Effect of Forest Management of *Picea abies* and *Fagus sylvatica* with Different Types of Felling on Carbon and Economic Balances in the Czech Republic

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Abstract. The selection of the most sustainable forest management under given site conditions needs suitable criteria and indicators. For this purpose, carbon and economic balance assessment, completed with environmental impact computation using the Life Cycle Assessment (LCA) were used. The aim of this study was to compare forestry operations and wood production of selected forest stands with different i) tree species composition (Norway spruce - *Picea abies* and European beech - *Fagus sylvatica*) and ii) type of felling (chainsaw and harvester). Carbon and economic balance methods consist in the comparison of quantified inputs (fossil fuels, electricity, used machinery, fertilizers, etc., converted into emission units of carbon in Mg of C-CO₂–eq. or EUR) with quantified outputs (biomass production in Mg of carbon or EUR).

In this contribution, similar forest stands (“forest site complexes”) in the 4th forest vegetation zone (in the Czech Republic approximately 400-700 m above sea-level) were selected. Forestry operations were divided into 5 main stages: i) seedling production, ii) stand establishment and pruning, iii) thinning and final cutting, iv) skidding, and v) secondary timber transport and modelled for one rotation period of timber production (ca. 100 years).

The differences between Norway spruce and European beech forest stands in the carbon efficiency were relatively small while higher differences were achieved in the economic efficiency (forest stands with Norway spruce had a higher economic efficiency). Concerning the comparison of different types of felling in Norway spruce forest stands, the harvester use proved to induce significantly higher environmental impacts (emission of carbon) and lower economic costs. The comparison of forestry operation stages showed that the main part of carbon emissions, originating from fuel production and combustion, is connected with a thinning and final cutting, skidding and secondary timber transport in relations to different types of felling.

1. Introduction
In the year 2014, the total forest area in the Czech Republic was almost 2.7 million ha (33.8% of the total land area) [1]. Current forest composition consisted of 72.5% of coniferous forests, 26.3% of broadleaf forests and 1.3% unstocked area. About 50.7% of the forest area was formed by Norway
spruce, compared to the natural composition of forests consisting of 34.7% coniferous forests and 65.3% broadleaf forests [2]. Due to climate change, the Norway spruce stands in the middle and lower altitudes in the Czech Republic could become more fragile Jandl et al. [3], Lindner et al. [4].

In the Czech Republic, share of logging with using a harvester (and also with using crane-equipped forwarders) increased from 9% (year 2002) to 29% (year 2014) of total annual felling of timber products [2, 5].

The aim of this study was to compare forestry operations and wood production of selected forest stands with different i) tree species composition (Norway spruce - *Picea abies* L. Karsten and European beech - *Fagus sylvatica* L.) and ii) type of felling (chainsaw and harvester) in relations to carbon and economic balance. For skidding, forwarders (by chainsaw felling) and crane-equipped forwarders (by harvester felling) were used.

### 2. Evaluation and Methods

Ecosystem classification of the Czech Republic’s forests belongs to classification systems based on ecological factors of the environment. The ecological category (based on edaphic categories) and forest vegetation zone create “forest site complex” (FSC) which could be characterized as forest stand group with similar forest site conditions. A more detailed description of forest type classification of the Czech Republic was published by Viewegh et al. [6]. For this study, FSCs “4B” (*Fagetum eutrophicum* - Nutrient-rich Beech) and “4H” (*Fagetum illimerosum trophicum* - Loamy Beech) which are some of the largest FSCs in the 4th forest vegetation zone in the Czech Republic were selected. Carbon and economic balance methods consist in the comparison of quantified inputs (fossil fuels, electricity, used machinery, fertilizers, etc., converted into emission units of carbon in Mg of C-CO$_2$-eq. or EUR) with quantified outputs (biomass production in Mg of carbon or EUR). Forestry operations were divided into 5 main stages: i) seedling production, ii) stand establishment and pruning, iii) thinning and final cutting, iv) skidding, and v) secondary timber transport and modelled for one rotation period of timber production (ca. 100 years). Primary data were taken directly from forest owners and chose forestry companies.

To compare sustainable management, key indicators such as carbon and economic efficiencies (outputs in Mg C/emit. Mg C-CO$_2$-eq. ratio; economic profit/economic costs ratio in %) were used. To quantify C emissions, the LCA method was used (software SimaPro – method ReCiPe Midpoint (H) V1.12 / Europe ReciPe H) [7]. The function unit, for which all data collected were related, was 1 m$^3$ timber harvesting. The average distance for secondary timber transport was considered to be 25 km.

