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ARTICLE

Logging operations in pine stands in Belgium with additional harvest of woody biomass: yield, economics, and energy balance

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Abstract: Due to the enhanced demands for woody biomass, it is increasingly relevant to assess possibilities to harvest forest residues in addition to logs. Here, eight strategies for whole-tree harvesting from clearcuts and early thinnings of pine (*Pinus nigra* Arnold) stands in northern Belgium are evaluated. A detailed cost analysis using the machine-rate method was conducted along with scenario and sensitivity analyses of the variables affecting the harvesting cost. On average, we found much higher revenue for logs than for wood chips from forest residues. In clearcuts, a mobile chipper was more profitable than a roadside chipper. On the other hand, the harvesting cost of logs was higher for early thinnings than for clearcuts. However, the revenue remained higher than for chips, making the separate harvesting of logs and chips more cost effective than chipping whole trees. In the latter case, an excavator, a forwarder, and a roadside chipper were more cost effective than a harvester, a tractor with trailer, and a mobile chipper, respectively. Harvest of additional woody biomass required limited energy input compared with processing and intercontinental transportation of wood pellets. However, at present, we find very small profits from local additional biomass harvests. The low and fragmented forest cover and important sustainability issues further impede the development of a viable production sector in this region.

Key words: whole-tree harvesting, woody biomass, harvest strategies, economic analysis, energy balance.

Résumé : Étant donné la demande accrue de biomasse ligneuse, il est de plus en plus pertinent d'évaluer la possibilité d'exploiter les résidus forestiers en plus des billes. Huit stratégies d'exploitation par arbres entiers appliquées lors de coupes à blanc et d'éclaircies précoces dans des peuplements de pin (*Pinus nigra* Arnold) situés dans le nord de la Belgique ont été évaluées. Une analyse de coût détaillée par la méthode des taux de machinerie a été réalisée ainsi que des analyses de scénarios et de sensibilité des variables qui influencent le coût d'exploitation. En moyenne, nous avons obtenu un revenu beaucoup plus élevé pour les billes que pour les copeaux de bois produits à partir des résidus forestiers. Dans les coupes à blanc, une déchiqueteuse mobile était plus rentable qu'une déchiqueteuse en bordure de route. Par contre, dans les éclaircies précoces le coût d'exploitation des billes était plus élevé que dans les coupes à blanc. Cependant, les revenus sont demeurés plus élevés que pour les copeaux de telle sorte qu'il était plus rentable d'exploiter les billes et les copeaux séparément que de déchiqueter des arbres entiers. Dans le dernier cas, une excavatrice, un porteur et une déchiqueteuse en bordure de route étaient plus rentables qu'une machine multifonctionnelle, un tracteur avec une remorque et une déchiqueteuse mobile. La récolte de biomasse ligneuse additionnelle a nécessité un apport limité d'énergie comparativement à la fabrication et au transport intercontinental de granulé de bois. Cependant, nous constatons que les profits tirés de la récolte locale de biomasse additionnelle sont actuellement très faibles. Le couvert forestier clairsemé et fragmenté ainsi que les questions de durabilité constituent une entrave supplémentaire au développement d'un secteur de production viable dans cette région. [Traduit par la Rédaction]

Mots-clés : exploitation par arbres entiers, biomasse ligneuse, stratégies d'exploitation, analyse économique, bilan énergétique.

Introduction

The use of woody biomass for bioenergy has increased by almost 80% in the 27 European Union (EU) member states between 1990 and 2008 (Eurostat 2011). Moreover, the demand is expected to keep rising and to double by 2030, mainly as a result of the EU 2020 objectives (Mantau et al. 2010). More than two-thirds of this woody biomass originates from forests (Mantau et al. 2010). On the one hand, this rising demand resulted in increased import of woody biomass, mostly as pellets from North America for Belgium and the Netherlands (Sikkema et al. 2010). On the other hand, this also stimulated interest in local production of wood chips and pellets, stipulating new questions for the forestry sector about the cost effectiveness of different harvest strategies. The large-scale utilization of woody biomass for bioenergy also raises serious questions on sustainability aspects (Schulze et al. 2012).

In Flanders (the northern part of Belgium), the legislation only allows the production of renewable energy from smaller assort-

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ments of woody biomass that cannot be used in traditional ways (Flemish Government 2004). For this reason, the newly applied forestry methods to produce wood chips and pellets in Flanders include mainly whole-tree harvesting in early thinnings and additional harvest of biomass that was previously left in the forest floor after roundwood harvest. Traditional logging operations for roundwood production in coniferous forests are highly mechanized, and elaborate studies comparing productivity and economic return for different harvesting strategies have been published for different regions (e.g., North America (Adebayo et al. 2007), Fennoscandia (Ovaskainen et al. 2011), and central Europe (Mederski 2006; Visser and Spinelli 2012)). Harvest of woody biomass from early thinnings and of forest residues from clearcuts is also a highly mechanized and emerging practice, but empirical evidence is more scarce (but see Spinelli and Magagnotti (2010), Lehtimaki and Nurmi (2011), and Walsh and Strandgard (2014)). Studies focusing on the economic aspects of energy wood harvest are even more scarce and come from different regions, for different forest operations, and for different tree species: clearcuts in pine stands in Italy (Marchi et al. 2011), clearcuts in pine stands in the United States (US) (Conrad et al. 2013), clearcuts in poplar stands in Italy (Spinelli et al. 2012), and clearcuts and heavy thinnings in mixed stands of pine and cypress in an Italian mountain region (Spinelli et al. 2014). The emerging patterns from these studies are not always comparable and are very hard to transfer to other systems and other regions as harvest of woody biomass for bioenergy is species-, site-, and practice-specific (Helmisaari et al. 2014). Flanders and neighbouring regions, for example, are characterized by a low total forest area of 10%–20% (Hermy et al. 2008), disintegrated forest ownership with a mean size of the forest property of less than 1 ha (Van Gossum et al. 2011), and a very high urbanization rate (built-up areas amounted to 15% in 2005) (Hermy et al. 2008), resulting in short transportation distances for forest products. Harvesting costs for different harvest strategies for roundwood and additional biomass have, to our knowledge, never been investigated in this region. However, harvesting costs are extremely important, because together with transportation cost, they often represent about 70% of the total biomass cost (Panichelli and Gnansounou 2008).

Here we report the results of a large-scale field experiment in Corsican pine (*Pinus nigra* Arnold) stands in the Bosland region in Flanders, comparing several harvest strategies for roundwood production and additional wood chip production from clearcuts and thinnings. We specifically investigated (*i*) whether the currently applied roadside chipping strategy was more cost effective than on-site chipping both for clearcuts and for thinnings, (*ii*) how variation in the top bucking diameter (i.e., the diameter of the stem where the tree is separated for roundwood and for wood chip production) influenced the total harvest income and the quality of roundwood and wood chips in clearcuts, (*iii*) what the cost efficiency was of separately harvesting the stem for roundwood and the crown for wood chips compared with whole-tree chipping in early thinnings, (*iv*) whether a simpler combination of an excavator with a shear harvester head and a tractor with a trailer had a similar efficiency as a typical harvester–forwarder combination in harvesting whole trees for wood chip production in thinnings. Moreover, we examined the energy input in the production process of the locally produced wood chips as one aspect of sustainability and compared it with pellets imported from North America.

