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Considerations for sustainable biomass production – Assessing the nutritional status of oak dominated stands

Viktor J. Bruckman[a]*

[a]*Austrian Academy of Sciences, Commission for Interdisciplinary Ecological Studies, Dr. Ignaz Seipel-Platz 2, 1010 Vienna, Austria*

Abstract

Anthropogenic induced climate change, geopolitical concerns and availability of mainly fossil sources fuelling our current energy system have led to a shift towards renewable and regional energy systems such as solid biomass from agriculture and forestry. A shift from traditional forest management towards more intensive biomass extraction scenarios with shorter rotation periods may implies higher rates of nutrient extractions. Here we present results from a macronutrient assessment in traditionally managed oak dominated stands considered as potential source for solid biofuel extraction.

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Keywords: climate change, macronutrients, forest biomass, renewable energy, sustainable forestry, short rotation, *Quercus petraea*

1. Introduction

Our current energy system is mainly based on carbon (C) intensive metabolisms, resulting in great effects on the earth's biosphere. Anthropogenic induced climate change as a consequence of greenhouse gas emissions is seen as a threat in a number of places around the world, limiting agricultural productivity and therefore livelihood of people in these regions. The majority of the energy sources are fossil (crude oil, coal, natural gas) and release CO_2 in the combustion (oxidation) process which takes place during transformation of energy. C released to the atmosphere was once sequestered by biomass over a time span

* Corresponding author. Tel.: +43-1-51581-3200; fax: +43-1-51581-3203.
E-mail address: viktor.bruckman@oeaw.ac.at.

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of millions of years and is now being released back into the atmosphere within a period of just decades. In the context of green and CO_2 neutral energy, there is an on-going debate regarding the potentials of obtaining biomass from forests on multiple scales, from stand to international levels.

Especially in the context of energy, it is highlighted that biomass is an entirely CO_2 neutral feedstock since the carbon stored in wood originates from the atmospheric CO_2 pool from where it was taken up during plant growth. It needs systems approaches in order to justify this statement and ensure sustainability covering the whole life-cycle from biomass production to (bio)energy consumption. Life-cycle assessments (LCA) are important tools to present the total impact of a given system. However, the current paper describes the first steps of the whole cascade of bioenergy utilization from forest biomass. Forests play in general a very important role in the global C metabolism. Forest soils represent the largest terrestrial C pool [1] and at the same time provide essential elements and water which are vital for biomass production.

There are a number of *Quercus* woodland management systems focussing solely on woody biomass production for energetic utilization or a combination with traditional forestry aiming at high quality timber production for trades and industry. They have often developed regionally as a consequence of specific demands and local production capacities, which are mainly driven by environmental factors such as climate and soil properties.

The nutritional status of a common *Quercus*-dominated forest ecosystem in northern Austria is studied here, where biomass C and macronutrient pools were compared with the respective belowground pools in order to identify potential site limits if the management shifts towards systems with a higher level of biomass and consequently nutrient extraction.

Table 1. Comparison of traditional *Quercus* woodland management systems. See [2] for a wider context and comparison with a number of other management systems.

Woodland management system	Characteristics
High forest	• Management target: production of high quality stems for trade, biomass for thermal utilization is a by-product (“residues”, thinning harvests, slash, sawdust) • Genetic regeneration • Rotation period ~120 years • Degree of mechanization: medium • Extraction of nutrients from the soil: low to medium
Coppice with standards	• Management target: biomass for energetic utilization (coppice) and a certain share of stems with higher quality (standards). Standards provide shade and act as a back-up if vegetative regeneration is not successful (seed trees). • Vegetative (coppice) and genetic regeneration (standards) • Rotation period ~ 30 years for coppice and 60-120+ years for standards • Degree of mechanization: medium • Extraction of nutrients from the soil: medium to high
Coppice	• Management target: traditional method of production of biomass for energetic utilization (fuelwood and charcoal) • Vegetative regeneration • Rotation period ~ 30 years • Degree of mechanization: low to medium • Extraction of nutrients from the soil: medium to high

2. Material and Methods

The experimental plots are situated in North-Eastern Austria, relatively close to the capital Vienna and its 62.5 MW CHP biomass powerplant. 40 x 40 and 50 x 50m permanent plots were set up in stands representing different ages and associated developing stages. See [3] for more detailed descriptions of the sampling protocol, plot layout, as well as climatic and geological background and stand characteristics. The current silvicultural management is to produce quality logs in a classical high forest system, but this might change in future as a consequence of rising demands for biomass for energetic utilization. Two other historically adapted systems are common in this region, coppice and coppice with standards. While the silvicultural aim of the first is to produce only fuelwood at relatively short rotation periods, latter represents a hybrid of the high forest and the coppice system. Table 1 summarizes the characteristics of these systems, with special emphasis on the silvicultural aim and the potential nutrient extraction.