### 3. Results and Discussions

The results focusing on carbon balance indicate only small differences between total carbon emission (per 1 m$^3$ of wood) caused by forestry operations of forest stands European beech and Norway spruce using chainsaw felling (9.2-9.4 kg C-CO$_2$-eq. m$^3$). On the other hand, the high differences between total carbon emission of chainsaw and harvester felling in Norway spruce forest stands were found (9.4 kg C-CO$_2$-eq. m$^3$ with chainsaw felling and 16.1 kg C-CO$_2$-eq. m$^3$ with harvester felling). Of the total carbon emissions, skidding (ca. 30%) and secondary timber transport (ca. 46%) accounted for the most carbon emissions by using felling with chainsaw (ca. total 76%) while thinning and final cutting (ca. 41%) and secondary timber transport (ca. 27%) were highest by using felling with harvester (ca. total 68%) (Figure 1).
Figure 1. Carbon emission in kg C-CO2-eq. m\(^{-3}\) of different tree species composition and type of felling.

Total carbon emission per 1 m\(^3\) (European beech or Norway spruce) are very similar with results reported by Berg and Lindholm [8] for Sweden (from 12.5 to 17.1 kg C-CO2-eq. m\(^{-3}\)) and slightly lower compared to Michelsen et al. [9] who published emission of carbon for Norway (25 kg C-CO2-eq. m\(^{-3}\)). In these studies, largest emission of carbon was mainly caused by secondary timber transport and logging, similarly to results in the Czech Republic. Differences between carbon emission caused by different types of felling (chainsaw and harvester) in the forest were confirmed e.g. by Karjalainen et al. [10], Plch et al. [11].

In relation to carbon balance, different findings in economic balance focusing on economic costs were obtained. Higher total economic costs (per 1 m\(^3\) of wood) were in forest stands with European beech (28.6 EUR m\(^{-3}\)) compared to stands with Norway spruce using chainsaw felling (24.5 EUR m\(^{-3}\)) and lowest in Norway spruce stands with harvester felling (23.2 EUR m\(^{-3}\)). Main part of the total economic costs consists of seedling production (ca. 38-41%); European beech forest had higher economic costs with higher requirement of seedling amount per 1 ha compared to Norway spruce. Differences between economic costs in forest operation stage thinning and final cutting (ca. 17-25%) were very small across all tree species and felling alternatives (for European beech 5.1 EUR m\(^{-3}\), Norway spruce 5.7-5.9 EUR m\(^{-3}\)). These results are in the contrary to carbon emission from thinning and final cutting (Figure 1, 2).
The relationships between carbon efficiencies and economic efficiency are shown in Figure 3. Within similar forest stands (forest site complexes “4B” and “4H”), the highest differences in carbon efficiency related to forest operations with different type of felling were found (by Norway spruce). Concerning all tree species alternatives and types of felling, higher carbon efficiencies in European beech with chainsaw felling were accounted (32.6 Mg C wood product/ Mg emit. C-CO₂-eq.), while lowest efficiency was found in Norway spruce with harvester felling (17 Mg C wood product/ Mg emit. C-CO₂-eq.). In contrast to economic efficiency, only small differences between different type of felling were identified (for Norway spruce with chainsaw felling 127% and with harvester felling 137%). Very high differences of economic efficiencies were detected between forest stands of different tree species (for European beech with chainsaw felling 73%, for Norway spruce 127%) (Figure 3).

Except economic costs, average price of timber also has an important role in the forestry economic balances (or economic efficiency). Generally, Norway spruce has a higher average year price of timber compared to European beech in the Czech Republic (e.g. saw timber in 3rd A/B class quality per year 2015 - average price of timber was 83 EUR.m⁻³ and 59 EUR.m⁻³, respectively), [12].

4. Conclusions
Assessment of sustainable forest management needs a combination of useful tools and suitable criteria and indicators. In this contribution, two different methods, i) carbon balance (including the method of Life Cycle Assessment) and ii) economic balance were used to compare forestry operations and wood production (with main used indicators – carbon emission, economic costs, carbon and economic efficiencies). In the similar forest stands (selected “forest site complex” of Czech Republic), differences between carbon and economic efficiencies caused by different tree species (European beech and Norway spruce) were found.
spruce) and also different types of felling (chainsaw and harvester) were relatively high (Norway spruce had a highest economic efficiency and lowest carbon efficiency in contrast to European beech that had a lowest economic efficiency and highest carbon efficiency).

![Figure 3. Carbon and economic efficiencies of different tree species composition and type of felling.](image)

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