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Dear Readers,

From 7th-9th October 2013 Mierzęcin (Poland) played host to the Forest Biomass Conferenceorganised within the Polish-German project entitled "Development of trans-border decision support system for remote and model assessment of forest dendromass in Pomerania Region". The papers presented at the conference covered a broad spectrum of issues connected with dendromass, such as dendromass estimation by remote detection methods, the development of allometric equations, the allocation of dendromass and carbon dioxide fixation, determining element content, renewable energy and the wood biomass market. The topics presented in the papers proved to be extremely engaging and this led to their publication in a scientific journal from the field of wood science. This special issue of the journal is the result of co-operation between the Faculty of Forestry at the University of Life Sciences in Poznan (organiser of the conference) and the Editorial Board of the journal "Drewno".

The project, which ran in the years 2011–2013, and the conference were co-financed by the European Union under the 3rd objective of the Operational Programme "European Territorial Co-operation" – "Cross border co-operation" between Mecklenburg-West Pomerania / Brandenburg and the Republic of Poland (Zachodniopomorskie Province) 2007–2013 (INTERREG IV A) and by the Polish Ministry of Science and Higher Education.

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Organizational Committee President
Forest Biomass Conference

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PRACE NAUKOWE – RESEARCH PAPERS

Daniel B. Botkin, Michael R. Ngugi, David Doley

ESTIMATES AND FORECASTS OF FOREST BIOMASS AND CARBON SEQUESTRATION IN NORTH AMERICA AND AUSTRALIA: A FORTY-FIVE YEAR QUEST

A half-century of forest inventory research involving statistically-valid field measurements (using statistically representative sample size and showing confidence limits) and well-validated forecasting methods are reviewed in this paper. Some current procedures overestimate global and large-scale forest biomass, carbon storage, and carbon sequestering rates because they are based on statistically-invalid methods (errors in estimates are unavailable and unreported), or they fail to consider key dynamic characteristics of forests. It is sometimes assumed that old-growth forests can serve as fixed, steady-state storage of biomass and carbon for indefinitely long periods, but it is shown by both modelling and remote sensing that forests are dynamic systems, the state of which can change considerably over as short a time as a decade. Forecasting methods show that maximum biomass and carbon storage in some important forest types occurs in mid-succession, not in old-growth. It is proposed, therefore, that realistic biomass and carbon storage estimates used for carbon credits and offsets be determined as the statistical mean minus the confidence interval and that practical carbon sequestering programs include specific timeframes, not indefinitely long periods of time.

Keywords: Forest modeling, forest inventory, biomass inventory, carbon sequestering, model validation

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Introduction

An invitation from IUFRO to the senior author (Botkin) provided an opportunity to reflect on almost half a century of work in forest ecology. This has involved trying to understand how forests work, to use that understanding to solve forest-related environmental problems, and come to know what our place within forests should be – what would be best both for humans and for forest ecosystems. Because this is primarily a personal research history, it does not attempt to provide an exhaustive review of the fields of study covered, but highlights the long-recognized need for justifiable estimates of forest stocks and growth.

The possible effects of human-induced climate change on forests have been a source of personal concern to the senior author since 1968, leading to the development of the JABOWA forest dynamics model [Botkin et al. 1970], the first well-known gap model. During the last 40 years, many tree-based forest growth models have been developed and evaluated [e.g. Pretzsch et al. 2002; Stage 2003; Valentine, Mäkelä 2005]. However, the JABOWA model concept is still considered valid [Long et al. 2014], is used [Ashraf et al. 2012, 2013] and has formed the basis for many other models [e.g. Monserud 2003; Hanson et al. 2011; Larocque et al. 2011]. The water relations of forests have also been a concern to forest ecologists, including the authors, in different parts of Australia for many years [e.g. Doley 1967; Ngugi et al. 2003]. This work became more relevant with the determination to expand native species hardwood plantations in parts of the country with relatively low rainfall in response to the threat of climate change [Ngugi et al. 2004]. In parallel, government forest management agencies in Queensland, Australia developed one of the most comprehensive long-term forest monitoring systems and databases in the developing world [Beetson et al. 1992]. These data have been used to validate a variant of the JABOWA model and to investigate carbon storage and uptake in selected Australian forests [Ngugi, Botkin 2011; Ngugi et al. 2011, Ngugi et al. 2013].

The need

Concern over the possibility of greenhouse-induced climate change drives the need for more quantitative knowledge of the global carbon cycle, including amounts and rates of change of carbon storage in major biomes. More generally, this knowledge is fundamental to the understanding of the dynamics of Earth's biosphere, which is itself fundamental to Earth System Science. However, in spite of repeated calls by scientists that such knowledge should be obtained, terrestrial ecosystem carbon storage and exchange remain poorly documented [e.g. Detwiler, Hall 1988; Canadell, Mooney 1999; Canadell et al. 2010].

Statistically based estimates of terrestrial carbon stocks have been obtained for only a few large areas, including boreal forests and eastern deciduous forests of North America [Botkin, Simpson 1990; Botkin et al. 1993; Brown et al. 1997; Hollinger 2008] and portions of temperate forests of Australia [Keith et al. 2010; Moroni et al. 2010; Moroni 2012] and tropical forests of the Amazon [Baker et al. 2004]. As a result, discussions about the global carbon cycle [e.g. Thompson et al. 2007] often rely on highly uncertain estimates of the size of national or regional carbon storage [IPCC 2006], and ignore the large range in carbon storage and annual rate of change across an extensive landscape.

