Harvesting and Transport of Root Biomass from Fast-growing Poplar Plantations

Raffaele Spinelli, Carla Nati and Natascia Magagnotti

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Recovery of tree root biomass can be attractive, since the stump-root system represents a substantial portion of the tree mass and its removal may prove instrumental to re-cultivation. Most available studies concern Nordic technologies, particularly suited to mature conifer stands. Unlike spruce, plantation poplar develops a deep taproot, whose extraction requires completely different methods.

The aim of the study was to investigate poplar root recovery operations in plantations with time studies, and to determine the productivity and delivery costs of the operations. Seven operation systems developed to work with poplar plantations in Italian conditions were studied. Extraction and cleaning units were based on general-purpose prime movers.

Under favourable conditions extraction and cleaning units achieved a very high productivity: 150 stumps per hour for the extraction unit and 170 for the cleaning unit. Delivered cost varied widely, ranging from 28 to 66 €Mg^{-1}. Transportation was the most expensive single work task. It accounted for about 40% of the total recovery cost. Extraction and cleaning contributed approximately 25% each to the total cost, and loading 9%. Guidelines to recovery system improvement and efficient operation are provided.

Keywords root recovery, harvesting, biomass, productivity, cost, logistics
Authors' address CNR/IVALSA, Via Madonna del Piano - Palazzo F, I-50019 Sesto Fiorentino (FI), Italy **E-mail** spinelli@ivalsa.cnr.it
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1 Introduction

The roots of harvested trees represent an interesting source of wood biomass, and their recovery deserves special attention for the following reasons: first, the stump-root system represents a substantial portion of the tree mass (Hakkila 1975, De Simiane 1977); second, root wood often has higher heating values than stem wood, and may prove to be a better fuel (Nurmi 1997); third, the removal of the root system in tree plantations is considered as a service rendered to the landowner. Therefore, harvesting tree roots does not require the payment of a concession, and may carry additional revenues in terms of landowner payments.

Records exist of root extraction performed during the forest clearings of the early 1900 (Reinhold 1951) but it is only in the early 1960s that one starts talking about industrialised root recovery (Colquitt 1980, Czereyski et al. 1965). In most cases, one used large crawler tractors equipped with special ripper blades (Robel 1964, USDA 1971). In the 1970s, the Scandinavian boom of pulp manufacturing justified special efforts to find new sources of wood raw materials. Pine and spruce root systems were extracted using modified excavators, equipped with the *Pallari* grapple (Hakkila 1972, Hakkila and Mäkelä 1973): a special attachment designed to uproot and split flat stumps. This was successfully tested in Denmark (Baadsgaard-Jensen 1983), France (Simiane et al. 1976) and Sweden (Fryk and Nylinder 1976) – and eventually adapted to local conditions (Nylinder 1977, Simiane and Vallart 1982). Root cleaning was achieved by shaking the roots just after extraction and leaving the extracted root systems outdoors, so that the rain would wash out any soil still clinging to the wood. In Sweden, a vibrating screen-bunk was developed, which was mounted on the forwarder collecting the extracted root systems (Jonsson 1978). Finnish researchers have opened the way to mechanized root wood harvesting in the 1970s and today they are leading the revival of root wood harvesting, made possible by a renewed interest in biomass fuels (Hakkila and Aarniala 2004).

Less information is available on the root harvesting technologies used in Southern Europe, where mechanized root collection has also been performed for decades – particularly from poplar plantations, which represent an important wood source in France and in Italy (Coaloa 1999), among other countries. In France, poplar plantations cover 240 000 hectares and produce annually 1.5 million m^3 of roundwood (AFOCEL 2004). In Italy these figures are respectively 120 000 hectares and 1.8 million m^3 (ISTAT 2002). Poplar plantations have a great potential for biomass recovery, due to the abundance of the residue, the ease of access and the industrial character of management. Compared to spruce, poplar trees have deep taproots that a *Pallari*-type unit cannot handle very well.