Materials and methods

Study site

Bosland (centre of study region: 51.17°N, 5.34°E) has a total surface area of 22 000 ha of which approximately 45% is nature and forest area. Public forests cover more than 4500 ha. Soils are dry, sandy, and nutrient poor. Until 1850, Bosland was mainly covered by extensive heath. Afterwards, gradual afforestation took place, with Scots pine (*Pinus sylvestris* L.) and Corsican pine as dominant tree species (Vangansbeke et al. 2015). The Bosland project is managed by a statutory partnership of four different public owners from different levels and two nonprofit organizations (Vangansbeke et al. 2015). The project covers the area of three municipalities (Hechtel-Eksel, Lommel, and Overpelt) in the northwestern part of the province of Limburg, on the border of the Campine plateau.

Table 1. Characteristics of the four older Corsican pine stands that were clear-cut in Lommel (L1–L4) and the four younger stands that were thinned in Overpelt (O1–O4). More information about the harvest strategy can be found in Table 2.

	Area (ha)	Year of planting	Standing stock ($m^3 \cdot ha^{-1}$)	Thinning intensity (%)	Harvest strategy
L1	1.15	1965	349.3	—	C1
L2	1.17	1965	364.4	—	C2
L3	0.89	1965	341.8	—	C3
L4	0.92	1965	365.5	—	C4
O1	1.05	1979	272.48	20.1	T1
O2	1.00	1979	315.84	24.9	T2
O3	1.35	1979	327.83	21.2	T3
O4	1.55	1979	305.01	15.8	T4

In 2012, eight monoculture Corsican pine stands of similar size (average 1.14 ha) were selected for the field trial (Table 1). In Lommel, we selected four stands of an older stand type for a clearcut (47 years old, median diameter at breast height (dbh) of 26 cm). These stands had been thinned once, at an age of about 30 years. In Overpelt, we sampled four stands of a younger stand type (33 years old, median dbh of 15 cm) for early thinnings. Trees within these stands were harvested as roundwood for a factory producing orientated strand board (OSB) and as wood chips for combustion. All stands were equally accessible for the various forest machines, and a place for stocking of logs and wood chips was available within 500 m of all stands. The dbh of all trees in three randomly located square plots of 400 m^2 per stand was measured before and after the harvest. The standing stocks of the old stand type (average 355 $m^3 \cdot ha^{-1}$) differed significantly from the young stand type (305.29 $m^3 \cdot ha^{-1}$) (analysis of variance (ANOVA) and a Tukey post hoc test with stand as a blocking factor; overall p value < 0.01). Within each stand type, no significant differences were found between the stands (for the four older stands, $p = 0.162$; for the four younger stands, $p = 0.483$). Therefore, the selected stands were suitable for our analysis as the circumstances were comparable for all stands within each stand type and it was presumed that terrain circumstances provide no explanation for possible differences between harvesting efficiencies.

Tested harvest strategies

A literature review was performed, and the possible strategies for combined harvest of roundwood and wood chips were listed (cf. Spinelli and Hartsough 2001; Spinelli and Magagnotti 2010; do Canto et al. 2011; Lehtimaki and Nurmi 2011; Marchi et al. 2011; Conrad et al. 2013; Walsh and Strandgard 2014). To increase the practical relevance of our empirical study, we invited local policymakers, forest-harvesting experts, and stakeholders from the Belgian woody biomass industry to take part in a board of experts. On 14 May 2012, 12 experts discussed the different options and jointly selected the eight most promising harvest strategies from the list based on criteria of technical and economic suitability and practical knowledge gaps (Table 2; Appendix A, Table A1).

The specifications of the harvesting were outlined and sent to different forest-harvesting companies. Three companies sent in

Table 2. Selected strategies for combined harvest of stem wood and wood chips for clearcuts (C1–C4) and early thinnings (T1–T4) in Flanders.

Strategy	Strategy	Motivation of selection by board of experts
C1	Harvester + forwarder for stem wood (Ø = 12 cm) + forwarder for crown wood + chipper on roadside	Interesting to see what influence an increase in top bucking diameter has (more biomass–less stem wood)
C2	Harvester + forwarder for stem wood (Ø = 7 cm) + forwarder for crown wood + chipper on roadside	The actual standard approach, the board of experts believes this to be the most efficient strategy
C3	Harvester + forwarder for stem wood (Ø = 12 cm) + crown wood chipped in stand by mobile chipper behind tractor	Interesting to see what influence an increase in top bucking diameter has + if terrain chipping can be economically feasible
C4	Harvester + forwarder for stem wood (Ø = 7 cm) + crown wood chipped in stand by mobile chipper behind tractor	Highly interesting to test if terrain chipping can be economically feasible
T1	Harvester + forwarder for whole trees + chipper on roadside	The actual standard approach for early thinnings
T2	Harvester + whole trees chipped in stand by mobile chipper behind tractor	Highly interesting to test whether terrain chipping can be economically feasible in early thinning operations
T3[a]	Harvester + forwarder for stem wood + forwarder for crown wood + chipper on roadside	The actual standard approach for early thinnings in older stands; interesting to see if it is economically more feasible to harvest stem wood separately
T4	Excavator with shear harvester head + tractor with trailer for whole trees + chipper on roadside	Interesting to test what economic outcome will be of this low-tech variation of the actual standard approach

Note: Ø, top bucking diameter.
[a]Not in original shortlist but added by board of experts because of the relatively high age of stands for early thinning in Overpelt.

offers, and as usually done in Flanders, the company proposing the best financial conditions was selected. We expected that this market-based selection would result in a cost-efficiency-driven and close-to-reality harvesting approach. Before the start of the harvest, a meeting was set up with the operator to outline the conditions for the experiment in detail (different harvest strategy for every stand and presence of scientists during operations).

The board of experts deliberately selected simple harvest strategies involving relatively basic forestry equipment (Fig. 1; Appendix A, Table A1). The high-tech harvest strategies (e.g., T5, T6) are probably not economically feasible for Flemish and western European forests with their low forest area, small stands, and short hauling distances. The harvest strategy including the mobile terrain chipper behind a tractor was perhaps the only exception because, to the best of our knowledge, this combination was never used in Flemish forestry before. The mobile terrain chipper used in the experiment was mostly used for chipping operations on trees along public roads and was not equipped with forestry tires. Before every operation with the mobile chipper, a mulcher was used to flatten the terrain. By simply equipping the mobile chipper with forestry tires, the use of the mulcher could have been avoided, and for this reason, the costs of the mulcher were not included in the cost comparison.

To avoid operator-training bias, each machine was operated by the same operator in the different stands, but the operator for each different type of machine was chosen by level of skill to enhance machine efficiency. To minimize operator bias, the harvesting company selected experienced operators with more than 3 years of working experience for each machine. Note, however, that the operator for the mobile chipper had an equal amount of experience with the machine as the other operators but mostly from harvesting of tree lines on roadsides and less in forest harvesting.