The Intergovernmental Panel on Climate Change (IPCC) has compiled detailed biome-averages for carbon storage and uptake for plantation forests in major global biomes, but some of the largest forest areas are occupied by less intensively managed mixed species native forests subjected to varying degrees of disturbance [IPCC 2006]. Therefore, establishing baseline carbon storage and net rate of flux in natural undisturbed and disturbed native forests is crucial to estimating global greenhouse gas emissions and sequestration potential. Since carbon stocks vary across landscapes and vegetation types, a biome-average value cannot represent this variation adequately for an entire region or country [Gibbs et al. 2007], especially in Australia where the forests extend from wet coastal to dry inland regions and from temperate to tropical latitudes.

Ground-based baseline estimates of forest carbon stocks are needed to support carbon sequestration efforts through calibrating and validating remote sensing based estimates of the global carbon cycle and for successful implementation of climate change mitigation policies [Saatchi et al. 2011; Hoover et al. 2012].

Many estimates of carbon stocks are based on forest inventory data [Houghton 2005; Sierra et al. 2007; Mackey et al. 2008; Hu, Wang 2008; Keith et al. 2010; Keith et al. 2009]. However, because carbon stocks of managed or disturbed forests are dynamic in relation to the time since last disturbance, estimates of carbon stocks and changes may be difficult to relate to potential carbon storage.

One point here needs qualification: While global estimates lack the necessary statistical validity, today in the United States there is research in local areas – forested areas covering 12,000 or more hectares – which is following legitimate, scientific and statistical methods based on both combinations of inventories, remote-sensing and biophysical measurements [e.g. Hoover 2008; King et al. 2011; Huntzinger et al. 2012; Ashraf et al. 2013]. But for many smaller areas, the goals remain local and are aimed at selling carbon credits from these forests.

Problems

There are four major problems with existing estimates of forest biomass and carbon storage:

1. A lack in estimates of variance: Many global, biome, and large-area forest storage estimates in use by the IPCC and in major scientific literature are based on estimates without indications of confidence limits. The lack

of any estimate of sampling or observation error makes them scientifically invalid.
2. Not comparable methods: Global estimates use data from a variety of small area estimates, which do not use consistent methods and are therefore not strictly or directly comparable.
3. Data from studies whose purpose was not global biomass or carbon storage: Most of the estimates are from isolated studies not originally carried out to seek large-area estimates.
4. Steady-state old-growth assumptions: Most, perhaps all, estimates assume that storage can be achieved in a steady-state system, stored indefinitely or at least for a very long time.

The solution

1. Develop an international program that uses comparable, if not uniform, methods to estimate forest biomass.
2. Ensure these methods include statistically valid estimates of stocks and confidence intervals.
3. Base realistic estimates of carbon sequestration credits and offsets on agreed calculations, such as the mean minus the confidence interval.
4. Determine how close the international scientific community is to achieving these methodological goals.

The first statistically testable estimates of biomass and carbon storage for any large area of Earth

Starting in the 1980s, one of the authors (Botkin) realized that it was necessary to begin to develop statistically testable estimates of biomass and carbon storage for large areas. While the measurement of biomass is conceptually simple, the logistics of a valid sampling scheme over a large area are complex, as has been indicated in recent works [Gregoired Valentine 2008; Mandallaz 2008]. The North American boreal forest was selected for a first estimate because: it was understood to contain a sizable fraction of the Earth's organic matter; it is floristically simple; and, although encompassing some of the most remote regions of the globe, it had good available transportation. Furthermore, oven-dry biomass equations of all trees and most shrubs were available, which greatly simplified measurement procedures.

Direct ground-based measurements involved two steps. The first was dimensional analysis in which the height and diameter of a tree was measured, and then, ideally, cut down and all the parts were weighed. This was repeated for the range of tree sizes found for each tree species of interest. From these data equations were developed to estimate biomass and carbon storage for each tree in a plot, and the sum of all trees was extrapolated to an estimate for a forest.

As discussed in Woods et al. [1991], the most cost-effective and long-term solutions to increasing the precision of biomass estimation are sacrificing more trees to fit models or sampling larger areas of forests. Both of these approaches require investments that many land managers are loath to make. Consequently, caution is necessary when relying solely on results from general allometric estimates, particularly in relation to the implementation of climate change mitigation policies, such as the reduction of emissions from deforestation and degradation [Saatchi et al. 2011].

Field sampling

The second step is to carry out non-destructive sampling. The technique of "survey sampling," commonly used in agriculture and forestry, was employed to obtain reliable estimates of crop yields and timber volumes. Environmental features were used to delineate the outer boundaries of the North American boreal forest region because there is no agreement on the exact present boundaries of the boreal forest in North America. The area was subdivided into 12 strata whose boundaries were defined by climate, geology, and soil patterns (fig. 1). July mean temperature isotherms delineated north and south boundaries; other climatic factors, along with geological and soil features, delineated east-west boundaries. Some strata were also delineated by accessibility as determined by a Canadian study [Bonnor 1985].