In 1958, CNR developed a prototype wheel-cradle, used with a tractor to topple the tree with its roots attached, and to tow it to the yard for processing (Currò 1963). In 1960 an Italian manufacturer built an auger, designed to fit the rear end of a farm tractor and to receive power through the power take-off (FAO 1962). The auger was hollow inside, and large enough to contain the taproot of a mature poplar tree. It was lowered over the stump and driven into the ground to the depth of approximately 150 cm. Then the auger was raised with a soil "carrot" inside it, which contained the taproot. An ejection ram pushed the "carrot" out of the pipe, dropping it to the ground (Currò and Ghisi 1968). Mass production began shortly afterwards, and today auger-type extractors are widely used in Italy and abroad, especially in Hungary and in the Balkans (Markovic 1973). The core-sampler system is ideal for trees with a strong taproot (poplar, pine etc.) but produces dirty "carrots" that need cleaning. Active on-site cleaning allows reducing storage time and transportation cost, and it is performed with chain-flail cleaners: these are mounted on a wheeled chassis and towed by a loader or a farm tractor. The two flail axles are powered by independent hydraulic motors, connected to the pump of the carrier. The loader picks up the "carrots" and dips each one for a few seconds between the rotating flails. It then throws the clean roots 5–6 m away, to form small heaps. Clean roots are loaded directly onto 3-axle trucks driven into the field, using the same loader that cleaned them. If the soil is wet, farm tractors are used instead of trucks.

Detailed field studies on a representative sample of poplar root recovery operations were conducted with the goal of obtaining crucial information on

