m^3 per scheduled machine hour (SMH) for three typical cases.

harvesting work in plantation forests and processing work from decks.

An example of the possible use of the models presented in this article is shown in Figure 1, representing an estimate of overall productivity for three of the most common cases in Italy, namely, the harvesting of spruce with a dedicated harvester (160 kW), the harvesting of plantation poplar with an excavator-mounted harvester (130 kW), and the processing of hardwood stems at the roadside, with an excavator-based processor (75 kW). The delay coefficients were 50, 21, and 44 percent, respectively, and the assumed slope gradients were 25, 2, and 2 percent. The dedicated harvester was assumed to be working in a spruce selection cut, with a prescribed removal of 150 trees per ha representing 50 percent of the original tree density. Tree volume has been adjusted for the respective ranges, and productivity is reported in cubic meters per scheduled machine hour.

Discussion and Conclusions

This study is unique because of the wide range of equipment observed and the very substantial size of the data set, with observations exceeding several times the reference values presented in a bibliography (Murphy 2005), and therefore suitable for representing a large variety of machines and operations. A further asset of the study is that all data were collected by the same principal investigators, limiting errors caused by different interpretations of the same data collection protocol (Nuutinen et al. 2008). In fact, the collection of such a large data pool required approximately 10 years and was a rare endeavor. In recent years, new automatic data collection techniques have appeared that will allow for the automatic recording of large data sets within a relatively short time (Peltola 2003). Even so, the intervention of the researcher will often be needed because of the limited flexibility of the automatic data collection procedure (Väätäinen et al. 2003), hence the intrinsic value of the present study.

As in numerous previous studies, tree volume was found to be a primary variable affecting the total time to harvest or process a tree. Following careful analysis of source data, this study elected a linear model to represent the relationship between time consumption and tree volume, as already done by other authors (Hånell et al. 2000, Sirén and Aaltio 2003, Nakagawa et al. 2007). However, it is important to remember that not all authors agree on the choice of linear models, and some prefer to use quadratic equations (Wang and Haarlaa 2002, Kärhä et al. 2004, Nurminen et al. 2006), which have also proved acceptable. A quadratic equation would firmly establish the concept of diminishing returns, with productivity inevitably decreasing beyond a certain point. This could be a logical consequence of the size limitation inherent to any specific model, and under this light quadratic models are conceptually safer, hence the importance of using the linear models presented in this article with caution, avoiding extrapolation beyond the range of tree volumes contained in the origin data, which is, however, quite wide and ranges from 0.005 to 7 m^3. Again, we note that the trends were clearly linear rather than quadratic for the observations in this study, indicating that machine limits had not been reached.

The models also include several other independent variables, such as slope gradient, stand type, and tree density, all of which are known to affect time consumption, especially moving. On the other hand, the models did not integrate tree selection criteria, which impact productivity both in thinning (Eliasson 1999) and in final cuts (Hånell et al. 2000). However, the same authors also indicate that the effect of different selection criteria is often mediated through variations in tree size so that our models can indirectly reflect tree selection criteria (Eliasson and Lageson 1999). Like most other models, ours are indifferent to tree position in the stand, which may explain the relatively poor accuracy of the equation developed for felling time.

The study also allowed us to quantify some important effects of machine type and size, the latter indicated by the rated power of the prime mover. More power resulted in less time consumption for the same task, which applied to most work phases. Head size, as indicated by felling diameter capacity, did not have any significant effect on productivity when considered in addition to machine power. This is due in large part to the strong correlation between felling capacity and machine power, as machine owners generally selected heads that were well matched to the carriers. On the other hand, stroke-type heads proved significantly less productive than roller- or track-type heads, as expected.

The analysis also showed that dedicated carriers had higher productivity than others and in particular that tractors and spider bases were particularly slow in most tasks, possibly because of less effective design for the observed tasks. In particular, the loaders on these machines lack the agility of the parallel cranes mounted on dedicated harvesters and the power of excavator booms. On the other hand, spider-based units were the only ones to be found indifferent to slope gradient when felling, which makes them an interesting option for steep-terrain harvesting. In fact, the models developed with the study can help determine a breakeven slope gradient above which a spider-based harvester will offer better results than a dedicated unit, thanks to its superior steep-terrain mobility. In this respect, Figure 2 shows the results of a simulation conducted for a hypothetical spruce stand with removals of 150 trees per ha (50% of the original stocking), and an average tree size of 0.3 m^3. The simulation included the same 160-kW dedicated unit described earlier and an 88-kW spider-based harvester. Slope gradient varied from 0 to 50 percent—the simulation indicates that beyond a 40 percent

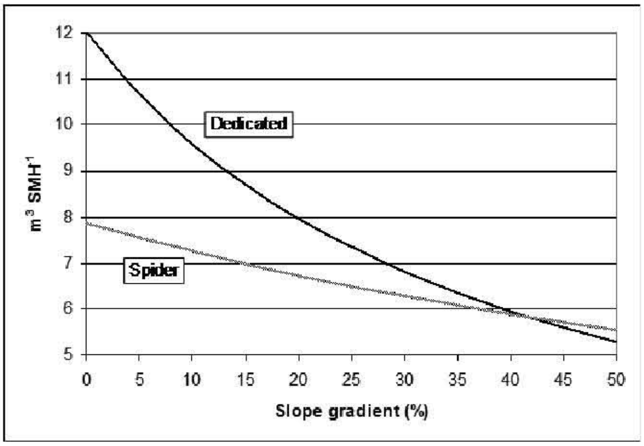

Figure 2.—Comparison of dedicated and spider-based harvesters in a selection cut of young spruce (average volume per tree = 0.3 m^3).

slope gradient, the spider is more productive than the dedicated harvester.