Source: Botkin, Simpson [1990]

Fig. 1. Sampling strata for the North American boreal forest

An equal-area map was produced from which the location and size of each stratum, as well as the overall size of the study area, could be calculated (table 1). The total area was found to be approx. 5 million km^2. Each stratum was sampled with primary sampling units (PSU) of equal size (24 × 24 km) each representing an 8 × 8 pixel square on a digital image on the geographical information system (GIS). The number of PSUs allocated to a stratum was proportional to the stratum's relative size. However, to achieve an unbiased estimate of the variance, at least 2 PSUs were allocated to each stratum.

PSUs were randomly selected within the strata using the GIS and a table of random coordinates. Each PSU was then subsampled with four randomly located secondary sampling units (SSU) for a total of 152 SSUs. Each SSU consisted of five non-independent plots, so that a total of 760 plots were measured. SSUs were selected using a table of random Universal Transverse Mercator (UTM) Grid system coordinates representing all possible locations of SSUs within a 24 × 24 km primary sampling unit (UTM coordinates locate areas of equal size in contrast to latitude/longitude coordinates which delineate areas of decreasing size with increasing latitude). Each set of coordinates represented a 400 m^2 area of the PSU.

The northwest corner of the 400 m^2 area was used as the center-point for the SSU. To locate them in the field, SSUs were plotted on topographic maps (Canada – 1:50,000; US – 1:24,000). All terrestrial sites were accepted regardless of present use, condition, or cover, except that points occurring on bodies of water were excluded (Canada is approx. 7.6% water [Bonnor 1985]).

Field crews traveled to each secondary sampling unit, which consisted of five sub-plots: one 20 m diameter circular sub-plot located at the center and four 20 m diameter sub-plots located tangentially to the central sub-plot, one in each cardinal direction. This layout resulted in an overall sample size of 1571 m^2 per SSU. The center point of each secondary sampling unit was located in the field using maps and aerial photographs. Where possible, established SSU centers were then located with satellite navigation devices or by aerial photography to a precision that would allow them to be correlated later with remote sensing data. Field measurements were obtained during the summers of 1987 and 1988. The diameter at breast height (DBH) (1.3 m above the ground), total height, and species were recorded for all trees with DBH > 2 cm in each sub-plot. A 2-m diameter micro-plot was established at the center of each sub-plot within which the species and stem diameter at the base and 15 cm above the ground were recorded for all shrubs and for trees with DBH < 2 cm.

Data analysis

Oven-dry biomass for each stem was estimated from diameters and heights using dimensional analysis relationships available at that time [Whittaker 1966; Aldred, Alemdag 1988]. Biomass equations for trees were developed by the Canadian Forestry Service [Evert 1985]; those for shrubs and seedlings were obtained from a variety of sources [Stanek, State 1978; Ribe 1979; Smith, Brand 1983]. It was assumed that the estimates from these equations were accurate for trees and shrubs throughout the boreal forest region [Evert 1985]. The total biomass of an SSU was calculated by summing the individual stem results from the biomass equations for all plots. Biomass density per hectare was calculated by dividing the total SSU biomass by the SSU area.

The mean oven-dry biomass per unit area (kg/m^2) of the boreal forest and its 95% confidence interval was calculated with a set of standard survey-sampling equations based on the sample design [Yamane 1967]. The mean and total biomass equations weighted the SSU results by strata and sample size. Variance equations used strata and sample sizes to weight variance that was partitioned into PSU components, allowing comparisons within units and between units. In this study, carbon content was taken to be 45% of the oven-dry biomass following Whittaker [1975].

North American boreal forest results

The above ground biomass of trees and shrubs for the North American boreal forest averaged 4.18 ± 1.01 (95% C.I.) kg/m^2 and totalled $21.5 \times 10^9 \pm 5.2 \times 10^9$ (95% C.I.) metric tons for the 5,126,427 km^2 (table 1). This estimate is as little as one-fourth of the previously published estimates for above ground biomass (12 to 18 kg/m^2) used in analysis of the global carbon budget (table 2), and is significantly lower (95% C.I.) than all the others.

Table 1. Estimates of above-ground biomass and carbon in the North American boreal forest

Source	Biomass [kg/m^2]	Carbon [kg/m^2]	Total Biomass [10^9 MT]^c	Total Carbon [10^9 MT]^c
Botkin, Simpson [1990]	4.2 ±1.0	1.9 ± 0.4	22 ± 5	9.7 ± 2
Ajtay et al. [1979]	17.5	7.9	90	40
Whittaker, Likens [1973]	15.4	6.9	79	35
Olson et al. [1978]	14.8	6.7	76	34
Olson et al. [1983]	12.4	5.6	64	29
Bonnor [1985]	5.9	2.7	30	13.8

Sources for previous studies are given in Botkin, Simpson [1990]

Carbon content was calculated to be 1.9 ± 0.4 kg/m^2 and totalled $9.7 \times 10^9 \pm \pm 2.3 \times 10^9$ metric tons (table 1). This value is much lower than previous estimates of carbon content used in analyses of the global carbon budget, which range from 12 to 18 kg/m^2 for above-ground biomass and up to 7.9 kg/m^2 for carbon content (table 1). Only the biomass inventory directed by the Canadian Forestry Service gave values close to Botkin and Simpson [1990], with a mean biomass value of 5.9 kg/m^2 for all of Canada [Bonnor 1985]. The Canadian Forestry Service estimate was the most reliable prior to the one presented in the study, but was acknowledged to be not statistically reliable for the entire boreal forest region because it was based on the results of a number of different studies using a variety of methods. That estimate also included all Canadian forests, which accounts, at least in part, for a value slightly higher than the one presented and was related to political rather than natural areas.