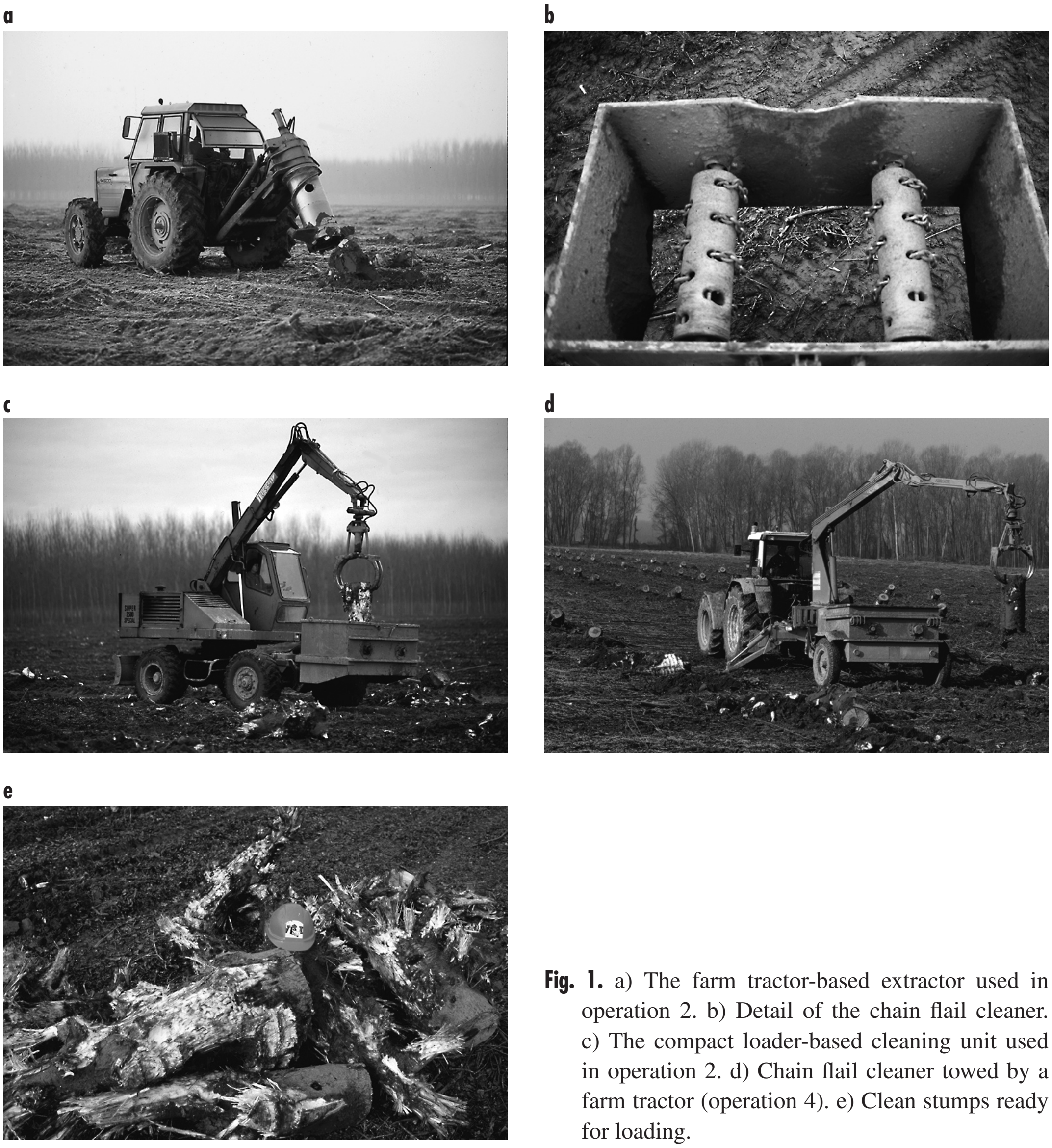

Fig. 1. a) The farm tractor-based extractor used in operation 2. b) Detail of the chain flail cleaner. c) The compact loader-based cleaning unit used in operation 2. d) Chain flail cleaner towed by a farm tractor (operation 4). e) Clean stumps ready for loading.

system performance, delivery cost and improvement opportunities.

2 Materials and Method

After a survey of manufacturers and operators, seven representative contractors were selected for conducting productivity studies. Table 1 provides a description of sites at the time of the study, which was conducted in late winter – from January to March. Numbering follows a chronological order.

Table 2 describes the resources used at each site, separated according to the work task performed. In principle, all operations involved three teams: the extraction team, the cleaning-loading team and

Table 1. Site description.

	Operation 1	2	3	4	5	6	7	$\bar{x}$
Clone	I-214	I-214	I-214	Canadian	Canadian	Canadian	Canadian	-
Age, years	11	13	13	10	11	12	11	12
Density, trees ha^{-1}	333	333	278	278	370	333	237	309
Terrain	Rutted	Even	Rutted	Even	Even	Even	Even	-
Ground	Mud	Solid	Mud	Solid	Solid	Solid	Solid	-
Soil	Clay	Sandy	Sandy	Sand	Sandy	Sand	Sandy	-
Weather	Overcast	Sun	Sun	Sun	Overcast	Sun	Overcast	-
Morning temp., C°	4	-3	2	-4	5	4	0	1.1
Stump mass, kg	52	68	65	61	39	60	52	56.7
Moisture cont., %	40	40	40	44	44	44	44	42.3
Biomass, Mg(od) ha^{-1}	10.4	13.6	10.8	9.5	8.1	11.2	6.9	10.1

Table 2. Resources used in the 7 operations studied.

	Operation 1	2	3	4	5	6	7
	Extraction						
Prime mover type	Dedicated	Farm tractor	Farm tractor	Farm tractor	Farm tractor	Dedicated	Farm tractor
Power, kW	118	107	132	92	59	132	59
Auger ∅, cm	45	50	50	45	50	45	45
Crew size	1	1	1	1	1	1	1
Investment, k€	109	127	154	116	92	127	92
Cost, €$hour^{-1}$	56	71	72	61	54	61	54
	Cleaning and loading						
Prime mover type	Loader	Loader	Forestry loader	Farm tractor	Loader	Forestry loader	Farm tractor
Power, kW	80	88	110	99	78	110	92
Crew size	1	1	1	1	1	1	1
Investment, k€	70	70	103	105	70	103	126
Cost, €$hour^{-1}$	52	45	58	62	50	58	67
	Transport						
Vehicle type	Tractor trailer	10-Ton truck	10-Ton truck	Tractor trailer	Tractor trailer	10-Ton truck	Tractor trailer
Payload, T	10	10	10	10	10	10	10
Crew size	1	1	1	1	1	1	1
Investment, k€	118	116	116	106	106	116	115
Cost, €$hour^{-1}$	70	72	72	60	60	72	70

Table 3. Description of time elements.

