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Biomass and nutrient content of sessile oak (*Quercus petraea* (Matt.) Liebl.) and beech (*Fagus sylvatica* L.) stem and branches in a mixed stand in southern Belgium

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ABSTRACT

Accurate estimates of the amounts of nutrients immobilised in the organs and tissues of different tree species are of prime importance to make appropriate tree species selection and determine the harvesting regime that will ensure forest sustainability. Sixteen sessile oaks (*Quercus petraea* (Matt.) Liebl.) (64–129 years; stem diameters: 17–57 cm) and twelve beeches (*Fagus sylvatica* L.) (43–86 years; stem diameters: 9–50 cm) were destructively sampled from a mixed stand located on an acid brown soil in southern Belgium. Statistical models were developed to investigate the differences in nutrient concentrations between tree species, between aboveground tree compartments of the same species, and between tissues of the same compartment. For stem tissues, vertical concentration profiles were described using a versatile equation. Allometric equations were used to predict biomass and nutrient content of tree compartments based on tree dimensions. Broadly speaking, nutrient concentrations tended to be somewhat higher for oak compared with beech, but the amplitude and the direction of inter-species differences varied greatly, depending on the nutrient and the tree compartment. For both species, living branch nutrient concentrations tended to decrease with increasing branch diameter, except for Ca (oak) and Mg (beech). Nutrient concentrations were consistently higher in bark than in wood; this difference between tissues was quite pronounced for Ca, particularly in the case of oak. The biomass and nutrient content equations were used to investigate the effects of tree species and harvesting regime on nutrient exports at harvesting. For equivalent harvesting scenarios, beech was found to induce higher Mg exports than oak, and inversely for Ca. Assuming stand clear cutting, complete tree harvesting would increase average nutrient exports from 65% (Ca) to 162% (P) compared with a stem-only harvesting scenario. These results provide valuable information in the current context of the more intensive utilization of forest products.

1. Introduction

Increasing concentrations of CO_2 in the atmosphere contribute to global warming and climate change and, combined with the rising costs of fossil fuels, are leading to the development of energy policies promoting the use of renewable forms of energy (Blok, 2006). Biofuel is one of the key alternatives to fossil fuels and the interest in wood as a CO_2-neutral energy source has strongly increased in recent years (Stupak et al., 2007). As a consequence, a more intensive harvesting of forest products is expected, by using tree stems and smaller-sized branches (Smeets and Faaij, 2007).

The balance between forest ecosystems and their environment is often delicate. One reason for this fragile balance is the generally low initial fertility that characterises forest soils which has often been further limited by intensive litter raking over the preceding centuries as well as by acidic deposition (Hofmeister et al., 2008). In the future, the use of wood as biofuel could threaten the chemical fertility of forest ecosystems as it will be accompanied by substantial nutrient removal, given the high nutrient content of the tree compartments earmarked for this purpose (Adams et al., 2000; Walmsley et al., 2009; Eisenbies et al., 2009). Therefore, accurate estimates of the amounts of nutrients immobilised in the different tree compartments are of prime importance for determining the harvest intensity that will ensure the sustainability of forest management practices.

Besides the appropriate harvesting regime, tree species selection is another way to act on the nutrient cycle. Indeed, species composition may notably influence the amount and chemistry of the inputs into the cycle via atmospheric deposition (André et al., 2008a,b) but also the outputs associated with harvesting as the nutrient composition of tree tissues and organs is likely to vary between species (Meerts, 2002; Hagen-Thorn et al., 2004). Comparing two tree species on the same site avoids confounding species and site effects. Such comparisons were already carried out for European beech (*Fagus sylvatica* L.) and common Oak (*Quercus petraea* (Matt.) Liebl.); however, the

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comparisons were mainly restricted to the stems (Mussche et al., 1998; Penninckx et al., 2001; Hagen-Thorn et al., 2004) while the species effect could vary from one compartment to the other (Mussche et al., 1998; André and Ponette, 2003).

This study aimed (i) at comparing the nutrient content of aboveground tree compartments of two tree species (European beech and common oak) growing on the same site and (ii) at investigating the differences in nutrient content between aboveground tree compartments for the same species and between tissues for the same compartment. We used allometric equations to predict biomass and nutrient content of tree compartments based on tree dimensions and investigated the effects of tree species, tree size and harvesting regime on nutrient removal at harvesting. Finally, to evaluate the effects of a simplified sampling scheme (chemical analysis of tree cores taken at breath height), the vertical profiles of nutrient concentrations in the stem were also analysed.

2. Material and methods

2.1. Study area

This research was carried out on a 60 ha mixed sessile oak–beech forest located near Chimay, in the western part of the Belgian Ardennes. The study stand is located on a plateau about 300 m above sea level (50°01′N, 4°24′E).

The climate is temperate. The mean annual precipitation is 1044 mm and is evenly distributed throughout the year. The average annual incident wet deposition is 6.5 kg Ca $ha^{-}y^{-1}$, 0.9 kg Mg ha^{-1} y^{-1}, 1.2 kg K ha^{-1} y^{-1}, 5.3 kg S–SO_4 ha^{-1} y^{-1}, and 9.9 kg N ha^{-1} y^{-1} with contributions of N-NO_3^- and N-NH_4^+ amounting to 47% and 53% respectively (André et al., 2007). The mean air temperature is around 8 °C and ranges from 0.4 °C in January to 15.8 °C in July. The prevailing wind direction is south to southwest.

