Forest Ecology and Management 365 (2016) 119–127

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Comparison of harvest-related removal of aboveground biomass, carbon and nutrients in pedunculate oak stands and in fast-growing tree stands in NW Spain

Esteban Gómez-García [a,b,c,*], Ulises Diéguez-Aranda [b], Mário Cunha [c], Roque Rodríguez-Soalleiro [b]

[a] Centro de Investigación Forestal de Lourizán, Xunta de Galicia, Pontevedra, Spain
[b] Unidade de Xestión Forestal Sostible (UXFS), Universidade de Santiago de Compostela, Lugo, Spain
[c] Departamento de Geociências, Ambiente e Ordenamento do Território, Universidade do Porto, Porto, Portugal

ARTICLE INFO

Article history:
Received 15 December 2015
Received in revised form 15 January 2016
Accepted 16 January 2016
Available online 29 January 2016

Keywords:
Quercus robur L.
Eucalyptus globulus Labill.
Pinus radiata D. Don
Pinus pinaster Ait.
Clear-cut
Whole-tree harvesting

ABSTRACT

In northern Spain, the use of biomass to produce bioenergy has led to increased exploitation of both natural pedunculate oak (*Quercus robur* L.) stands and fast-growing plantations of natural or exotic species. In this study, we developed a model for estimating aboveground biomass, carbon and nutrient contents in different pedunculate oak components at individual-tree and at stand level. Six harvesting methods were simulated in an average stand, ranging from whole-tree to stem wood extraction (stem without bark) and including the conventional harvesting method used in the region (extraction of stem plus branches of diameter >7 cm). The biomass and macronutrients extracted were compared with those removed during harvesting of fast-growing tree species (*Eucalyptus globulus* Labill., *Pinus radiata* D. Don and *Pinus pinaster* Ait.) on the same temporal basis (mean annual values). Harvesting pedunculate oak stands generally extracted lower amounts of nutrients than harvesting fast-growing species, although the differences depended on the species, macronutrients and harvesting regime considered.

1. Introduction

In the last few decades increasing attention has been given to climate change (IPCC, 2007), and two compatible strategies for tackling the problem have been suggested: the use of forest fuels to produce bioenergy, and the incorporation of carbon in durable products such as lumber and engineered wood items (Nicholls et al., 2009). The use of forest biomass to produce bioenergy generates CO_2 but is carbon–neutral, i.e. the C has already been removed from the atmosphere during growth of the biomass (Wahlund et al., 2004). Moreover, in Europe the use of bioenergy is reducing fossil fuel dependence. The contribution of renewable sources of energy (including bioenergy generated from forest biomass) to total primary energy consumption is expected to increase to 20% by 2020 in Europe (European Commission, 2009). As a consequence, more intensive systems of biomass harvesting are being considered, and the logging residues from forest operations (clear-cutting or thinning) are considered a useful source of biomass for bioenergy production. Moreover, new biomass harvesting methods and industrial uses have been developed (Nicholls et al., 2009). As a result of the increasing interest in forest biomass, studies have been undertaken to quantify biomass, determine the amount of biomass available for harvesting and the effects of harvesting operations on the sustainability of the system (e.g. Olsson et al., 1996; Achat et al., 2015). Thus, it is already known that increased extraction of nutrients via harvesting may have an impact on the chemical fertility of the whole forest system (Adams et al., 2000; Walmsley et al., 2009; Eisenbies et al., 2009; Thiffault et al., 2011; Helmisaari et al., 2011; Wall, 2012).

Forestry is an important industry in Galicia (NW Spain) and more than 50% (8–9 Mm^3) of all wood harvested annually in Spain is felled in the region. In 2014, the timber harvest in Galicia comprised 4.49 Mm^3 of *Eucalyptus* spp. (mainly *E. globulus*, although *E. nitens* is increasingly important), 3.50 Mm^3 of conifers (mainly *Pinus pinaster* Ait. and fewer *Pinus radiata* D. Don), and only 0.81 Mm^3 of native broadleaf species (mainly *Quercus* spp., *Betula* spp. and *Castanea* spp.) (AFG, 2015). The three main species in the region, in terms of production, i.e. *E. globulus*, *P. radiata* and *P. pinaster*, are considered fast-growing trees, and the mean stand rotation ages (respectively 18, 35 and 40 years) are much lower

* Corresponding author at: Centro de Investigación Forestal de Lourizán, Xunta de Galicia, Carretera de Marín km 3.5, 36153 Pontevedra, Spain.

