Imitated Whole Tree Harvesting Show Negligible Effect on Economic Value of Spruce Stands

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Abstract: The increased removal of forest-derived biomass with whole-tree harvesting (WTH) has raised concerns about the long-term productivity and sustainability of forest ecosystems. If true, this effect needs to be factored in the assessment of long-term feasibility to implement such a drastic forest management measure. Therefore, the economic performance of five experimental plantations in three different forest types, where in 1971 simulated WTH event occurred, was compared with pure, planted and conventionally managed (CH) Norway spruce stands of similar age and growing conditions. Potential incomes of CH and WTH stands were based on timber prices for period 2014–2020. However, regarding the economics of root and stump biomass utilization, they were not included in the estimates. In any given price level, the difference of internal rate of return between the forest types and selected managements were from 2.5% to 6.2%. Therefore, Norway spruce stands demonstrate good potential of independence regardless of stump removal at the previous rotation.

Keywords: Norway spruce; whole-tree harvesting; full biomass removal; stump harvesting; hemiboreal forest

1. Introduction

The importance of forest-derived biomass has increased over the last decades [1]. Therefore, bioenergy sources such as forest-residues have potential as partial alternatives for conventional fossil fuels [2]. The use of biomass for energy production also reduces carbon emissions [3,4]. However, the increased removal of biomass from forest stands with whole tree harvesting (WTH) raises uncertainties about the long-term productivity of forest ecosystems [1,4–9]. Compared to WTH, conventional harvesting (CH) has a lower impact on site productivity in long-term, mainly because the nutrient-rich components such as foliage and twigs are left in the forest stand [1]. Norway spruce (Picea abies (L.) Karst.) is an economically important tree species which covers extensive areas [10] and has high potential as a source of renewable energy in Northern Europe [11]. Under such conditions, it is crucial to understand responses of the species to intensifying management, including WTH and particularly its effects on the economic value of forests.

The application of WTH might affect soil nutrient dynamics and sustainability of forest ecosystems [12] via changes in soil structure and biochemical cycles [6]. The decrease of soil carbon and nitrogen pools can significantly reduce tree growth, and hence accumulation of biomass [13,14]. However, the effect of WTH can differ regionally and locally [1,5,15,16], for instance in boreal forests no or slight effect of WTH on seedling growth has been observed [8,12,15,17]. On the other hand, 10 to 20 years after a WTH event, some negative effects on tree growth have been reported [8]. Significant growth reduction for Sitka spruce has been reported [18], and growth loss occurs if a high amount of nutrients has been removed from the stand, particularly in nutrient-poor sites [5]. Accordingly, local information is necessary to evaluate the potential for application of WTH as a source for...
additional biomass. The aim of this study was to evaluate the effect of WTH on economic performance of Norway spruce stands in hemiboreal forests in Latvia. We hypothesized that WTH might have reduced the growth and economic performance of Norway spruce stands growing on mesotrophic soils, compared to conventionally managed stands.

2. Materials and Methods

2.1. Site Description

Five experimental plantations of Norway spruce located in the eastern part of Latvia (56°68′ N, 25°99′ E) growing on dry mineral (Hylocomiosa), wet mineral (Myrtilloso-sphagnosa) and drained mineral (Myrtilloso mel) soils were studied. The plantations were established in 1971, in an area where, after clearcutting, stumps with the top layers of soil and nutrient-rich residues were pushed away with a bulldozer. The experimental design was the same as previously described for Scots pine [19]. As a result, areas of up to 0.5 ha with heavily scarified bare soil and practically absent residual woody biomass were formed. The areas were reforested using two-year-old bare rooted seedlings of Norway spruce raised in a local nursery; the spacing between seedlings was 1 × 2 m. Mechanized plough was used for soil preparation (harrowing). Accordingly, such management and soil erosion resulted in soil depletion [20]. Such effects were previously evidenced by the ground cover vegetation under oligotrophic conditions [19,21]. After reforestation, mechanical weed control was administered for three years; no other management was performed.

In each of the experimental plantations, two circular sampling plots of 500 m² (r = 12.62 m) were established. Within each sampling plot, diameter at breast height (DBH) of all living trees of DBH ≥ 6.1 cm was measured. In addition, within each sampling plot, tree height of 10 to 15 living trees of different canopy status were measured with accuracy of 0.2 m. For comparison, data from the National Forest Inventory (NFI) were acquired. Data on pure, planted and conventionally managed Norway spruce stands of similar age, growing in comparable conditions across Latvia were selected. Data on 68 plots were selected in total. The NFI uses the same methodology (sampling plots and measurements), as the experimental plantations were sampled.

2.2. Data Analysis

For each tree in the sampling plots of the experimental plantations, height was estimated (extrapolated) based on DBH according to Näslund’s and Gaffrey’s approach [22]. The tree volume with tops was calculated according to a local equation [23], based on the measured DBH and the estimated tree height as follows:

\[
v = 2.3106 \times 10^{-4} \times H^{0.78193} \times DBH^{0.34175} \times \lg(H) + 1.18811
\]

where H is height of tree (m) and DBH is stem diameter at breast height (cm).