Biomass and carbon storage of North American eastern deciduous forests

Using the same methods, Botkin and Simpson [1990] obtained an estimate of the above-ground biomass and carbon storage for the eastern deciduous forest of North America (table 2). The results are consistent with those from the North American boreal forests: mean values are much lower than have been reported commonly in literature, and the statistical confidence intervals are a similar percentage of the mean (table 3) [Houghton 2005].

Table 2. Above-ground carbon in temperate deciduous forests of North America

Data sources	Carbon density [kg/sq m]	Total carbon [gigatons]	Ratio to Botkin and Simpson results
Botkin, Simpson [1990]	3.6 ± 0.6	8.1 ± 1.4	1.00
Presettlement			
Minimum	4.2 ± 0.7	9.3 ± 1.4	
Maximum	7.3 ± 1.2	16.1 ± 2.6	
Previous studies			
Atjay et al. [1973]	9.7	22	2.72
Whittaker and Likens [1973]	10.4	23	2.84
Olson et al. [1978]	7.7	17	2.10
Olson et al. [1983]	7.7	17	2.10
Houghton et al. [1983] Undisturbed	10.4	23	2.84
Houghton et al. [1983] Secondary	7.7	17	2.10

Source: Botkin, Simpson [1990]

Table 3. Comparison of Houghton [2005] and Botkin and Simpson [1990] (for North America boreal forest); Botkin and Simpson [1993] (for North America deciduous forest)

Region	Forest area [106 km^2]	Forest Total living biomass [Pg C]	Average forest biomass [Kg Cm^{-1}]	Source
Canada (Boreal)	316	12.9	4.1	Houghton [2005]
Canada + USA (Boreal)	512	9.7 ± 2	1.9 ± 0.4	Botkin, Simpson [1990]
United States (Eastern Deciduous)	212	13.3	6.3	Houghton [2005]
United States (Eastern Deciduous)	223	8.1 ±1.4	3.6 ± 0.6	Botkin, Simpson [1993]

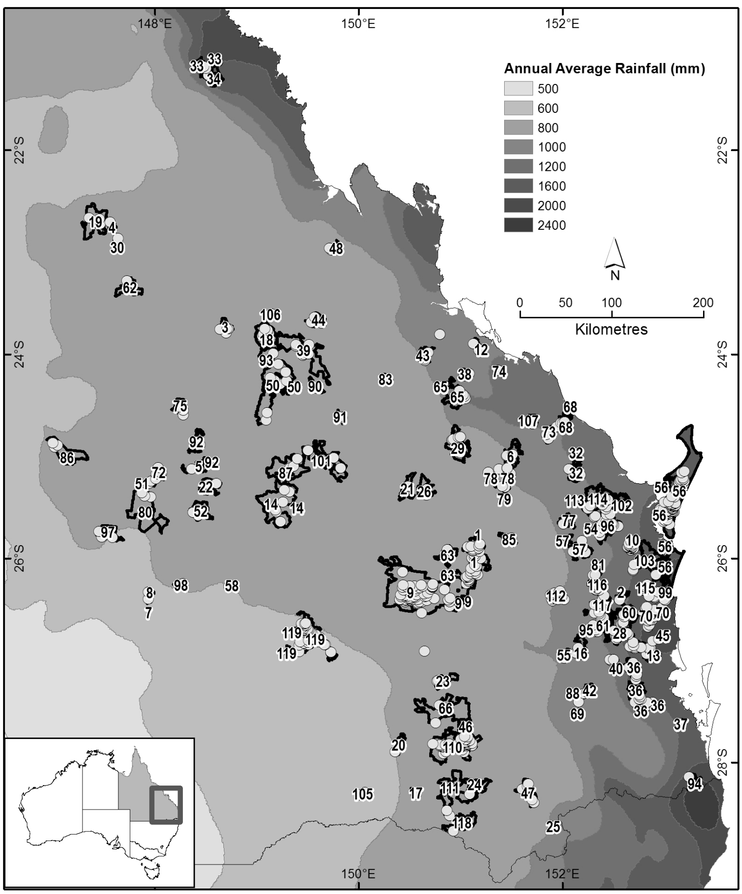


Fig. 2. Map of Australia showing Queensland State, the study area, annual rainfall zones, and distribution and location of forest plots

Forest carbon storage monitoring in Queensland, Australia

This study involved 2.6 million hectares of state-owned uneven-aged mixed species native forests in sub-tropical Queensland, between latitudes 21° and 29°S and longitudes 146° and 154°E, including a rainfall gradient from 500 mm/yr to 2,000 mm/yr (fig. 2). Within this forested area, 604 long-term permanent inventory plots were established, commencing in 1936 and measured up to 2011. The sampling procedure used a subset of a systematic inventory grid, resulting in an average sampling intensity of 1 plot per 43 km^2. Systematic sampling was the necessary consequence of operational simplicity and economy but it has been justified in recent analyses [Valentine et al. 2009].