Time element	Description
	Extraction
Move	Machine moves from one stump to the next. Includes positioning the auger on the stump
Plunge	Auger is driven in the ground, encasing the taproot
Lift	Rotating movement stops and auger is lifted from the ground.
Eject	The ejection ram pushes the taproot off the auger
Other	Any other time
	Cleaning
Move	Machine moves from one work station to the next
Pick up	Crane reaches for a taproot, lifts it and takes it above the chain flail tub
Dip	Crane keeps the taproot between the rotating flails, turning it to complete cleaning
Dump	Crane throws the clean taproot into a small pile
Other	Any other time

the transportation team. They generally worked separately and assembled only during loading: when a transportation unit arrived on site, the loader attached to the chain-flail stopped cleaning and came to load it. Occasionally, the extraction unit was also called in for towing the transportation vehicle through difficult terrain. Extractors were mounted on farm tractors or dedicated *Elefante* prime movers, each coming in a number of versions. All were equipped with *Ellèttari mod. 200* extraction kits. Cleaning was done with the ubiquitous *Masèra-Ellèttari* chain-flail trailers, attached to a wheel loader or to a farm tractor. The chain-flails powered by wheeled loaders were directly connected to the hydraulic system of their prime movers. On the contrary, the hydraulic system of farm tractors was not powerful enough for driving both the chain-flail and the loader mounted behind the tractor cab, so that an additional pump was installed. Transport vehicles were either 3-axle 10-Ton trucks or farm tractors with a 3-axle 10-Ton trailer. The tractor used in operation 1 was a high-speed model (JCB Fastrac), capable of reaching 80 $km\,h^{-1}$ on asphalt road.

Each operation was studied at least for a whole day, and the study was prolonged or repeated if one day was not sufficient to obtain reliable figures. Productivity data were recorded separately for each of the units carrying out the recovery work, and namely: extraction unit, cleaning unit, loading unit and transport unit. Data sets for each unit contained information on both output and time consumption (Bergstrand 1991).

Output was estimated by a piece count, i.e. the number of taproots extracted, cleaned, loaded or transported – depending on the unit observed. All the taproots produced in each study session were weighed on a certified weighbridge, after cleaning. This allowed knowing the weight of the average taproot in that session, and therefore transforming unit output into mass output. Samples were collected from roots of the two main clones for moisture content (m.c.) determination, which was obtained with the gravimetric method – i.e. weighing the samples fresh and after drying in a ventilated oven set to 105 C° until reaching constant weight.

The net time consumption of the unit observed during each individual study session was recorded with Husky Hunter 16 hand-held computers running the dedicated Siwork3® time-study software (Kofman 1995). Cycle times were subdivided into significant time elements (Table 3). Unit productivity was calculated on the basis of net work time. The studies were too short for obtaining an accurate estimate of delay times, which were accounted for by increasing net work time by 30%: the additional time is meant to include all type of delays, including preparation, service and minor repairs (Brinker et al. 1986). Each visit also included intense discussion with the contractor, concerning the technical and economical problems of root harvesting.

Machine costs were estimated with the method developed for the USDA by Miyata (1980), which is based on common financial mathematics for calculating the operating cost of agricultural machinery. Of course, costing hypotheses reflect the Italian situation and may not apply to conditions found elsewhere: readers must be aware of that and are invited to recalculate the cost, if necessary. The primary assumptions are a depreciation period of 10 years, a service life of 10 000 hours and a machine utilization of 70%. Interest rate was estimated at 8% and the insurance and tax rate at 7%. Fuel cost was assumed to be 0.85 €l^{-1}. Operator cost has been set to 23 Euros per hour, which includes administration costs and entrepreneur benefits, since the operator is most often also a contractor. The investment costs and the hourly costs of all equipment are reported in Table 2.

3 Results

All contractors were located in Northern Italy, in the vicinities of two plants that use root wood for particle board manufacturing. At the time of the study, many contractors had changed to root-crushing, due to a drop in root wood prices, so that only those contractors operating near dedicated plants still performed root recovery. Temporary conversion to root-crushing is very easy: it only requires substituting a screw propeller for the hollow auger, without changing the main attachment or the tractor configuration.