The assortment outcome from each harvested tree was calculated using a local model [24]. The calculation of the economic performance of CH and simulated WTH stands was based on timber prices for the period 2014–2020 (Table 1). Considering the local specifics regarding the economics of root and stump biomass utilization [25], they were not included in the estimates.

| Assortment  | Length, m | Diameter at the Top End, cm | Price, EUR m³ |
|-------------|-----------|-----------------------------|--------------|
|             |           |                             | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
| Sawlog A    | 3.0       | 26.0                        | 73   | 69   | 67   | 68   | 76   | 74   | 64   |
| Sawlog B    | 3.0       | 18.0                        | 71   | 67   | 60   | 66   | 74   | 70   | 60   |
| Sawlog C    | 3.0       | 14.0                        | 50   | 49   | 56   | 46   | 55   | 53   | 43   |
| Pulpwood    | 3.0       | 6.0                         | 36   | 30   | 31   | 39   | 55   | 44   | 25   |
| Energy-wood | 3.0       | 3.0                         | 22   | 22   | 22   | 21   | 28   | 30   | 21   |
For each tree based on DBH, incomes were calculated as:

\[
A = \left( 1.013 \times 0.958 + (-0.112) \times DBH^{0.203} \right) / \left( 0.958 + DBH^{0.203} \right)
\]  

(2)

where \( A \) is the sawlog assortment relative incomes (%) and DBH is the stem diameter at breast height (cm).

Potential income from the forest stand on ha was calculated using following equation:

\[
NWV = I_{ha} - H
\]  

(3)

where \( I_{ha} \) is the potential income from the selected forest type on ha; \( T \) is the total timber value per sample plot; and \( S \) is the area of the sample plot in m\(^2\).

For the calculation of net wood value (NWV), the following equation was used:

\[
NPV = \frac{(NWV - E)}{(1 + r)^n}
\]  

(4)

where \( I_{ha} \) is the income from harvesting and \( H \) is the harvesting costs (according to the data from Central Statistics Bureau of Latvia). Income and costs were included in the analysis for calculation of net present value (NPV), which was calculated as the discount value of the expected net cash flow:

\[
NPV = \frac{(NWV - E)}{(1 + r)^n}
\]  

(5)

where \( E \) is the establishment costs from 2014 to 2020 year; \( r \) is the discount rate (3% and 5%); and \( n \) is the number of years (48). The establishment costs were acquired from the Central Statistical Bureau of Latvia. To estimate the profitability of the WTH event, the internal rate of return (IRR) was calculated using the following equation:

\[
IRR = r_a + \frac{NPVa}{NPVa - NPVb} (r_b - r_a)
\]  

(6)

where \( r_a \) is the lower discount rate (3%); \( r_b \) is the higher discount rate (5%); \( NPVa \) is NPV at \( r_a \); and \( NPVb \) is NPV at \( r_b \) discount rate.

Linear mixed effect models were used to assess the effect of management (CH or WTH) on the economic indicators and stand productivity (basal area and wood volume). The model in general form was:

\[
Y_{ijk} = \mu + M_i + F_i + M_i : F_i + \left( t_{ij} \right) + \left( p_k \right) + \epsilon_{ijk}
\]  

(7)

where \( Y_{ijk} \) is the calculated economic indicators and stand productivity; \( M_i \) is the fixed effect of management (two levels: CH and WTH); \( F_i \) is the fixed effect of forest types (three levels); and \( M_i : F_i \) is the interaction of both. To account for dependencies in data arising from the different locations (sample plots and forest stands) (\( t_{ij} \); 77 levels) and years (\( p_k \); 7 levels), they were included in models as nested random effects. The models were estimated in program R v.4.0.4. [26] using the package “lme4” [27].

3. Results and Discussion

From the management perspective, maintaining long-term forest productivity (across tree generations) is essential, and it is also crucial to ensure the overall sustainability of management, since different forest ecosystem services depend on the state of trees in a stand [28]. However, the ecological and economic effects of WTH are still controversial [1]. Regarding such management, there are many concerns, particularly related to nutrient and carbon depletion [29], and excessive disturbance to soil [6,30]. Among of the studied factors, only forest type had a significant individual non-interacted effect on basal area and stand
wood volume (Table 2), which could be explained by differences in stand productivity [31]. However, no effect of management type on standing volume and basal area was observed, which might be related to soil mixing (harrowing) during the planting, which has reduced soil compaction and has facilitated ascent of nutrients [32]. In boreal forests in Sweden, long-term studies showed significant loss of basal area and wood volume for Norway spruce 20 years after a WTH event [31]. In boreal forests, lack of nitrogen after biomass removal causes greater tree growth loss compared to CH [17,33]. In hemiboreal forest, however, no nitrogen limitation has been observed after WTH [34]; accordingly, WTH had a negligible effect on Norway spruce stand productivity (Table 3). The variance of random effects (Table 2) of location demonstrated high variability of growth of Norway spruce between and within stands. This implies varying responses to disturbances [1] independent from management (CH and WTH) during the 50-year period. Although the studied experiment represented only ca. half of rotation period of conventional stands in the region (According to Law on Forests in Latvia), the effects of WTH can decrease with age [9]; hence, the observed results could be extrapolated for a full rotation period.