Data collection

Machine costs were calculated using the machine-rate method (Miyata 1980), separating fixed costs, variable costs, and labor cost. We used a stopwatch to measure the time of every separate step in the harvest and the breaks, also the reason for a break was registered (i.e., operator break vs. technical break). The total fuel consumption for every machine for each of the harvest strategies was measured as well. Each machine started with a full fuel tank, which was refilled after each operation by means of a field fuel pump that registered the amount of fuel that was added. Most of the data about the machinery (e.g., purchase price, economic life, salvage value, annual use, repair and maintenance cost, fuel cost) were provided through the harvesting companies. For estimating the utilization rate (i.e., the ratio between productive hours and scheduled machine hours, SMH), we first determined the ratio between all breaks and productive hours in the field trial. To compensate for transporting the machinery, this value was then decreased by 10% for our final estimate of the utilization rate (inferred from Mederski (2006)). Data about interest rate, insurances, and taxes (do Canto et al. 2011), lubricant cost (Conrad et al. 2013; Adebayo et al. 2007), overhead, and labour cost (Marchi et al. 2011) were obtained from literature and double-checked with the harvesting companies for accuracy.

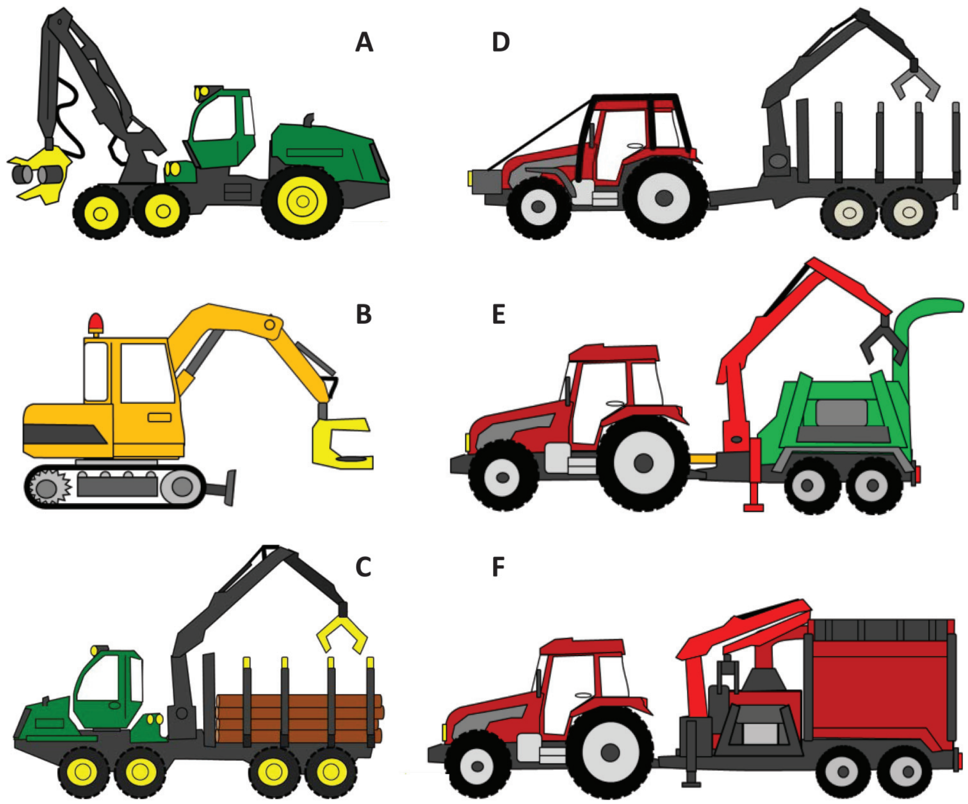
The values for fresh mass of the wood chips harvested in each stand and the total mass of the roundwood of the clearcuts and of the early thinnings (strategy T3) were obtained from the OSB factory, and the volume of the harvested stem wood from every stand was obtained from the operator. Also, one pooled sample of the harvested wood chips was obtained for every treatment by taking 10 subsamples from every container. The sampled chips from every stand were dried in the oven at 105 °C for 2 days to determine the moisture content on wet basis and the dry mass (according to the NEN-EN 14774-2 norm). The particle distribution of the chips was determined with sieves according to the NEN-EN 15149-1 norm, and the ash content was determined through gradual heating of a grinded subsample of the chips to 550 °C according to the NEN-EN 14775 norm.

Data analysis

For every harvest strategy, the total cost was calculated by combining the machine cost per SMH, calculated using the machine-rate method (Miyata 1980), with the productive time and utilization rate for each machine. The harvesting cost per green metric ton (GMt) of roundwood and wood chips at the edge of the stand for each strategy was then calculated by dividing the total cost for each strategy by the fresh mass of the harvest.

The variables used to determine the harvesting cost of wood and biomass were obtained mostly by interviews and literature and are, therefore, deterministic rather than stochastic. A sensitivity analysis was carried out to determine the variables that have the highest impact on the harvesting cost. A Monte Carlo simulation (50 000 trials) was performed for the harvesting cost of roundwood and wood chips for each strategy, varying the variables following a normal distribution with a standard deviation of 10% of the estimated value (given in Table 4). The sensitivity of the harvesting cost for a certain variation of each variable was determined as the amount of the harvesting cost variance that was explained by the variance of that variable in a linear model

Fig. 1. Drawings of the machines used in the experiment: (A) harvester, (B) excavator, (C) forwarder, (D) tractor with trailer, (E) roadside chipper, and (F) terrain chipper (drawings by Inverde, after Osselaere and Vangansbeke 2013).



(R^2 value) (Van Dael et al. 2013). All analyses were performed in R 3.0.1 (R Core Team 2013).

We calculated the ratio between the total fossil energy consumed during the additional harvest of the biomass and the energy output of the harvested wood chips under the different strategies as a sustainability criterion (Marchi et al. 2011). The total fossil energy consumed was estimated by multiplying the energy content of 37 MJ·L^{-1} (Bailey et al. 2003) for diesel with the measured consumption for additional harvest and increasing this value by 20% to account for the production and transportation of the fuel and then by 30% for manufacturing, repair, and maintenance of the machines (following Mikkola and Ahokas 2010). The theoretical energy output of oven-dried wood chips was estimated using a net calorific value (NCV_0) of 18.5 MJ·kg^{-1} (Francescato et al. 2008).

Results

Amount of harvest

An average of 355.4 GMt of roundwood was harvested per hectare from the clearcuts (Table 3A). As expected, a higher amount of roundwood was found for smaller top bucking diameters (average 365.2 GMt·ha^{-1} vs. 345.3 GMt·ha^{-1}). The extra biomass from the clearcuts, harvested as wood chips from the tree tops, amounted to an average of 89.5 GMt·ha^{-1}. The amount of wood chips from the clearcut stands where a 12 cm top bucking diameter was used was higher compared with using a 7 cm top diameter (average 92.6 GMt·ha^{-1} vs. 86.4 GMt·ha^{-1}). For the thinned stands where whole trees were chipped, the average harvest per hectare was 113.74 GMt of wood chips. In the other thinned stand, we harvested 60.5 GMt of roundwood and 42.3 GMt of wood chips per hectare. In both the thinned and the clearcut stands, some harvest residuals were left on the site, even after the additional biomass harvest, but were not measured in this study.