E-mail addresses: esteban.gomez.garcia@xunta.es (E. Gómez-García), ulises.dieguez@usc.es (U. Diéguez-Aranda), mcunha@mail.icav.up.pt (M. Cunha), roque.rodriguez@usc.es (R. Rodríguez-Soalleiro).

http://dx.doi.org/10.1016/j.foreco.2016.01.021
0378-1127/

than the 110–145 years required to maximize stem volume production in pedunculate oak (*Quercus robur* L.) stands (Gómez-García et al., 2015). Galicia is one of the few regions in the European Union where fast-growing plantations of native species (maritime pine) or exotic species (radiate pine and eucalypts) coexist with native broadleaf species. Pedunculate oak covers approximately 125,000 ha in pure stands, traditionally managed by pollarding; however, previously non-merchantable products (diameter <7 cm) from non-pollarded trees are increasingly in demand as firewood, and it has been estimated that 0.45 Mm^3 of oak is used annually for this purpose. Removal of these products entails extraction of larger amounts of biomass and carbon stocks from a long-term C sink. Regional policies aim to promote active management of oakwoods as high forests in order to provide both quality timber and biomass (in the form of firewood or woodchips) for bioenergy production (Xunta de Galicia, 2014).

Removal of biomass and nutrients during harvesting of *E. globulus*, *P. radiata* and *P. pinaster* in NW Spain has been addressed in previous studies (Merino et al., 2005; Rodríguez Soalleiro et al., 2007). Other studies have considered nutrient contents and nutrient removal in oak stands (Balboa-Murias et al., 2006; André and Ponette, 2003; André et al., 2010; Rapp et al. for *Quercus pyrenaica*, 1999), and comparison between species has only recently revealed stronger effects for conifers, at least in terms of nutrient removal (kg ha^{-1}), than for broadleaf species (Achat et al., 2015). We took into account the findings of previous studies and data on European oak in order to compare a range of pine species, evergreen broadleaf species and a deciduous native species. We hypothesized that mean annual nutrient removal through harvesting of natural oak stands is much lower than in previously studied fast-growing plantations in the region. We standardized the nutrient removals as mean annual values (kg ha^{-1} $year^{-1}$), i.e. the average nutrient loss over the lifetime of an average stand.

The aims of the present study, focused on *Q. robur* stands, were therefore as follows: (i) to characterize the distribution of aboveground biomass, carbon and nutrients in *Q. robur* in NW Spain, at both individual-tree and stand-level; (ii) to propose a model to simulate biomass, carbon and nutrient removals during harvesting operations; and (iii) to compare the average annual removals in a *Q. robur* stand and in fast-growing stands in relation to harvesting extraction method, with a view to establishing the optimal harvesting regime.

2. Materials and methods

2.1. Study area

The study was carried out in the temperate-climate region of Galicia, where the annual average minimum temperature ranges between 7 and 13 °C and the average maximum temperature ranges between 15 and 24 °C. The total annual precipitation ranges between 1000 and 1500 mm, with a slight water deficit in summer (40–150 mm). The soil humidity and temperature regimes are respectively Udic (mean period with partial drought, 1 month) and Mesic (mean frost-free period, 10 months). The most representative soils are developed on granitic rocks, schist and shale, which have a loam or sandy loam texture and are well drained. The soils are rich in organic matter, acidic (pH predominantly in the range 4.0–4.5) and are classified as Humic or Dystric Cambisols and Alumi-humic Umbrisols (IUSS Working Group WRB, 2006). Galician soils have low concentrations of exchangeable Ca, Mg and K, a cationic exchange complex saturated by Al and a low concentration of available P due to the predominance of scarcely alterable minerals in the rocks, high rainfall and open systems that rapidly eliminate the more mobile cations. Nitrogen inputs to the forest systems are usually high because of the presence of N-fixing legumes, the high organic matter contents and intermediate mineralization rates. As a result, the main limiting nutrients for tree growth are P, K, Mg, Ca and N (see Eimil-Fraga et al., 2015, for additional information).