2.1. Aboveground biomass

Aboveground stand biomass was directly measured using inventory methods and classified into seven sub-groups: i) bark of stems with a diameter at breast height (DBH) of more than 8 cm; stembark >8, ii) wood, excluding bark, of stems with a DBH of more than 8 cm; stemwood >8, iii) wood and bark of stems <8 cm; stem (B+W) <8, iv) branches with a diameter of more than 2 cm; branches >2, v) branches with a diameter of less than 2 cm; branches <2, vi) regeneration of *Quercus* species with a maximum height of 1.3 m (equals to the breast height); regen. <1.3 and vii) foliage of *Quercus* species; foliage.

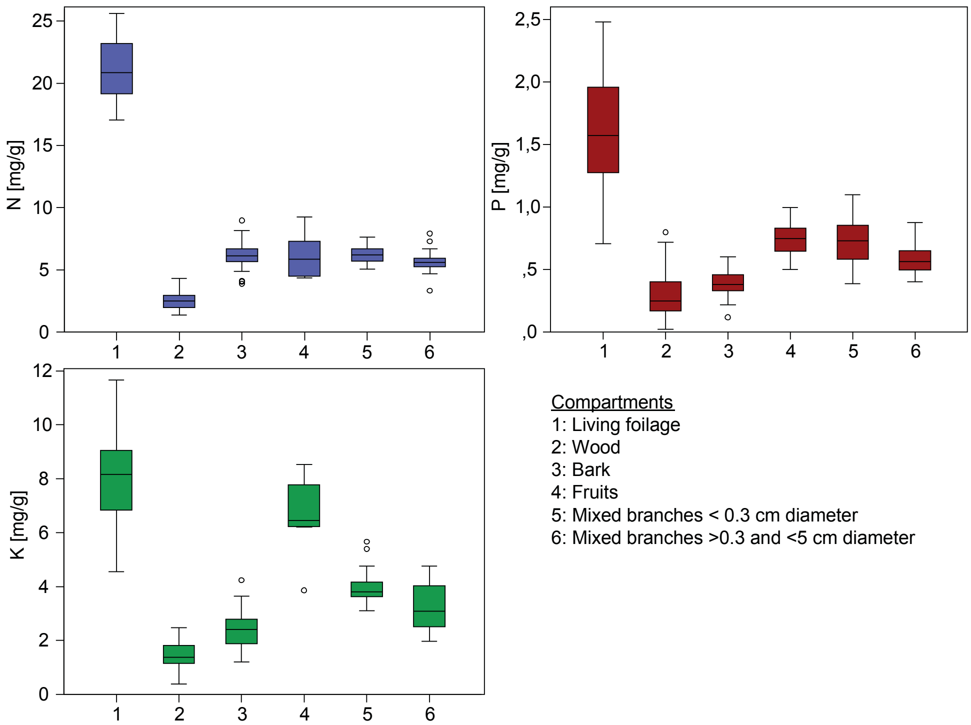

Fig. 1. Macronutrients nitrogen (N), phosphorous (P) and Potassium (K) contents in mg/g of *Quercus petraea* compartments. This figure is a reproduction from [2].

The amount of biomass (dry weight) was calculated for each sub-group and the macronutrient concentration (nitrogen, phosphorus and potassium, NPK) measured using inductively coupled plasma optical emission spectrometry (ICP-OES) according to ÖNORM standard procedures [4]. Macronutrients were determined in the following compartments of a living tree: i) foliage, ii) wood, iii) bark, iv) fruits, v) branches < 0.3 cm diameter and vi) branches > 0.3 and < 5 cm diameter. The obtained nutrient concentrations were then multiplied with the dry masses of the biomass stand compartments.

2.2. Soils

Soil samples were collected by means of a hand auger to a depth of 50 cm. Two soil cores were taken and pooled at each of the nine sample points in five soil horizons described in [3]. The samples were sieved using a 2mm-sieve and subsequently analysed using ICP-OES following the ÖNORM standard procedure [4]. Bulk density was determined gravimetrically by dividing the oven dry mass of the sieved sample by the core segment volume (represents a specific soil horizon) corrected for the volume of stone fractions. Subsequently, nutrient concentration values of N and K derived from ICP-OES were transformed into contents per area unit in order to be able to compare it with aboveground nutrient contents of living biomass compartments. The measured values represent plant available (exchangeable) stocks of nutrients in order to be able to compare it with biomass-incorporated stocks. Phosphorus concentrations were estimated from data of the Austrian forest soil inventory [5], using investigation points in the same region with attention paid to select comparable parent materials and the same soil type.