Harvesting cost of logs and wood chips

The cost per SMH was highest for the mobile chipper (€130.28), followed by the roadside chipper (€96.62), the harvester (€64.76), and the forwarder (€52.07) (Appendix A, Table A2). The cost is also determined by the effective working time of the machines in each strategy, which was generally highest for the harvesters (Table 3B). A higher wood harvesting cost was found for the logs in the thinning operation (€12.09·GMt^{-1}) in comparison with the clearcut operation (average of €6.19·GMt^{-1}) because of the more difficult harvesting conditions due to the remaining stand (Table 3C). In the clearcuts, no difference was found between the harvesting cost of the logs in relation to the top bucking diameter. However, a lower wood chip harvesting cost was found under strategies with the mobile chipper (average €12.76·GMt^{-1}) and with a larger top bucking diameter (average €14.17·GMt^{-1}) compared with the strategies with a roadside chipper (average €16.19·GMt^{-1}) and a smaller top bucking diameter (average €14.78·GMt^{-1}), respectively. The lower wood chip harvesting cost for a larger top bucking diameter was caused by the larger dimensions and higher cohesion and density of the biomass that made chipping easier and more efficient. The better result for the on-site mobile chipper was explained by the shorter waiting breaks and the resulting higher utilization rate.

The thinnings where whole trees were chipped resulted in the highest total harvesting cost for wood chips of all strategies, mainly due to the inclusion of the cost for felling. Among these three strategies, the combination of excavator, tractor with trailer, and roadside chipper (€16.13·GMt^{-1}) led to the lowest harvesting cost, and the combination of harvester, forwarder, and roadside chipper (€17.66·GMt^{-1}) scored slightly better than the combination of harvester and mobile chipper (€18.68·GMt^{-1}). The lowest harvesting cost for whole-tree chips under strategy T4 was due to the use of the excavator, which had a lower cost per SMH

Table 3. (A) Total harvest of logs and wood chips of a forest stand for the different strategies; (B) productive time and total cost for each machine under the different strategies; (C) calculated harvesting cost per green metric ton (GMt) logs and wood chips at the edge of the stand; and (D) moisture content and ash residue of the wood chips from the different harvest strategies.

	C1 (1.15 ha)	C2 (1.17 ha)	C3 (0.89 ha)	C4 (0.92 ha)	T3 (1.35 ha)	T1 (1.05 ha)	T2 (1.00 ha)	T4 (1.55 ha)
(A) Total harvest of logs and wood chips								
Total harvest of logs (GMt)	401.91	426.58	304.37	336.44	81.74	—	—	—
Total harvest of wood chips (GMt)	107.78	100.33	81.44	80.06	57.12	99.72	136.52	170.08
(B) Productive time and total cost for each machine								
Harvester productive time (h)	19.73	17.38	12.13	14.16	8.05	6.89	9.72	—
Harvester cost (€)	1728.97	1523.03	1062.97	1240.86	705.43	603.78	851.44	—
Excavator productive time (h)	—	—	—	—	—	—	—	11.65
Excavator cost (€)	—	—	—	—	—	—	—	802.53
Forwarder wood productive time (h)	12.95	15.87	10.53	13.77	4.23	—	—	—
Forwarder wood cost (€)	866.30	1061.45	704.57	920.85	283.17	—	—	—
Forwarder biomass productive time (h)	5.81	5.78	—	—	5.00	4.60	—	—
Forwarder biomass cost (€)	388.84	386.84	—	—	334.44	307.68	—	—
Tractor + trailer productive time (h)	—	—	—	—	—	—	—	11.94
Tractor + trailer cost (€)	—	—	—	—	—	—	—	743.23
Tractor + roadside chipper productive time (h)	5.08	4.83	—	—	2.22	3.25	—	4.58
Tractor + roadside chipper cost (€)	1328.79	1263.47	—	—	579.43	849.57	—	1198.08
Tractor + mobile chipper productive time (h)	—	—	6.83	7.09	—	—	11.49	—
Tractor + mobile chipper cost (€)	—	—	1010.44	1049.07	—	—	1699.13	—
(C) Calculated harvesting cost								
Harvesting cost of logs ($€·GMt^{-1}$)	6.46	6.06	5.81	6.43	12.09	—	—	—
Harvesting cost of additional wood chips ($€·GMt^{-1}$)[a]	15.94	16.45	12.41	13.10	16.00	—	—	—
Harvesting cost of whole-tree wood chips ($€·GMt^{-1}$)[a]	—	—	—	—	—	17.66	18.68	16.13
(D) Moisture content and ash residue of the wood chips								
Moisture content of the wood chips (%)	58.25	59.58	60.66	61.05	55.41	57.33	60.72	58.74
Ash residue of the wood chips (%)	2.77	3.90	1.12	1.42	8.10	2.04	0.63	0.74

[a]For "additional wood chips", we did not account for the cost of felling, which was included in the cost of log production. In contrast, for "whole-tree chips" (T1, T2 and T4), we did assign the felling cost in the cost for wood chip production.

and similar utilization rate and productivity ($GMt·h^{-1}$) as the harvester in thinnings. The harvesting cost under this strategy could have been even lower if a forwarder had been used, as the tractor and trailer had a lower cost efficiency because of the lower productivity ($GMt·h^{-1}$) for a similar cost per SMH and utilization rate. The highest harvesting cost for wood chips under strategy T2 was due to the more pronounced drawbacks of the on-site mobile chipper in thinnings: the machine and operator had less experience in real forest operations, and maneuvering the tractor with mobile chipper (including a chip container) through the thinning corridors cost extra time. In T3, where logs were produced, the harvesting cost of wood chips was comparable with the clearcut strategies using the roadside chipper.

Sensitivity and scenario analysis

The sensitivity analysis revealed that for every wood harvest strategy, the harvesting cost of logs depended mainly on the utilization rate (explaining, on average, 30.3% of the variation in harvesting cost), the purchase price (11.2%), and the annual use of the harvester (9.9%) (Table 4). The labour cost (16%) and the utilization rate of the forwarder (10.9%) were also important.

For the harvesting cost of additional wood chips, the utilization rate of the chipper (both mobile and roadside in the respective scenarios) was by far the most important variable (explaining, on average, 51.2% of the variation in harvesting cost). Other important variables were the purchase price (8.1%) and annual use of the chippers (6.8%), the labour (only for the roadside chipper, 7.33%), the utilization rate of the tractor of the mobile chipper (6.9%), and the repair and maintenance of the mobile chipper (5.7%). Looking at the harvesting cost for whole-tree chips, the utilization rate of the chippers remained the most important variable (accounting for 33.3% of the variation in harvesting cost), followed closely by different variables for the different scenarios, i.e., the labour cost (T1, T4; 14.5%), the utilization rate of the harvester (T1, T2; 10%), and the utilization rate of the trailer (T4; 12.7%).

To illustrate the importance of the difference in utilization rates between the chippers, a scenario analysis was conducted, varying the utilization rate of the roadside and mobile chipper for strategies C2 and C4, respectively (Fig. 2). For a similar utilization rate, the harvesting cost of the wood chips of the roadside chipper was always lower, even for a 10% higher purchase price for the roadside chipper and a 10% lower purchase price for the mobile chipper (the second most influential variable). Currently, the harvesting cost of the wood chips of the mobile chipper was lower due to the much higher utilization rate. The utilization rate of the roadside chipper should increase to at least 56% to compete with the mobile chipper under current purchase prices.