The average recovered taproot weighed 58 kg when fresh, and 33 kg when dry. Average moisture content was 42.3% (wet base), which compares favourably to the average moisture content of poplar stem and branch wood, which is generally above 50%. I-214 clones seemed to produce more dry taproot biomass than "Canadian" clones: this may partly depend on the longer rotation of I-214 stands. The average cut yielded 10 oven-dry tonnes of root wood per hectare – corresponding to about 18 tonnes of fresh biomass.

Table 4 shows the productivity and the cost estimated for each operation. Delivered cost varied widely, ranging from 28 to 66 €Mg^{-1}. Transportation was the most expensive single work task. It accounted for about 40% of the total recovery cost. Extraction and cleaning contributed approximately 25% each to the total cost, while loading added another 9% (Fig. 2).

The results of this study may help guiding system improvement. Extraction proceeded much faster in operations 2, 3 and 4, where modern tractors were used. Older units like those deployed in operations 1, 5 and 7 allowed for a substantial reduction of operational cost, but the productivity losses were even higher, resulting in higher extraction costs. Fig. 3 shows time consumption by element and helps elucidating these results. Within a cycle, the largest time share was taken by driving the auger into the soil ("plunge"): this time element was larger in operations 5 and 7 than in the other ones, which must be related to the limited power of the old farm tractors deployed there. The "plunge" element also took a long time in operation 6, possibly because of the poor

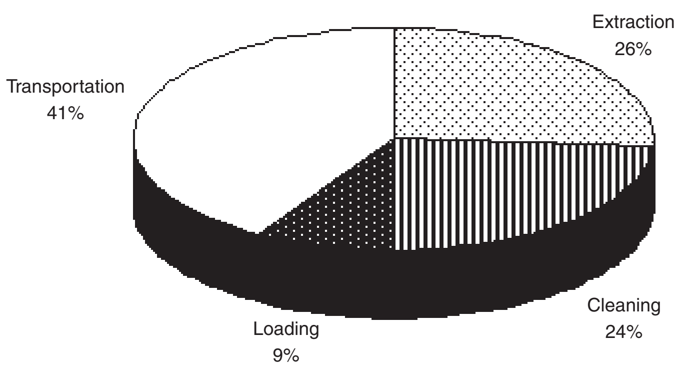

Fig. 2. Contribution of each work phase to the total delivered cost.

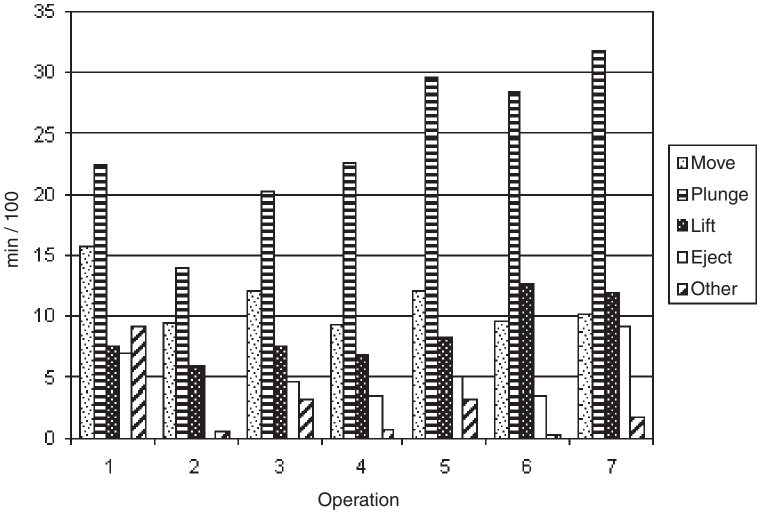

Fig. 3. Extraction: average time consumption by operation and element.

Table 4. Estimated productivity and cost.