The substrate is uniform over the research area. It consists of acid brown soil (FAO: Dystric Cambisol; USDA: Dystrochrept) with moder-type humus and an A_hB_wC profile. The soil developed on a loamy and stony solifluxion sheet in which the weathering products of the bedrock (Lower Devonian: sandstone and schist) were mixed with periglacial loess. The pH(H_2O) of the hemiorganic horizon is around 4.0, averaging 4.3 at a depth of 20 cm and reaching 4.5 at a depth of 80 cm. Exchangeable aluminium largely dominates the weathering complex and concentrations of exchangeable base cations (Ca, Mg, and K) are low, ranking as follows: $K \leq Mg < Ca$; base saturation (BS) is consistently less than 20%, and 15% for the hemiorganic and the mineral horizons respectively. Further details on soil chemical properties are presented in Jonard et al. (2008).

During the early 20th century, the stand was treated as a sessile oak coppice that was regenerated vegetatively from stump–sprouts in 1880. It was then progressively converted to a high forest and invaded by beech. The area is now covered by relatively even-aged (≈120 years) sessile oak trees and uneven-aged beech trees. Inventory data collected in 2001 indicated a total stand basal area of 23.7 m^2 ha^{-1} almost equally shared between oak and beech in the proportions of 48.2% and 47.4% respectively; the remaining 4.4% corresponded to cultural species, mainly represented by hornbeam. The top height of the over-storey is 24 m and average stem diameters at breast height are 35.5 cm and 31.2 cm for oak and beech respectively. The under-storey consists of beech regeneration and hornbeam shrubs, whose canopy cover amounts to 16.1% and 22.4% respectively.

2.2. Measurements and sampling

Sampled trees were selected in four equally-spaced trunk diameter classes covering the range of dimensions observed in the stand (oak trunk diameters: 17–57 cm; beech trunk diameters: 9–50 cm); four sessile oaks and three beeches were randomly selected within each diameter class, resulting in total numbers of sixteen oaks and twelve beeches. Trees with abnormalities (forking and twisted trunks) were rejected. Different kinds of measurements were carried out from the ground on standing trees: stem diameter at breast height (DBH), total tree height (Ht), height of widest crown development (Hc), height of insertion of the lowest living branch on the stem (Hb) and crown radius (Cr) in eight azimuthal directions. The trees were felled in February 2006 and the stem diameters were measured on every meter. The stem was defined as the main axis extending from the soil to the Delevoy height (Hd: height at which stem diameter is half the diameter at breast height). The parts of the trees above the Delevoy height together with the branches attached to the stem were considered as crown. The age of the sampled trees was determined from a disk taken at the base of the stem; it ranged from 62 to 129 years for sessile oak and from 43 to 86 years for beech.

The stems were sliced into logs 1 m long for the lower 0–3 m boles, and into 3 m logs above. Six diameter classes (LB0: <1 cm, LB01: 1–4 cm, LB04: 4–7 cm, LB07: 7–14 cm, LB14: 14–21 cm and LB21: >21 cm) were identified for the living branches while all dead branches were included in a single class, irrespective of their size. All these compartments were weighed fresh in the field immediately after sorting, using an electronic balance hanging on the front hoist of a tractor.

A 3 cm-thick disk was taken from the lower section of each bole log and, for each tree, five (diameter ≥ 7 cm) or ten (diameter < 7 cm, dead branches) disks were randomly removed from each branch category. These disks were labelled, put into plastic bags and sent to the laboratory for the following determinations: (i) water content (constant weight at 65 °C), (ii) weight proportion of woody tissues (see below) and (iii) nutrient concentrations. For sessile oak stems, tissues were separated into heartwood, sapwood and bark while wood (heartwood + sapwood) and bark only were distinguished for beech stems as well as for the ≥7 cm diameter living branches of both species; no tissue distinction was carried out for the thinner (diameter < 7 cm) living branches and for the dead branches. Tissue separation was performed from two triangular portions of constant open angles cut out from the disks, one along the shorter radius and the other along the longer one. The material from each disk was then pooled per tissue and branch size or stem level before grinding and chemical analysis.

2.3. Chemical analyses

The samples were analysed for carbon (C), nitrogen (N), calcium (Ca), magnesium (Mg), manganese (Mn), potassium (K), phosphorus (P), sulphur (S) content. Carbon and nitrogen were determined by dry combustion (CN analyser). For the other elements, the samples were processed using wet digestion (HNO_3 65%, 200 °C, 15 min) in a microwave oven (MARS express) and concentrations were measured by atomic emission spectroscopy (ICP-AES). For quality control purposes, the National Institute of Standards and Technology standard reference materials 1575a (Pine Needles) and 1515 (Apple Leaves) were included evenly spread 15 times over the batch of 648 analytical samples. Average precision for the investigated elements was between 2% (Ca) and 5% (P and S). Moreover, the laboratory participated regularly in FFCC (Forest Foliar Coordinating Centre) and IPE (International Plant-Analytical Exchange) ring tests.

For the tree compartments whose tissues were separated, overall concentrations (wood: heartwood + sapwood; total: wood + bark) were also determined for comparison with other tree compartments and/or with other studies. The overall concentrations were computed as averages of individual tissue concentrations weighted by their respective mass. For each tree compartment, the nutrient contents were computed by multiplying the average nutrient concentration and the corresponding dry mass.