Wood chip quality

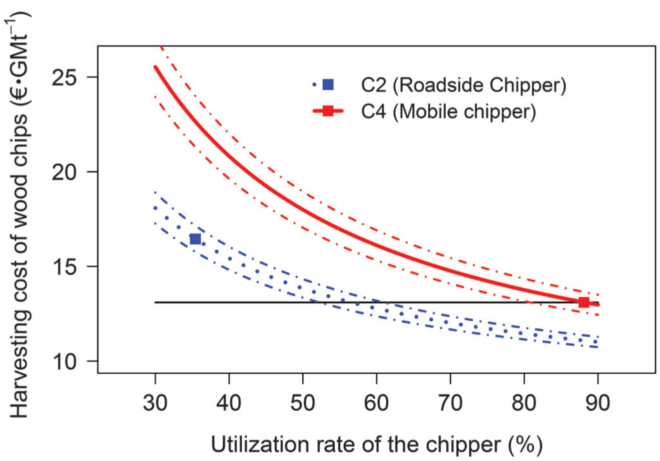
The analysis of the wood chip quality showed several differences between the harvest strategies. For the clearcut strategies, a difference between the locations of chipping was observed. When the crowns were chipped in the stand (strategies C4 and C3), a larger share of the smaller chip fractions, a lower ash residue, and a slightly higher moisture content were found (Fig. 3; Table 3D). This smaller average fraction was due to the very low degree of large chips (>32 mm) caused by a smaller mesh size of the screen of the mobile chipper. In a chipper, the woody biomass is comminuted until the particles can permeate through a screen. A smaller mesh size thus results in smaller particles and also a lower efficiency of the chipper because of the longer chipping process (Nati et al. 2010). The lower quality of the chips from the roadside chipper (higher ash residue) and the lower moisture content were due to the extra handling under these strategies, which increased the chance of pollution with soil and the extra opportunity to dry in the air. We also found a larger share of smaller chips, a higher ash

Table 4. Sensitivity analysis of the cost calculations.

	Harvesting cost of roundwood					Harvesting cost of additional wood chips					Harvesting cost of whole-tree wood chips		
	C1	C2	C3	C4	T3	C1	C2	C3	C4	T3	T1	T2	T4
Utilization rate of harvester	**0.330**	**0.277**	**0.286**	**0.266**	**0.358**	*	*	*	*	*	0.107	0.092	—
Labour	0.153	0.168	0.166	0.171	0.142	0.063	0.064	*	*	0.093	0.126	0.068	0.164
Purchase price of harvester	0.121	0.102	0.105	0.098	0.132	*	*	*	*	*	*	*	—
Utilization rate of forwarder	0.084	0.134	0.125	0.145	0.059	*	*	*	*	0.091	*	*	—
Annual use of harvester	0.108	0.091	0.093	0.087	0.117	*	*	*	*	*	*	*	—
Utilization rate of roadside chipper	—	—	—	—	—	**0.497**	**0.493**	—	—	**0.409**	**0.314**	—	**0.271**
Purchase price of roadside chipper	—	—	—	—	—	0.104	0.103	—	—	0.086	0.064	—	0.056
Annual use of roadside chipper	—	—	—	—	—	0.092	0.091	—	—	0.077	0.058	—	*
Economic life of roadside chipper	—	—	—	—	—	0.055	0.055	—	—	*	*	—	*
Utilization rate of mobile chipper	—	—	—	—	—	—	—	**0.581**	**0.581**	—	—	**0.415**	—
Utilization rate of tractor of mobile chipper	—	—	—	—	—	—	—	0.069	0.069	—	—	0.050	—
Purchase price of mobile chipper	—	—	—	—	—	—	—	0.057	0.057	—	—	0.043	—
Repair and maintenance of mobile chipper	—	—	—	—	—	—	—	0.057	0.057	—	—	*	—
Annual use of mobile chipper	—	—	—	—	—	—	—	0.039	0.039	—	—	*	—
Utilization rate of trailer	—	—	—	—	—	—	—	—	—	—	—	—	0.127
Fuel price	*	*	*	*	*	*	*	*	*	*	*	*	0.063

Note: For every harvesting cost, the R^2 values of the five most important variables influencing the costs are shown, indicating the importance of the variable in the variation of the cost price after 50 000 trials. The R^2 value of the most important variable is in bold type. If a variable was not relevant in a harvesting cost calculation, it was represented with a dash (—); R^2 values for variables that were less important for a strategy are represented with an asterisk (*).

Fig. 2. Scenario analysis on the impact of utilization rate and purchase price of roadside and mobile chipper on the harvesting cost of a green metric ton (GMt) of wood chips for harvest strategies C2 and C4. The dashed–dotted lines show the harvesting cost with a 10% reduction or a 10% increase in purchase price. The squares show the current situation; the horizontal line shows that the utilization rate of the roadside chipper should increase to 56% to compete with the mobile chipper.



residue, and a slightly higher moisture content in strategies C2 and C4 (with a smaller top bucking diameter) compared with strategies C1 and C3, respectively. This lower chip quality under strategies with a small top bucking diameter was related to the relatively higher share of green material than wood.

The analysis of the wood chip quality showed that the chips from strategy T3, where logs were harvested separately, had the highest ash residue, the lowest moisture content, and the largest share of small chips because of the relatively lower share of wood than green material. The chips from strategy T2, involving the on-site mobile chipper, had the lowest ash residue and the highest moisture content of the thinned stands, for the same reasons as raised for the clearcuts. The chips from strategy T4 had lower ash residue and higher moisture content than the other thinning strategies with the roadside chipper (T3 and T1). This higher chip quality was due to the use of an excavator instead of a harvester. The excavator lifted the trees after felling and was better suited to putting the trees softly on the ground, reducing their pollution with soil particles.