Queensland data analysis

In this and an earlier Queensland study [Ngugi et al. 2013], conversion of biomass dry weight to live above-ground carbon stock was based on the assumption that woody tissue is 50% carbon [Gifford 2000]. (Note the slight difference (45%) used in the North American studies discussed earlier.) Since all the plots had a history of human disturbance, the long-term data sequence was examined from each of the 604 plots for the entire sequence. Data collected post-1993 were used to estimate carbon stocks, basal area, and the stem density component of trees < 10 cm DBH. The mean basal area and live above-ground carbon stock for each plot were calculated as the respective means of all measurement occasions for the plot for its entire measurement history.

The net annual changes in basal area and live biomass were calculated as the difference in observed attributes between two consecutive measures divided by change in time (the length in years of the measure interval). The plot statistics were then aggregated using rainfall zone and broad vegetation grouping to provide respective mean estimates for each group. Data management and calculations of carbon stocks were undertaken using R programming language [R Development Core Team 2011] and errors expressed as a 95% confidence interval (CI) of the mean.

Queensland results

Live above-ground tree carbon stocks and change across a rainfall gradient

This study provided empirical estimates of live above-ground carbon stocks and their annual net changes based on over 355,000 tree measurement records. Table 4 shows the mean plus and minus the 95% CI. A benchmark value for each rainfall zone was estimated as the mean maximum carbon stock for each plot across the entire inventory period of up to 70 years. This carbon stock value varied from 43.4 ± 3.4 to 138.1 ± 14.4 t C ha^{-1} (table 4).

Table 4. Estimates of mean (± 0.95 CI) live above-ground carbon (C) stock and annual change for trees with DBH > 5 cm in six annual rainfall zones in Queensland.

Rainfall zone [mm]	Sample size	Mean C stock [t ha^{-1}] ± CI	Conservative C stock [t ha^{-1}] ± CI	Benchmark C stock [t ha^{-1}] ± CI	C stock change [t ha^{-1} yr^{-1}]
500–600	41	29.4 ± 1.3	28.1	43.4 ± 3.4	0.67 ± 0.05
600–800	277	38.1 ± 0.7	37.4	50.0 ± 1.6	0.70 ± 0.03
800–1000	55	60.8 ± 4.3	59.4	67.8 ± 7.5	0.96 ± 0.18
1000–1200	102	57.4 ± 3.1	54.3	78.8 ± 7.9	1.01 ± 0.08
1200–1600	89	119.2 ± 6.9	112.3	138.1 ± 14.4	1.94 ± 0.20
1600–2000	40	101.8 ± 6.6	93.2	116.5 ± 12.7	2.21 ± 0.29

The important point here is that 95% CI is a sizable percentage of the mean. One can use these values to derive minimum and maximum carbon storages and then to consider what is reasonable to use for the determination of carbon offset credits, whether it should be the benchmark, the mean, or the mean minus the 95% CI to get the minimum likely storage. While one could use the benchmark or the mean plus the 95% CI, the authors consider that either of these estimates would be an unreliable basis for the making of long-term investment decisions. Instead, using the mean minus the 95% CI (the Conservative estimate in table 4) is recommended; it may be 20% to 50% lower than the benchmark estimate, but is more realistic for less than ideal environments. It is relevant that the discrepancy is greater for the lower rainfall areas, which constitute the bulk of land potentially available for carbon storage.

The mean live above-ground carbon stock increased with increasing mean annual rainfall from 600 mm to 1600 mm, then decreased slightly from the 1600 mm to the 2000 mm rainfall zone (table 4). The relationship between the conservative estimate of live above-ground carbon stock (LAC_c, t ha^{-1}) and mean annual rainfall (R, mm) is given by a quadratic equation, $LAC_c = -54.13 + 0.165R - 0.00004R^2$, $r^2 = 0.82$. Across most rainfall zones, the annual carbon increment was slightly less than 2% of the standing carbon stock.

Queensland net carbon stocks and change among broad vegetation groups

Queensland forests growing in comparable geology, geomorphology and soil conditions have been classified within the last 20 years into Broad Vegetation Groups (BVGs). Their mean carbon stocks range from 33.6 ± 0.9 t C ha^{-1} in *Callitris* forests (BVG 20a) to 146.4 ± 11.1 t C ha^{-1} in wet tall open forests (BVG 8a) (table 5). Note that the highest BVG carbon stock (146 t C ha^{-1}) observed in wet tall forests (BVG 8a) is substantially greater than the mean value for the entire 2000 mm rainfall zone (101.8 t C ha^{-1}, table 4), reflecting the fact that a range of forest types occur in this rainfall zone, and these do not all share the same high carbon stock values. This difference has important implications for the selection of an appropriate target value for carbon sequestration in a particular region. Therefore, classification of forest locations on both rainfall and forest type is essential for the development of reliable carbon inventories.

The mean live above-ground carbon net change ranged from about 0.7 t C ha^{-1} yr^{-1} or less in forests characteristic of rainfall zones of 1000 mm yr^{-1} or less (BVGs 10a, 12a, 18b and 20a) to 2.92 ± 0.25 t C ha^{-1} yr^{-1} in BVG 8b (open forest dominated by tall individuals of *E. pilularis* Sm.). The overall mean live above-ground carbon net change among all the broad vegetation groups and rainfall zones was 0.95 t C ha^{-1} yr^{-1}, due to the bulk of the forest sites being located in the lower rainfall zones.