	Operation 1	2	3	4	5	6	7
	Extraction						
Observations, n	168	197	299	260	165	317	246
Productivity, stumps hour^{-1}	75	155	97	108	80	85	71
Productivity, Mg hour^{-1}	3.9	10.5	6.3	6.6	3.1	5.1	3.7
Unit cost, €Mg^{-1}	14.4	6.7	11.4	9.3	17.4	12.0	14.6
	Cleaning						
Observations, n	138	131	138	138	214	471	297
Productivity, stumps hour^{-1}	62	142	181	91	78	174	82
Productivity, Mg hour^{-1}	3.2	9.7	11.7	5.5	3.1	10.4	4.3
Unit cost, €Mg^{-1}	16.2	4.7	4.9	11.2	16.4	5.5	15.7
	Loading						
Observations, n	216	308	338	360	330	622	374
Productivity, stumps hour^{-1}	133	302	422	253	287	388	165
Productivity, Mg hour^{-1}	6.9	20.5	27.4	15.4	11.2	23.3	8.6
Unit cost, €Mg^{-1}	7.5	2.2	2.1	4.0	4.5	2.5	7.7
	Transport [a)]						
Observations, n	2	3	2	2	2	3	2
Payload, Mg	10.5	10.5	11.0	10.7	6.4	10.8	9.7
Productivity, Mg hour^{-1}	3.0	5.0	5.6	3.4	2.2	5.5	2.7
Unit cost, €Mg^{-1}	22.9	14.5	12.9	17.4	27.8	13.2	25.6
	Total delivered cost						
€Mg^{-1}	61	28	31	42	66	33	64
€ Mg(oven-dry) $^{-1}$	103	47	53	74	118	59	112

[a)] Equalised over a 20 km distance and a 18 min. unloading time.

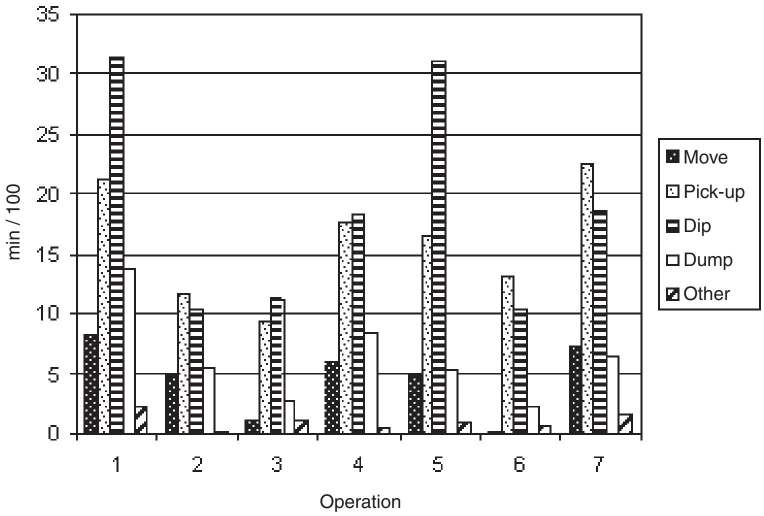

Fig. 4. Cleaning: average time consumption by operation and element.

conditions of the dedicated prime mover, which was over 15 years old. It is worth noticing that operation 2 recorded virtually no ejection time: the operator had fitted his tractor with an auxiliary pump, which allowed powering the ejection ram while lifting the auger.

Cleaning productivity was the highest in operations 3 and 6, where self-propelled forestry loaders were used. The good performance recorded in operation 2 was obtained with a self-propelled loader that carried the chain flail rather than towing it: such a compact arrangement strongly enhanced manoeuvrability. Cleaning productivity was quite low when using farm tractors (operations 4 and 7): these units were the most expensive to purchase and to operate. The results of the time study can provide more detail on this matter (Fig. 4). The most productive cases also recorded the shortest dipping time – i.e. the time during which the stump was kept between the flails. Since good quality cleaning was achieved in all operations, the short flailing time may indicate either a lower adhesion of the soil to the stump or a higher efficiency of the flail, namely a faster rotational speed. Soil characteristics explained the lower productivity obtained in operation 1, conducted on a clay site. All the other operations were conducted on sandy soils, which favours the second explanation, also consistent with the high hydraulic capacity of self-propelled forestry loaders. Self-propelled forestry loaders proved also the most productive loading units: they are fast, powerful and have been specifically designed for the job. Loader-equipped farm tractors showed limited productivity.

Transport productivity was highest and cost lowest in operations 2, 3 and 6, where trucks were used. Trucks had a higher road speed, which allowed for shorter cycles.