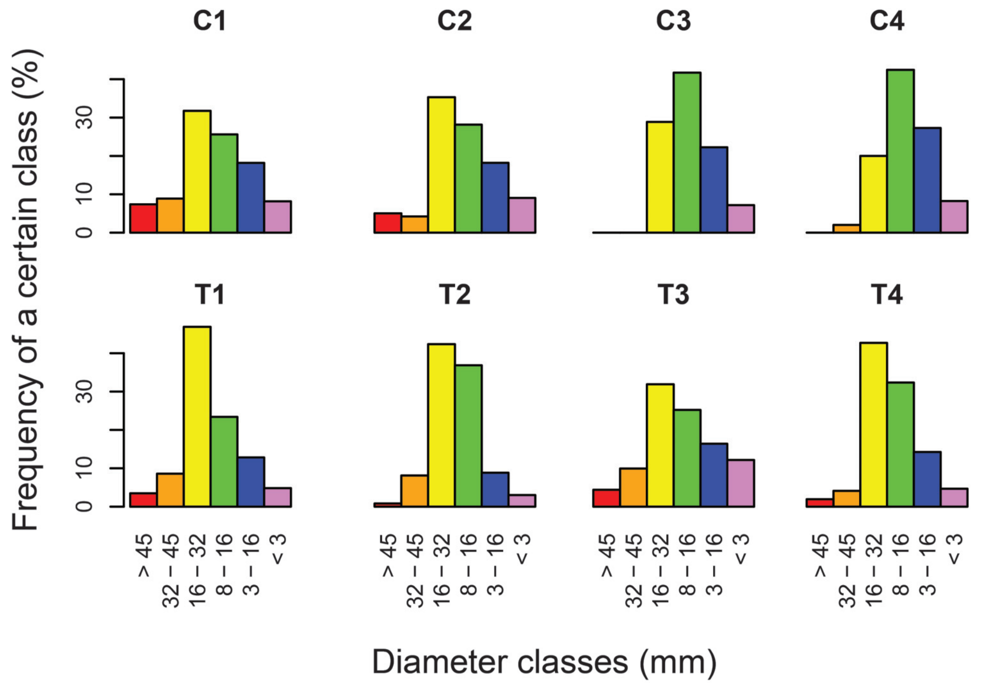
Energy balance

The ratio between the extra fossil energy input to harvest the additional biomass as wood chips on the one hand and the possible energy output from the wood chips on the other hand varied between 0.71% and 1.16% under the harvest strategies in which roundwood was harvested separately. In the clearcuts, a lower ratio was found under the harvest strategies with the mobile chipper (average 0.75%) and with a smaller top bucking diameter (average 0.91%) compared with strategies that included the roadside chipper (average 1.14%) and a larger top bucking diameter (average 0.98%), respectively. For the whole-tree wood chips from the thinnings, the ratio was higher and amounted to an average of 1.29% because all used fuel was accounted for.

Discussion

In Flanders and neighbouring temperate regions, pine stands make up a large part of the forests (e.g., 39% in Flanders (Forest and Green Areas Division (FGAD) 2001), 33% in the Netherlands (Dirkse et al. 2007)). Traditionally, these stands are thinned after 30 years and clear-cut at the end of the rotation period, which mostly varies between 40 and 110 years (Pussinen et al. 2002). Pihlainen et al. (2014) reported on longer rotation periods if carbon storage was co-included as a management target, whereas Dwivedi and Khanna (2014) evaluated much shorter rotation periods when focusing on biomass production. Thus, the two tested forestry operations, thinning and clear-cutting of 33- and 47-year-old pine stands can be considered as quite characteristic for pine stand management with a short to average rotation period. Given the importance of pine stands in Flanders and neighbouring regions and the sylvicultural system applied in these stands, the comparison between different harvest strategies for these forestry operations is probably the most relevant forestry experiment for the woody biomass industry in this region. Below we

Fig. 3. Distribution of the wood chips from each of the harvest strategies in the clearcuts in diameter classes.



elaborate on the results and try to draw relevant conclusions for the forestry sector in the region.

Harvesting cost and economic balance

In the clearcuts, the lowest wood chip harvesting cost was found for the strategy involving an on-site mobile chipper and using a larger top bucking diameter of 12 cm. In the thinnings, the cheapest strategy to produce wood chips was from the crowns of trees where stems were harvested separately as logs (which were, however, much more expensive to harvest than in the clearcuts). Marchi et al. (2011) used a similar setup for clearcuts in pine stands but found contrasting results: a harvesting cost of €18.3·GMt^{-1} for a terrain chipper and €12.3·GMt^{-1} for a roadside chipper. However, in this study, the roadside chipper had a utilization rate of 67.6%. Our scenario analysis showed a similar harvesting cost at this utilization rate. The costs using a terrain chipper are harder to compare between the studies because a different type of machine, without a built-in container, was used. The contrast with our results remains striking, certainly considering the limited experience with the mobile chipper in forest stands. However, photographic material from Marchi et al. (2011) also shows that the harvest residuals for terrain chipping were sloppily left all over the stand, making the residuals less accessible. Spinelli et al. (2012) also made a comparison between roadside and terrain chipping. Parallel to our results, they found a lower harvesting cost for terrain chipping (€16.3·GMt^{-1} and €17.1·GMt^{-1} for two different poplar clones) than for roadside chipping (€19.7·GMt^{-1} and €23.2·GMt^{-1}). However, these results were found for whole-tree chips from easily accessible stands with a short rotation period (Spinelli et al. 2012). It is thus speculative to draw conclusions from these three diverging studies, but terrain accessibility seems a key factor in explaining success of terrain chipping (note also the much higher harvesting costs for terrain chipping in the less accessible thinnings in this study).

As mentioned earlier, the harvesting cost calculated in this study covers only the process from the standing stock to the fresh logs and chips at the stocking place on the roadside. Afterwards logs and chips were sold and transported to the OSB factory and associated energy plant. We assumed a cost of €8·GMt^{-1} (the average price according to the operators) for the transportation of the chips and logs and a resale price of €30·GMt^{-1} and €50·GMt^{-1} for the wood chips and the logs, respectively, as was paid by the customer in the experiment. We calculated an economic balance that included resale value and transportation costs to obtain an overview and to make a complete comparison between the strategies (Table 5). Under the current circumstances, using a mobile chipper and a small top bucking diameter (e.g., 7 cm) was the most interesting clearcut strategy from an economic point of view. In the thinnings, it was found that harvesting logs separately was — by far — the most beneficial. The strategies in which the whole trees were chipped were less favourable. The best of these strategies was the one in which the trees were felled by an excavator, moved by a tractor and trailer, and chipped by a roadside chipper. The strategy using a mobile chipper was by far the least cost effective, but this result might be biased by the limited experience of the operator in harvesting in forest stands. The main conclusion from this economic analysis is that the revenue from the wood was much higher than the revenue from the wood chips because of the lower harvesting cost and the higher selling price. In the clearcuts, strategies using a smaller top bucking diameter resulted in a larger share of logs and less wood chips. This was much more profitable because the extra income of the higher share of logs exceeded by far the extra harvesting cost of the wood chips under the strategies using a smaller top bucking diameter. Moreover, the hypothetical price shift for the wood chips should be large to compensate for the lower income from logs under the scenarios with a large top bucking diameter. Using larger top bucking diameters could indeed have a positive impact on the large-scale bioenergy potentials, as stated in Räisänen and Nurmi (2014); however, this seems economically unfeasible. In a case study from pine plantations in the southern US Coastal Plain, Conrad et al. (2013) also compared the economical balance of harvesting wood for material and for energy purposes and came to the same conclusion: "until energy wood prices appreciate substantially, loggers are unlikely to sacrifice roundwood production to increase energywood production".

According to the economic balance, it was profitable to harvest additional biomass in the form of wood chips. However, the revenue was very small and forest management costs and the

Table 5. Balance and revenue of the production of logs, additional wood chips, and whole-tree wood chips under the different harvest strategies, given the current resale price (wood chips, €30·MGt−1; logs, €50·MGt−1) and transport cost (€8·MGt−1).

	C1	C2	C3	C4	T1	T2	T3	T4
Balance of logs (€·MGt−1)	35.54	35.94	36.19	35.57	—	—	29.91	—
Balance of additional wood chips (€·MGt−1)	6.06	5.55	9.59	8.90	—	—	6.00	—
Balance of whole-tree wood chips (€·MGt−1)	—	—	—	—	4.34	3.32	—	5.87
Revenue of logs (€·ha−1)	12421.70	13104.17	12377.53	13009.54	—	—	1810.73	—
Revenue of additional wood chips (€·ha−1)	568.29	476.00	877.80	774.19	—	—	253.90	—
Revenue of whole-tree wood chips (€·ha−1)	—	—	—	—	412.19	452.87	—	643.82
Total revenue (€·ha−1)	12989.99	13580.17	13255.34	13783.72	412.19	452.87	2064.63	643.82

potential cost of the loss of other ecosystem services due to this additional biomass harvesting were not yet included. Moreover, we did not investigate possible productivity losses in roundwood harvesting and extraction due to the subsequent biomass harvesting. These productivity losses have been reported to increase the unit cost of roundwood harvest and extraction by 4.9% (Walsh and Strandgard 2014). These future income losses should, in theory, be discounted to evaluate the profitability of this biomass harvest. It is questionable whether a profitable business model can be developed for this additional biomass harvest in Flanders under current price conditions. The small revenue per green metric ton asks for a large-scale harvest, which is hard to realize in the Flemish forestry context with limited forest cover.