3. Results and discussion

The highest concentration of N, P and K were found in foliage, followed by fruits, bark and wood. The trends are similar in all compartments except for K in fruits. We found comparable K concentrations in fruits and in foliage, while N and P concentrations were considerably lower in fruits than in foliage (Figure 1). The comparison between branches <0.3 cm and >0.3 <5 cm represents the fact that the share of bark is higher in fine branches and consequently, a higher concentration of nutrients was found. The following section is a slightly modified reproduction from [2]:

In the 91-year-old stand, foliage only accounts for 1.7% of the aboveground biomass, but represents 8.2% of the N pool, while 23.3% represent 37.5% in the youngest stand respectively. Wood (sapwood and heartwood) had the lowest contents. Similar patterns of nutrient distribution were previously reported for the same species [6]. Approximately 40% of the macronutrients are stored in stems >8 cm in diameter from an age of 50 years onwards (Figure 2) while representing approximately 60% of the stand aboveground biomass. Bark accounts for another 10% of the 40% stem pools. Consequently it was suggested to consider oak stem debarking to limit nutrient exports (especially calcium in the case of *Quercus* bark) from the stand [6]. A comparison with exchangeable soil pools revealed sufficient potential supplies from the soil matrix as the soil pools of macronutrients are well above the stand biomass pools. However, a simple comparison of pools does not necessarily represent the nutritional status of the vegetation since plant availability, stress and soil biogeochemical processes may cause uptake limitations of certain nutrients. For instance, the N:P ratio is well acknowledged as an indicator for either N or P limitation and values of <14 indicate N deficiency where values of >16 designate P limitation [7]. Obviously, pools of soil exchangeable P are very high (Figure 2) which is also represented in foliar N:P ratios. They are very stable at 14.2 for the 50, 74 and 91 year old stands and close to the threshold value (13.9) in the 32 year old stand. Interestingly the youngest stand (11 years) shows signs of N limitation with a ratio of 10.3. This might be caused by a combination of reasons. High rates of increment in the young stand lead to a great N demand.