4 Discussion

Poplar roots are an interesting supply of energy biomass, which is available in large quantities and is easy to tap, being located in flat terrain and close to the road infrastructure. The average poplar cut can yield 18 $Mg\,ha^{-1}$ of clean root biomass, endowed with a higher heating value than found in tops and branches.

Italian contractors have developed recovery systems that are both efficient and cheap. Extraction and cleaning units are based on general-purpose prime movers, easily available on the market. Under favourable conditions these units can achieve a very high productivity.

Study design did not allow for testing the effects of stump density and stump size on work productivity. Poplar growers generally follow a fixed spacing module with limited variations, so that stump density may not be an issue. Concerning stump size, the variation is much higher and the data indicate a good degree of positive correlation with machine productivity: although such a relationship may be logical and intuitive, the fact that each point refers to a different unit blurs the picture and imposes much caution. Further tests should be conducted before making any conclusive statements.

A survey in character, this study provides critical information on technology options and on their development: comparing the results obtained from the different operational set ups, one may select the most productive alternative. At the same time, comparing these results with those obtained from earlier studies may help checking the progress of technological development in the field.

In general, extraction units should be based on modern farm tractors, with a power of at least 100 kW. Ideally, the tractor should be fitted with integrated electro-hydraulic controls and auxiliary pump: such a machine can reach a gross productivity of 150 stumps per hour, twice as much as the lighter models and 50% more than an equally powerful tractor without improved controls. Costwise, powerful farm tractors are the best option: their higher operating costs are widely offset by increased productivity. Lighter machines are cheap to operate, but they are too slow and they are good for part-time business only.

A self-propelled loader should be used for cleaning and loading: such a machine is manoeuvrable, fast and agile. The chain-flail cleaner can be either towed or carried, the second option resulting in a more compact unit. Self-propelled forestry loaders perform best: they can clean 170 stumps per hour, and load 400 – twice as many as a loader-equipped farm tractor unit can. Farm-tractor units are less manoeuvrable than self-propelled loaders, and their crane is not as quick. Besides, the power available for the cleaner is limited, which results in a longer cleaning time.

Cleaning takes longer if the soil has a significant clay component, as in site 1. That for two reasons: first because the clay tends to stick to the root surface more than the sand does, and second because roots grown in clay soils are shallower and more branchy than those grown in sandy soils, so that more flailing is required to achieve thorough cleaning.

Transport is best performed by trucks, which are faster than standard farm tractors and can cover the same distance in less time, both empty and loaded. Standard farm tractors are not much cheaper than trucks: transport is at least 35% more expensive when using a standard farm tractor. In some cases transportation with farm tractors can cost twice as much. Transportation is indeed a bottleneck, limiting the productivity of the whole operation: recourse to high-speed farm tractors may prove an effective solution, as these machines offer good cross-country mobility and high road speed. Ideally, a container-shuttling system could be developed to facilitate load transfer between dedicated terrain units and road units, but this would require substantial investments that are not justified by the current market situation.

Under present conditions, root extraction is still regarded as a service rendered to the landowners, who are willing to pay between 200 and 300 € ha^{-1} for getting their fields cleaned. For an average yield of 10 Mg(oven dry) ha^{-1}, such payment represents an integration to the harvesting cost of 20 to 30 € Mg(oven dry)$^{-1}$, which is quite substantial and explains the survival of low-efficiency operations. However, if the biomass market will take off, competition among recovery operators is likely to reduce landowner fees, and therefore optimised harvesting methods will be required.

The extraction productivities recorded today are much higher than those reported for older versions of the same technology, which extracted between 30 and 60 stumps per hour (FAO 1962, Currò and Ghisi 1968, Markovic 1973). Comparison with the Scandinavian extraction systems is more difficult, because the stands, the stumps and the operational methods are radically different. For the mainstream *Pallari* method, Hakkila and Mäkelä reported a daily productivity of 10 and 20 m^3 per 8-hour day. These figures included extraction, splitting/cleaning and moving to a collection site (Hakkila and Mäkelä 1973). In our case, summing extraction, cleaning and loading time and applying a wood density of 850 kg per cubic metre to fresh poplar result in a daily productivity of poplar root recovery between 15 and over 35

m^3 per 8-hour day. The better result is certainly related to the easier working conditions offered by poplar plantations in agricultural land.

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