The revenue was no direct profit for the exploitation company that paid a price to the forest owner to execute the harvesting and to buy the logs and wood chips. In our case study, the harvesting company had to use a different harvesting strategy for each stand, leading to higher costs and a lower, thus not representative, price being paid to the forest owner. However, it is clear that the harvesting company could pay more to the forest owner for the clearcuts than for the thinnings and that there is hardly negotiation space to pay for additional biomass harvest because of the limited revenue. From the position of the forest owner, the total price paid for the harvest must at least compensate for the cost of managing the stand (e.g., for forest regeneration in 1965–1997). Moreover, the harvest of logs and wood chips could lead to a decrease in biodiversity (Berger et al. 2013), nutrient cycling (Schulze et al. 2012; Berger et al. 2013), carbon sequestration (Schulze et al. 2012; Berger et al. 2013; Helmisaari et al. 2014), and some other ecosystem services of the stands, which might have an economic consequence for the forest owner (e.g., by reducing stand productivity for next rotations; Walmsley et al. 2009; Wall 2012). Therefore, for the system to be economically sustainable, the money that the forest owner receives must also compensate for this potential economic loss.

Sensitivity and scenario analysis

The sensitivity analysis indicated that the utilization rate of the chipper is the single most important variable affecting the harvesting cost of the chips. For the roadside chipper, a utilization rate of only 35% is found, which is a clear explanation for the higher harvesting cost. The very low utilization rate of the roadside chipper in our study was also evident in the field by the high frequency of forced technical breaks because of the limited transport capacity. Whenever the containers were filled with wood chips, the mobile chipper had to wait for the containers to be transported and emptied at the energy plant. Spinelli and Visser (2009) found an average utilization rate of 73.8% for 36 different chipping machines and described two studies with comparable utilization rates also due to organizational delay. Our scenario analysis revealed that increasing the utilization rate of the roadside chipper could be a way to reduce harvesting cost of the wood chips. This asks for a better alignment of the truck transportation strategy to the productivity of the roadside chipper, meaning that more trucks for transport and thus more personnel are required to keep up with the roadside chipper. This, in turn, would require a larger scale of harvesting of additional biomass, reducing viability in Flanders and neighbouring regions to a (possibly very) limited number of companies. We expected a realistic and cost-efficiency-driven harvesting approach from the harvesting company. The results of our scenario analysis showed that better equipment balancing could easily increase the utilization rate of the roadside chipper and, consequently, reduce the wood chip production cost. It is clear that mobile chipping holds some potential under these circumstances, but more research with a control for equipment balance and operator training level could further answer these remaining questions.

Wood chip quality

Good quality wood chips include a small share of chips that are too big (>63 mm) or too fine (<3 mm) and a low degree of pollution (i.e., a low ash residue) (Spinelli et al. 2011). Spinelli et al. (2011) compared wood chips from four different feedstock types in Italy and concluded that quality of wood chips from forest residues is generally lower than wood chips from sawmill residue and from small whole trees. The amount of fines in the clearcuts in our experiment varied between 7% and 9%, which seemed acceptable and in line with the results from the roadside chipper in Marchi et al. (2011). However, the relatively high ash residue from the chips chipped at the roadside made the quality of this biomass inferior to the chips from the terrain chipper. The whole-tree chips from the thinnings had a relatively high quality, confirming the findings of Spinelli et al. (2011). In particular, the trees harvested with an excavator and the terrain-chipped biomass showed a very low degree of pollution. A really inferior quality was found for the chips from the thinnings where roundwood was extracted first.

For small installations, wood chips with a lot of small particles and a high ash residue (such as the wood chips from treatment T3) are unsuitable and thus in need of a pretreatment such as sieving. When the wood chips are used in a more robust, large energy plant, this is less important. In our case, the customer paid an equal price (€30·GMt−1) for all chips, in spite of the significant differences in chip quality. Production of higher quality wood chips (involving a higher share of stem wood) is not promoted. So, from an economic point of view, it is definitely more interesting to harvest as much of the trees as possible as logs, of course respecting the lower margin of 7 cm imposed by the particle board company.

Woody biomass: an efficient source of renewable energy?

Application of woody biomass for the generation of bioenergy is subject to fierce discussion. On the one hand, bioenergy from woody biomass strongly reduces greenhouse gas emissions compared with nonrenewable energy (Njakou Djomo et al. 2013). On the other hand, woody biomass left in the forest aids carbon sequestration and climate mitigation (Schulze et al. 2012). A good quantification of the greenhouse gas balance of forestry operation asks for a life cycle analysis that includes all direct and indirect emissions and falls beyond the scope of this study. However, Njakou Djomo et al. (2011) demonstrated a significant positive relationship between greenhouse gas emissions and energy efficiency (ratio between energy input and output) of the harvesting and production process, which is easier to calculate. We calculated the energy efficiency for wood chips from forest residues in clearcuts, harvested with an on-site mobile chipper (0.75%) and with a roadside chipper (1.14%), and for whole-tree chips from thinnings (1.29%). On-site chipping of harvest residues in clearcuts led to the highest energy efficiency, but in general, the amount of energy used during harvesting and chipping biomass was limited. Other processes in the production chain of, for example, imported pellets are much more important to calculate the total energy balance: drying (e.g., 10.71% dry mass loss when dried in a terminal), pelletizing (e.g., 24.6% of internal energy used), and intercontinental shipping (e.g., 6% of internal energy consumed for transporting by bulk container ship across the Atlantic Ocean) (Edwards et al. 2012).

Towards sustainable biomass

Sustainable development was defined by the United Nations (1987) as "a development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Sustainability is commonly represented as a set of triangular concepts with three pillars, i.e., economy, environment, and society, or with a triple bottom line, i.e., people, planet, and profit. Above we have extensively discussed the economic aspect of sustainability of local woody biomass production for Flanders and neighbouring regions. The harvest of additional woody biomass also raises additional questions on the ecological aspect of sustainability. For example, during whole-tree harvesting, more nutrients are exported from the forest than under conventional harvest as the nutrient concentrations (e.g., nitrogen, phosphorus, base cations) in the crown are much higher than in the logs (Olsson et al. 1996). Depending on forest and soil type and the studied period, whole-tree harvesting sometimes has an impact on the future productivity of a stand (Walmsley et al. 2009; Phillips and Watmough 2012; Wall 2012; Fleming et al. 2014). Additional harvest of biomass in forests might also have an impact on biodiversity, on the functioning of associated aquatic ecosystems, and on carbon sequestration (Berger et al. 2013; Helmisaari et al. 2014). It is clear that ecosystem impact assessment of additional biomass harvest is a complex issue, with sometimes contrasting results (Riffell et al. 2011).