In contrast to some other studies, we did not find any explicit productivity effects of clear-fell versus thinning, although these discrete differences may have been partly covered by the significant effects of removal and residual trees per hectare on move time and by the pervasive effect of tree size, which is strongly correlated to silvicultural treatment. In fact, clear-fell is being progressively banned from Italian forests by limiting the area of clear-cuts. Group or single-tree selection represents the main type of maturity cut applied to Italian forests, with the exception of coppice stands and short-rotation plantations. Coppice trees are generally felled by chainsaw because of the inherent difficulty of cutting multiple trees sprouting from the same stump so that processors rather than harvesters are used in coppice harvesting operations. Therefore, the only real clear-fell work performed by Italian harvesters is in poplar and pine plantations.

The models presented in this study are relatively accurate and can explain a large proportion of the variability in the process. The remaining error most likely depends on a number of other variables that were not included in the study. Some of these were difficult to introduce because their translation into suitable indicators would have required a subjective judgment by the researcher. This would be the typical case of such factors as working technique, operator proficiency, and operator experience, which do have a significant impact on productivity (Ovaskainen et al. 2004, Dvořák et al. 2008). Other variables were easier to record, and some of them were indeed recorded for at least part of the 38 origin studies. These are the number of logs, the number of log sorts, and a tree form coefficient. The number of logs sorts may have a significant effect on productivity (Brunberg and Arlinger 2001) and is not difficult to record. Tree form can be represented by appropriate numeric codes, as already done by other authors over the years (Raymond et al. 1988, Emeyriat et al. 1997, Puttock et al. 2005). However, it was estimated that the inclusion of these further factors into the model would have complicated its use more than it would have increased its value. The risk was that users could be overwhelmed by the number of input data necessary for the model to return its estimate and would provide approximate figures, thus canceling the benefit of increased model accuracy. Requiring only a few and relatively simple input data, this model was designed to offer a best-compromise solution and prove both user friendly and reasonably accurate.

Finally, it may be interesting to see how the Italian productivity standards, tentatively developed with this study, compare with the standards reported by other authors for other countries. To this purpose, three general models were selected, all designed to represent a cross section of mechanized operations in a given country and generally based on large data sets. Two models were those developed for Sweden and Finland, respectively, by Brunberg (1995) and Nurminen et al. (2006), already mentioned in the introduction of this article. A third and very interesting model was developed by Purfürst (2007) in Germany, using an extremely large data pool made of the records extracted from the onboard computers of about 30 machines. All three models calculate productivity after excluding delays longer than 15 minutes, and their results are not directly comparable to those obtained from the Italian model, which estimates productivity after including all delay time. Therefore, the delay factors on the Italian model were changed for the purpose, by applying a reduction factor of 0.39, also calculated from Spinelli and Visser (2008). The Italian comparison treatments were clear-fell harvesting of spruce and poplar, performed with a dedicated harvester, in order to reflect conditions similar to those in the foreign studies. The results are reported in Figure 3. The estimated productivity for the harvesting of Italian spruce is the lowest, and it is somewhat nearer to the estimate for Germany than to those for Finland and Sweden. That may partly depend on the heavier branching of Alpine spruce so that the descending southern gradient of spruce harvesting productivity might be related to a comparable and increasing branching gradient. In a way, Nordic softwood stands may offer conditions that are more similar to Italian poplar plantations than to alpine spruce forest, which might be the reason for the very similar productivities achieved in both stand types. In fact, the estimated productivity for Italian poplar is extremely close to that obtained for Swedish spruce, with the two graph lines almost overlap-

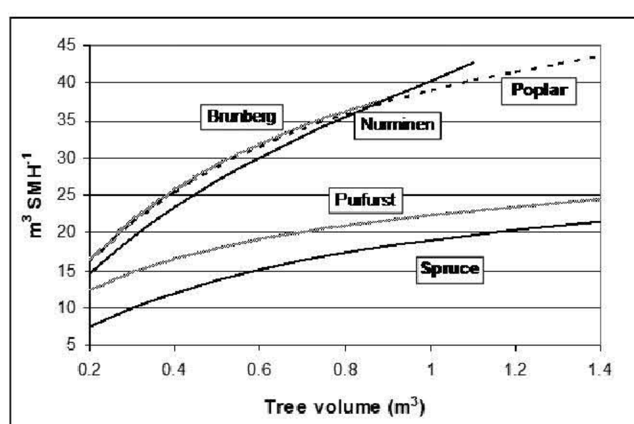

Figure 3.—Comparing the estimates for Italian spruce and Italian poplar with those obtained from some other popular models for softwood harvesting.

ping. The results of this comparison are a good witness to the sound structure of the Italian models, which return reasonable and justifiable figures. At the same time, they highlight the specific conditions of Italian forest operations and support the need for specific models.

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