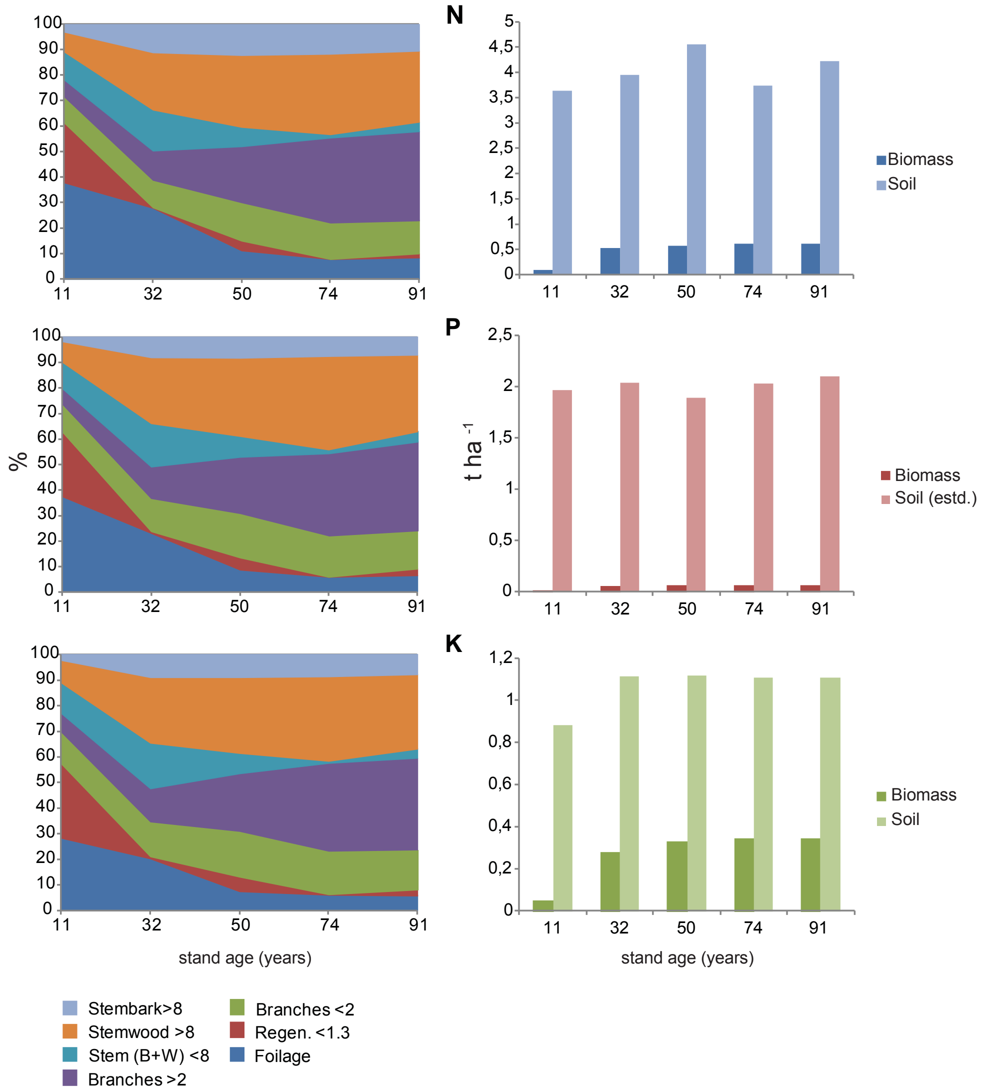

Fig. 2. Relative amounts of macronutrients in different compartments of Quercus petraea in stands of different age (left) and a comparison of exchangeable macronutrient soil and aboveground biomass stocks (right). This figure is a reproduction from [2].

Herbaceous vegetation on this specific site might compete with woody species for topsoil N and the relatively high coarse material content contributes to low water holding capacities. In combination with low rates of precipitation [3], water availability might inhibit mobilization and uptake of N at this site as suggested in a comprehensive review [8]. It is also shown that although the forest is surrounded by intensively managed agricultural land with associated atmospheric deposition of aerosols (dust), it has not led to P limitation as recently suggested [7]. In summary, despite evidence for N limits in the youngest stand, the macronutrient supply meets the demand under current forest management. However, it could be problematic if lower diameter compartments are extracted as biomass for energetic utilization. For instance, if the crown biomass is utilized at the final harvest and branches with a diameter >2 cm are being extracted, it will account for a twofold extraction of N as compared to stem-only harvests. In a scenario of whole tree harvesting, close to 90% of N in biomass will be extracted, compared to approximately 40% in the stem-only scenario. Stem debarking could further reduce N extraction to below 30% of the total aboveground biomass pool. This example demonstrates the importance of assessing the dynamic nutrient pools in order to provide profound recommendations for sustainable forest management. Forest nutrition not only has implications on species diversity, sequestration of carbon, and provision for a magnitude of environmental services, but it has distinct implications on site productivity and thus earning capacity of a given management unit. Sustainable nutrient management is therefore an essential component of successful forest management, especially if management aims at harvests that are more intensive for bioenergy production.

4. Conclusions

The rising demand for forest biomass as a source for bioenergy production induces pressure on existing forest management systems. If a considerable market price can be achieved, forest owners may consider utilizing so called “residual” or “waste” materials, mainly consisting of branches and bark as a source for bioenergy production. In some cases, even a complete shift of the silvicultural system towards shorter rotations and a higher share of fuelwood may be considered. However, the added value of fuelwood production is still way less than for high quality stems, even if the rotation is at least three times as long. The extraction of nutrients is significantly lower at a typical high forest system and natural deposition and weathering is usually sufficient to compensate for the extraction taking place during the final harvest.

If the management aim shifts towards a higher share of biomass production for energetic utilization, the sites have to be evaluated with emphasis on nutrient availability. As shown above, it is necessary to select a holistic and interdisciplinary approach; just a comparison of soil exchangeable with biomass pools potentially misses some important aspects. A careful consideration of long-term effects has to support the decision upon a change in silvicultural strategy, as an over-exploitation of nutrients likely leads to decreased increments in subsequent rotations. The coppice with standards system seems to be a suitable solution, since it provides flexibility in the share of production of different products (quality logs and fuelwood) while providing a range of services, e.g. seeds, shade for the understorey, vertical and horizontal structure, which is important for stand stability and biodiversity. Stem debarking at the harvesting site is recommended in oak stands in order to retain calcium when necessary.

A further effect of shorter rotations is soil compaction as a consequence of the use of heavy machinery which is likely to occur more frequently. Driving should be avoided in wet seasons and performed in winter when the topsoil is frozen. Clayey, heavy soils are more affected by negative consequences as compared to sandy soils.

A sustainable forest management in terms of nutrient retention and stable stands contributes to the general goal of an intact environment, capable of sequestering and storing carbon while producing biomass for a range of applications, from construction wood to fuelwood. In the long term, it does not only facilitate other ecosystem services, e.g. biodiversity, provision of clean water, recreational functions, carbon sequestration, but also ensures a basis for stable incomes for the forest owner. Biomass has certainly the potential to contribute to the future energy system, at a regional scale where demands can be covered from regional supply. Soils are a non-renewable resource and therefore it is inevitable to extract amounts of nutrients not exceeding the site potential.

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