Table 2. The effect (Chi square) of management, forest type and their interaction on economic performance and stand productivity, and the variances of random effect. The asterisks denote statistical significance ($p$-values) of the effects: * $< 0.05$, ** $< 0.01$, and *** $< 0.001$.

| Fixed Effect | Random Effect |
|--------------|---------------|
| Management   | Management $\times$ Forest Type | Sample Plot $\times$ Location | Location | Year | Residuals |
| NWV          |            | 0.02 | 19.50 *** | 0.33 | 28,975,815 | 975,125 | 1,449,187 | 989,183 |
| NPV (3%)     |            | 0.03 | 17.71 *** | 0.41 | 1,702,977 | 105,205 | 49,049 | 57,095 |
| NPV (5%)     |            | 0.03 | 15.01 *** | 0.43 | 284,443 | 20,837 | 7514 | 9353 |
| IRR          |            | 0.15 | 9.37 **  | 0.18 | 2.59 $\times 10^{-5}$ | 1.60 $\times 10^{-6}$ | 2.44 $\times 10^{-6}$ | 2.60 $\times 10^{-6}$ |
| Basal area (m$^2$·ha$^{-1}$) | 0.10 | 7.54 * | 1.50 | 67.02 | 0.27 | 8.83 |
| Wood volume m$^3$·ha$^{-1}$ | 0.19 | 11.25 ** | 0.56 | 1.14 $\times 10^{-4}$ | 1.10 $\times 10^{-7}$ | 9.46 $\times 10^2$ |

Table 3. The mean values of tree stand productivity for the analyzed forest types in the conventional (CH) and whole tree harvested (WTH) stands.

| Management | Forest Type | Basal Area, m$^2$·ha$^{-1}$ | Wood Volume, m$^3$·ha$^{-1}$ |
|------------|-------------|-----------------------------|-----------------------------|
| CH         | Hylcomiosoa | 29.1 ± 3.9                  | 295.0 ± 52.3                |
|            | Myrtillo-sphagnosa | 23.4 ± 2.9              | 206.5 ± 33.6                |
|            | Myrtillosa mel | 29.6 ± 3.0                  | 305.1 ± 37.1                |
| WTH        | Hylcomiosoa | 24.3 ± 0.5                  | 264.8 ± 7.1                 |
|            | Myrtillo-sphagnosa | 21.4 ± 2.8              | 203.7 ± 26.8                |
|            | Myrtillosa mel | 36.4 ± 4.3                  | 367.7 ± 44.4                |

The economic indicators, which integrate effects of stand productivity and market volatility, show no significant difference between WTH and CH (Table 2). Timber market has cyclic patterns, which is a result of interaction of demand, price and timber supplies (assortment structure) [35]. However, due to timber market fluctuation, the NPV provides more accurate estimates for comparison of management types [36,37]. The mean NPV (at 3% discount rate) was 2803 ± 136 EUR ha$^{-1}$, 2637 ± 292 EUR ha$^{-1}$ in favorable timber market conditions at conventional and WTH stands, respectively, which demonstrates good potential of financial return after 50 years. Regarding IRR, values in WTH stands ranged from 4.6% to 6.0% (data not shown) when timber prices were low (2015) (Table 1). In the conventional stands, IRR ranged from 2.5% to 6.2% in an unfavorable and from 3.9% to 6.2% in a favorable timber market (data not shown). Under such conditions, WTH stands show good profitability depending on timber market conditions; however, the estimated revenues might decrease due to parity costs [38]. The economic indicators were based on timber value with exclusion of below ground biomass. Hence, stump harvesting was not
considered due to technical challenges and costs of harvesting operations [26,39]. However, considering that studied stands did not lose productivity after the simulated repeated WTH, and due to increasing interest in renewable resources, stump harvesting is to be likely revisited as a sustainable resource of additional revenue [40].

4. Conclusions

Norway spruce stands showed good financial return as suggested by economic indicators (such as NPV), even when timber prices were low. If economically and ecologically feasible, WTH as management can be applied. Considering that studied experiments represented severe management practices imitating repeated WTH events, we suggest that additional harvesting of biomass from conventional mesotrophic Norway spruce stands would not compromise their sustainability (performance in following rotations).

Author Contributions: Conceptualization, Å.J. and I.D.; methodology, I.D. and Z.L.; formal analysis, A.K. and I.D.; data curation, A.A. and A.P.; writing—original draft preparation, A.K., R.M. and I.D.; writing—review and editing, Å.J., R.M. and Z.L.; supervision, Å.J.; project administration, Z.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by LVM project “Impact of forest management on forest and related ecosystem services”.

Data Availability Statement: Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

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