2.2. Data

Pedunculate oak data were obtained by measurement of permanent plots and felled trees (Table 1) and chemical analysis of samples from the felled trees (Tables 2 and A.1, Appendix A). For details on the plot network and on the felled trees analyzed, see Gómez-García et al. (2015). Briefly, a network of 172 research plots was established in even-aged stands dominated by *Q. robur*. A second inventory was subsequently carried out in 72 plots and a third inventory in 40 plots; this provided a total of 284 plot-inventory combinations. Because of the damage caused by the windstorm "Klaus" (January 2009), which mainly affected the height variable, only 263 plot-inventory combinations (hereafter referred to as plots) were finally available for this study. In addition, 31 oak trees were felled in 3 different stands in the winter of 2002–2003, and 19 oak trees were felled in 6 stands in the summer of 2009, providing a total of fifty felled trees. Trees of different sizes and crown classes were selected in each stand to represent the existing range of individual-tree diameter at breast height (d) and total tree height (h) in the research plots (Fig. A.1, Appendix A). Seven aboveground biomass components were considered: stem wood (sw, stem was considered to a top diameter of 7 cm); stem bark (sb); branches >7 cm in diameter ($b7$); branches between 2 and 7 cm in diameter ($b2$–7); branches of diameter between 0.5 and 2 cm ($b05$–2); branches of diameter <0.5 cm ($b05$); and leaves (l, present on 19 oaks felled in summer). These components were sometimes sampled together (e.g. branches <2 cm and leaves). In the laboratory, the samples were oven-dried at 65 °C to constant weight (the duration of drying depended on the component considered). The field wet weights, scaling factors (for the components that were sampled together) and the dry/wet weight ratios were used to determine total dry biomass in each component for each tree.

Table 1
Summary statistics of (a) 263 plot-inventory combinations (referred to as plots) and (b) 50 felled trees used in fitting.

	Mean	Min.	Max.	S.D.
(a) 263 plots				
t (years)	73	34	164	26.1
H (m)	17.9	7.3	25.8	3.2
N (trees ha^{-1})	874	302	3140	446
G (m^2 ha^{-1})	30.9	2.6	68.8	9.4
(b) 50 felled trees				
d (cm)	27.8	5.9	67.5	15.4
h (m)	16.9	5.3	27.6	4.7
w_{sw} (kg $tree^{-1}$)	407	1.1	2297	524
w_{sb} (kg $tree^{-1}$)	57.5	0.3	412	78.7
w_{b7} (kg $tree^{-1}$)	107	0.0	909	207
w_{b2-7} (kg $tree^{-1}$)	72.6	4.9	331	87.6
w_{b05-2} (kg $tree^{-1}$)	17.0	0.8	69.4	17.2
w_{b05} (kg $tree^{-1}$)	5.9	0.3	22.9	5.2
w_T (kg $tree^{-1}$)	667	7.4	3520	899
w_l^* (kg $tree^{-1}$)	4.3	0.4	20.0	5.2

Note (a): t = stand age; H = dominant height defined as the mean height of the 100 largest-diameter trees per hectare; N = number of trees per hectare; and G = stand basal area.
Note (b): d = diameter at breast height (1.3 m above ground level) over bark; h = total tree height; w_{sw} = stem (up to diameter of 7 cm) wood biomass; w_{sb} = stem bark biomass; w_{b7} = biomass of branches of diameter >7 cm; w_{b2-7} = biomass of branches of diameter 2–7 cm; w_{b05-2} = biomass of branches of diameter 0.5–2 cm; w_{b05} = biomass of branches of diameter <0.5 cm; w_T = total aboveground woody biomass; and w_l = foliar biomass (*leaves only obtained from 19 trees felled in summer).