The revenue of the additional biomass harvest from our experiments turned out to be very small. A larger scale would be needed to reduce harvesting cost of wood chips and to make this process economically more attractive. However, within the limited Flemish forestry context, this is hard to achieve. With the rising demands, mainly for bioenergy, prices may rise in the near future. However, material use of logs will remain more profitable than chipping of logs, unless the price for (good quality) wood chips rises dramatically. This supports, also from an economic point of view, a cascaded use for biomass giving priority to material application and future reuse and recycling over energy production.

Meanwhile, large amounts of wood pellets are imported, mainly from North America. In the production and transportation processes of the imported pellets, a higher share of fossil energy is used. From an energy perspective, local biomass is preferred, but local sustainable yield is limited. Sustainable harvest of additional biomass from forest ecosystems encompasses more than economic and energy balances and takes into account social and ecological factors. Strong criteria for local and imported biomass are needed to safeguard forest ecosystems from the possible impact of overharvesting on biodiversity and soil fertility, carbon sequestration, and other ecosystem services. We believe that more research and a scientifically supported policy are needed for safely implementing additional biomass harvest, independent of the economic feasibility.

Conclusion

We investigated the technical possibilities and the cost effectiveness of different harvesting strategies in pine stands in Belgium. These stands include a potentially important source of biomass: the temperate and boreal regions of Europe and North America. The current "conventional" harvest of logs could be expanded by harvesting additional biomass for bioenergy from leftovers. However, we found a very limited economic benefit for harvesting this additional biomass under the current circumstances. The harvesting of logs is much more profitable and should be maximized to obtain the highest profit. This is translated in a small top bucking diameter in clearcuts and in avoiding whole-tree chipping, even in early thinnings. In general, we found that a mobile chipper can achieve better results in cost effectiveness, energy balance, and chip quality than the currently used roadside chipper in clearcuts. However, the cost effectiveness of a mobile chipper seems highly dependent on terrain accessibility. Another very important factor in evaluating the cost effectiveness of the harvesting strategy is equipment balancing. In our study, poorly coordinated timing of the roadside chipper with the chip transport was the main reason for the lower cost effectiveness in these strategies. Therefore, an important recommendation is to optimize equipment balancing to reduce harvesting costs and for future studies to control for equipment balancing in the setup. More studies on the economics of additional biomass harvesting in this and other regions will further our understanding on how best to extract woody biomass from forests.

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Appendix A

Tables A1 and A2 appear on the next page.

Table A1. Rejected strategies for combined harvest of logs and wood chips for clearcuts (C5–C10) and early thinnings (T5–T7) in Flanders.

Strategy	Strategy	Motivation of selection or rejection by board of experts
C5	Harvester + forwarder for stem wood (Ø = 7 cm) + 1year later: forwarder for crown wood + chipper on roadside	Economically less feasible to come back 1 year later; drying of woody biomass expected to be only marginal
C6	Harvester + forwarder for stem wood (Ø = 12 cm) + 1year later: forwarder for crown wood + chipper on roadside	Economically less feasible to come back 1year later; drying of woody biomass expected to be only marginal
C7	Harvester + forwarder for stem wood (Ø = 7 cm) + bundler to collect crown wood + forwarder for crown wood + chipper on roadside or at energy plant	Bundler seems economically unfeasible for forestry in Flanders due to low forest area, small forest stands, and short hauling distances
C8	Harvester + forwarder for stem wood (Ø = 12 cm) + bundler to collect crown wood + forwarder for bundles + chipper on roadside or at energy plant	Bundler seems economically unfeasible for forestry in Flanders due to low forest area, small forest stands, and short hauling distances
C9	Harvester + forwarder for stem wood (Ø = 7 cm) + biobaler to collect crown wood + forwarder for bales + chipper on roadside or at energy plant	Interesting option, but the board of experts believes that the biobaler is not suited to operate in the rough terrain conditions of a clearcut (stumps, terrain topography, etc.)
C10	Harvester + forwarder for stem wood (Ø = 12 cm) + biobaler to collect crown wood + forwarder for bales + chipper on roadside or at energy plant	Interesting option, but the board of experts believes that the biobaler is not suited for operating in the rough terrain conditions of a clearcut (stumps, terrain topography, etc.)
T5	Harvester + whole trees chipped in stand by integrated mobile chipper	Highly specialized integrated chipper appears to be economically unfeasible for forestry in Flanders due to low forest area and small forest stands + expensive to get machine in Flanders
T6	Whole-tree harvested and chipped by integrated mobile chipper with harvester head	Theoretically interesting because of probably lower chip contamination; doubtful if this strategy can be made operational + too specialized for Flemish forestry context
T7	Harwarder for whole trees + chipper on roadside	Harwarder seems economically unfeasible for forestry in Flanders + expensive to get machine in Flanders

Note: Ø, top bucking diameter.

Table A2. Calculated machine cost for the forestry equipment used in the different harvest experiments.

Machine	Harvester	Excavator	Forwarder	Trailer	Tractor	Roadside chipper	Tractor	Mobile chipper	Tractor
Type	John Deere 1170E	Hyundai R145	John Deere 1010E	Own manufacturing	Valtra 8950	Jenz HEM420	Valtra T191	Greentec 952	Valtra N141
Used in harvest strategy	C1, C2, C3, C4, T1, T2	T4	C1, C2, C3, C4, T1, T3	T4		C1, C2, T1, T3, T4		C3, C4, T2	
Purchase price (k€)	375	110	235	110	85	220	100	180	130
Economic life (years)	10	7.5	10	7.5	7.5	5	7.5	5	5
Salvage value (k€)	75	30	30	70	15	30	25	54	39
Average value of yearly investment (k€)	240.00	75.33	142.75	92.67	54.67	144.00	67.50	129.60	93.60
Interest, insurance, and taxes (k€·year^{-1})	24.00	7.53	14.28	9.27	5.47	14.40	6.75	12.96	9.36
Annual use (SMH)	2000	1500	2000	1500	1500	1500	1500	1500	1500
Total fixed cost (€·SMH^{-1})	27.00	12.13	17.39	9.73	9.87	34.93	11.17	25.44	18.37
Fuel consumption (L·h^{-1})	12.79	18.2	11.36	—	8.29	—	35.66	—	19.19
Fuel and lubricant (€·h^{-1})	11.91	16.94	10.58	—	7.72	—	33.20	—	17.87
Repair and maintenance (€·h^{-1})	8.12	4.48	5.14	2.01	2.41	23.52	5.64	30.00	15.00
Use efficiency (%)	73.90	74.42	77.84	83.04	83.04	35.43	35.43	88.10	88.10
Total variable cost (€·SMH^{-1})	14.80	15.94	12.23	1.67	8.41	8.33	13.76	26.43	28.95
Overhead on variable cost (20%)	2.96	3.19	2.45	0.33	1.68	1.67	2.75	5.29	5.79
Total cost without labour (€·SMH^{-1})	44.76	31.27	32.07	11.73	19.96	44.93	27.68	57.16	53.12
Labour (€·SMH^{-1})	20	20	20	20		20		20	
Total cost (€·SMH^{-1})	64.76	51.27	52.07	51.69		92.62		130.28	

Note: SMH, scheduled machine hours.