Table 5. Mean and annual net change in live above-ground carbon (C) stock for forest type

Broad Vegetation Group (BVG)	Rainfall zone [mm]	Number of plots	Mean C stock [t C ha^{-1}]	Annual net change C stock [t ha^{-1} yr^{-1}]
8a Wet tall openforests	1000–2000	41	146.4 ± 11.1	1.96 ± 0.22
8b Moist open forests	800–2000	55	136.0 ± 9.3	2.92 ± 0.25
9a Moist to dry open forests	600–2000	116	60.7 ± 2.2	1.12 ± 0.08
10a *Corymbia citriodora*	600–1000	113	39.3 ± 1.3	0.66 ± 0.06
10b Moist open *Corymbia* spp	600–1600	40	46.3 ± 2.5	0.85 ± 0.09
12a Mixed eucalypts	600–1200	28	46.2 ± 2.5	0.71 ± 0.13
18b *Eucalyptus crebra*	500–800	32	41.5 ± 1.8	0.70 ± 0.07
20a *Callitris glaucophylla*	500–800	115	33.6 ± 0.9	0.70 ± 0.03

Mean estimates ± 0.95 confidence interval

Implications for global estimates

There are two important points here: that it is possible to give statistical confidence to these estimates, and this should be done for all estimates so that realistic expectations about the range of carbon storage become available; and that these statistically valid estimates are generally significantly lower than those in common use. To reinforce these conclusions, the results presented here were compared with the 2006 IPCC report values (table 6). Since rainfall has a major influence on forest growth, live above-ground carbon within our rainfall gradient was estimated and these estimates were compared with the biome averages for forests more than 20 years after disturbance compiled by the IPCC [IPCC 2006]. It can be noted that several IPCC estimates are based primarily on available single-measure estimates from a variety of sources using a variety of methods, and as a result there is no ability to calculate a statistically-valid mean and variance. The statistically-expected range for each of the three Queensland rainfall regimes that could be compared with the IPCC studies are given. This range is the lowest mean minus its 95% confidence interval and the highest mean plus its 95% confidence interval. In all cases, the entire range reported for the Queensland forests is considerably lower than the 2006 IPCC values. The statistically-valid minimum for Queensland subtropical humid forest is 66% of the 2006 IPCC value, while even the statistically--valid Queensland maximum is 87% of the IPCC value. The statistically-valid Queensland subtropical dry forest minimum is 67% of the 2006 IPCC value, while even the statistically-valid Queensland maximum is 81% of the IPCC value. The statistically-valid Queensland steppe minimum is 80% of the 2006 IPCC value, while the statistically-valid Queensland maximum is 10% higher than the IPCC value. Only the range of the Queensland steppe includes the IPCC estimate.

The Queensland results are consistent with the North American boreal and eastern deciduous forest findings. Together, these show that there appears to be a fundamental deficiency in the quality of information that is being used to make decisions, even though the necessary methods are readily available. Moreover, realistic carbon sequestering programs should be adjusted for these ranges. The most conservative estimate, the lower mean minus the 95% CI is the most practical, but more importantly, international carbon sequestering programs should select one of the statistically-valid values as the planned standard.

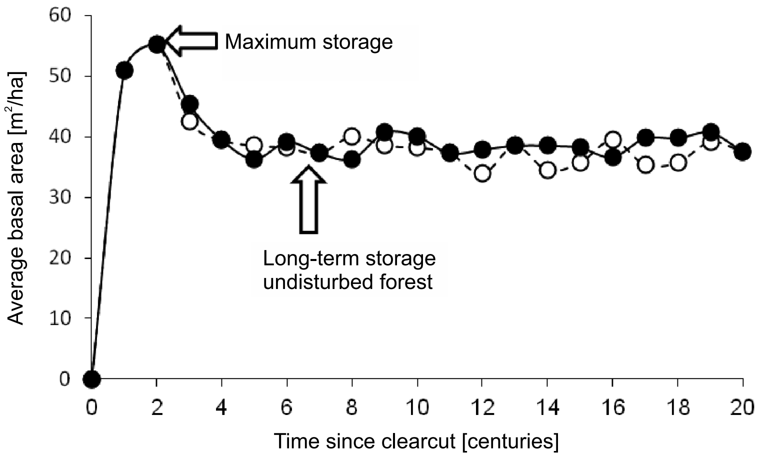
Table 6. Comparison of IPCC [2006] and Queensland study estimates of carbon storage. Within each of the rainfall ranges in Queensland, low is the mean minus the 95% confidence interval (CI) for the lower stock and the high is the mean plus the CI for the higher stock of the rainfall range

Biome and annual rainfall range estimates [mm/yr]	Source	Carbon storage	
		low [t C ha^{-1}]	high [t C ha^{-1}]
Subtropical humid 1600–2000	IPCC	145	145
Subtropical humid 1600–2000	Queensland	95.2	126.1
Subtropical dry 1000–1200	IPCC	80	80
Subtropical dry 1000–1200	Queensland	54.3	65.1
Subtropical Steppe 600–800	IPCC	35	35
Subtropical Steppe 600–800	Queensland	28.1	38.1

Can forests store maximum biomass and carbon over a long time?

The assumption underlying proposals for carbon trading is that one can obtain credit for a single value of the amount of carbon stored in a forest. A further common assumption is that to store carbon one simply allows a forest to grow whereupon it will reach its maximum biomass and carbon storage, and remain at that level indefinitely, not being subjected to any external disturbance such as forest fire, storms, or disease.

To the best of the authors' knowledge, this is not how even undisturbed forests exist over time. Here is output from the forest model that Botkin developed and a version of which is used by all the authors for simulating the growth of a forest from clearing or undisturbed state for several thousand years (fig. 3).

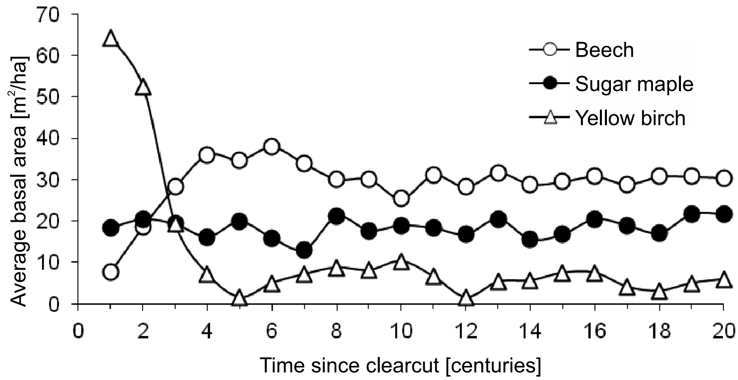


Source: Botkin et al. [1973]

Fig. 3. Computer simulation of long-term forest growth. Two long-term predictions of average basal area per plot of the model at 610 m elevation. Each line represents the average of 100 plots with identical site conditions, including a deep, well-drained soil and constant climate, but starting with different pseudo-random numbers

The model forecasts that the basal area, which is a good indicator of biomass and carbon storage, increases rapidly at first to a maximum, and then declines [Botkin et al. 1972; Botkin 1993; Botkin 2013]. For the North American eastern deciduous forests, which are modeled here, the maximum occurs between the first and second century after clearing. Thereafter, the forest never remains in a constant state, but varies over a range, which is considerably lower than the maximum. In the case shown, the long-term value averages approx. 70% of the maximum, while the variation over the long-term ranges from approx. 55% to 78%. Note that one can talk about the persistence of carbon storage around a mean value. Since the model involves stochastic birth and death, there are some random variations, but within a zone.

The early successional species are highly productive and rapidly growing (fig. 4). Yellow birch in particular adds biomass rapidly. Meanwhile, in the understory, sugar maple and American beech add more biomass to the forest, but more slowly than yellow birch. The forest maximum occurs at approx. 200 years, when there are many mature yellow birch and some sugar maple and American beech. But then yellow birch and the other early and mid-successional species are much diminished, and the shade-tolerant species become dominant.



Source: Botkin et al. [1973]

Fig. 4. Graphs for three species in the computer simulation of long-term forest growth: yellow birch, an early to mid-successional species, and sugar maple and American beech, which are characteristic of older forests. These show why this maximum and the decline in fig. 3 occur

Short-term forest dynamics influence carbon storage

It is commonly assumed that late stages in forest succession change little if at all and if there is change, it occurs very slowly. Remote sensing of successional stages in the boreal forest contradicts these assumptions. Landsat images ten years apart were used for two large study areas: the boreal forest in the U.S. Boundary Waters Canoe Area (BWCA), 4046.9 km² (1 million acres) in northern Minnesota, bordering Canada, which has its own large wilderness, Quetico Provincial Park, Ontario, covering 4.760 km², and contiguous with the BWCA, and the adjacent U. S. Superior National Forest, which covers 12.141 km² (3 million acres). Thus, a comparison was possible between an area protected from forest logging and one in which logging had taken place and was continuing at the time of the study (fig. 5) [Hall et al. 1991].

The Landsat images were calibrated carefully against field measurements obtained by field crews. The data comprised height and diameter measurements of all trees on circular plots 60 meters in diameter, representing twice the area of a Landsat pixel. Helicopters carried the same sensor that was in the Landsat satellite, and these measurements were used to calibrate the Landsat sensor against forest conditions. There were also high altitude aircraft carrying the same sensor, and then Landsat images were captured.

It was possible to measure five distinct states of forest succession: clearings, regenerating, broadleaf only, mixed deciduous and conifer, and spruce-fir only. Landsat images of these same areas in 1977 and 1987 were then overlaid. From these it could be determined how each pixel had changed state in ten years. It is interesting that in all cases, 1973, 1983, and in the wilderness and non-wilderness, more that 55% of the forest was in the two oldest stages (table 7).

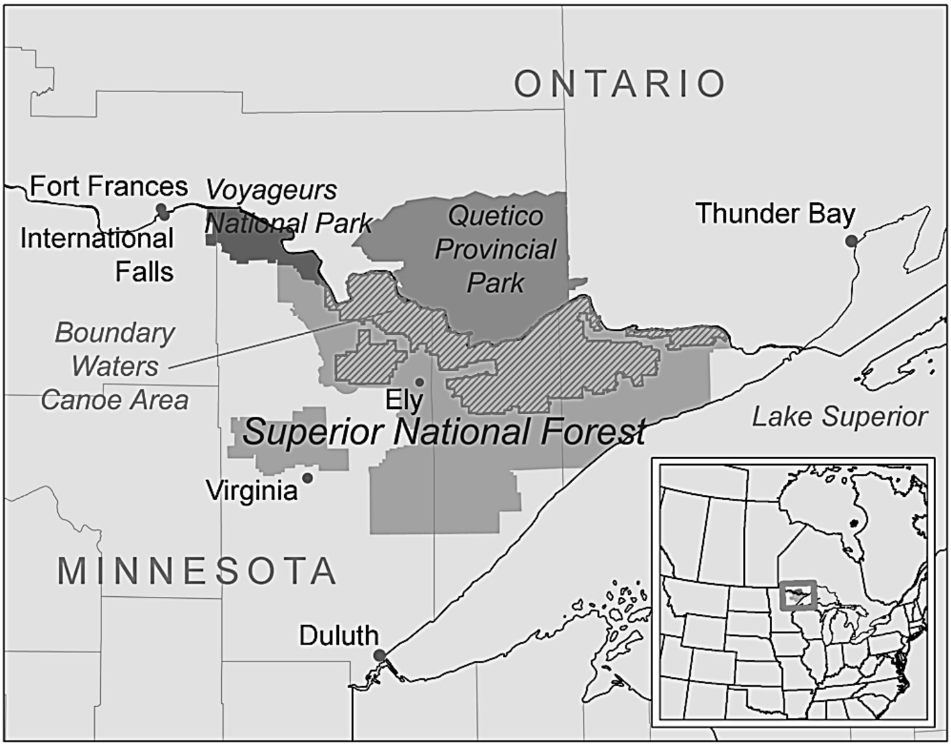


Fig. 5. Map showing the Boundary Waters Canoe Area, U.S. Superior National Forest, and Quetico Provincial Park, Ontario, Canada

Table 7. Landsat derived boreal forest areas in different successional stages, for the Boundary Waters Canoe Area and adjacent U.S. Superior National Forest

Ecological State class	Percent of land area by class*			
	1973 BWCA	1973 Superior Forest	1983 BWCA	1983 Superior Forest
	wilderness	non-wilderness	wilderness	non-wilderness
Clearings	3.91	8.95	1.93	7.35
Regeneration	11.2	15.2	13.4	22.2
Broadleaf	22.6	17.9	20.8	13.6
Mixed	37.9	33.5	40.6	35.4
Conifer	24.3	21.5	26.2	21.5
Percent mixed & conifer	62.2	55.0	66.8	56.9

*Water and clouds are omitted; hence some columns do not total 100%

As one would expect, the percentage in clearings was much higher in the national forest, where logging has been permitted, but also the most recent forest fire was concentrated in this forest rather than in the wilderness.

In the BWCA, 17% stayed as clearings and 45.54% changed to the regenerating (the second) successional stage (table 8).

Table 8. Transition matrices for Boundary Waters Canoe Area showing changes in ecological state in wilderness and surrounding non-wilderness area calculated from satellite images between 1973 and 1983. For an area of 534 km^2, with 14406 landscape elements, in protected wilderness of Boundary Water Canoe.

State	Clearings	Regenerating	Broadleaf	Mixed	Conifer	Other
Clearings	17.09	45.54	16.72	15.20	5.22	0.12
Regenerating	4.55	30.83	16.93	37.27	10.03	0.36
Broadleaf	1.12	19.72	47.06	27.61	4.16	0.28
Mixed	0.52	6.81	11.28	58.11	22.55	0.72
Conifer	1.04	4.37	1.81	31.02	57.80	3.93
Other	0.53	3.14	3.19	8.60	13.38	71.06

Diagonal elements are retention frequencies; off-diagonal are transitions from the state in column 1 to each of the states named in the adjacent columns

More than 50% of each of the two oldest stages stayed the same, but surprisingly, the rest changed state in this short time. Most of the transitions for these two stages were between one another. Thus 81% of the conifers remained in either conifer or mixed, while 80.66% of mixed remained either in conifer or mixed. But 20% of what were supposed to be old-growth stands changed to very different, much earlier successional states, in just ten years. This is a remarkably rapid rate of return to an earlier successional stage.

Conclusions

Concern over the possibility of greenhouse-induced climate change drives a need for more quantitative knowledge of the global carbon cycle, including amounts and rates of change of carbon storage in major biomes. This knowledge is fundamental to the understanding of the dynamics of Earth's biosphere, which is itself fundamental to Earth System Science. However, in spite of repeated calls by scientists that such knowledge should be obtained, terrestrial ecosystem carbon storage and exchange remain poorly documented.

It has been shown that statistically-valid estimates of carbon storage can be obtained using well-known ground-based methods, which have been used in North America and Australia. The North American results show substantially different and statistically lower carbon storage values from those widely adopted in scientific literature, while more recent studies of forests in Queensland, Australia, yield results more similar to those of the IPCC, but still different and mostly lower. Resulting mean values are considerably lower than those in wide use and the confidence interval is greater than 20% of the mean.

Furthermore, it is common to assume that forest storage of carbon can be treated as a single, scalar quantity — that forests will grow to a maximum carbon storage and remain at that storage indefinitely. Here the opposite is shown – that even in undisturbed environments, long-term forest patterns include a peak in what is usually termed late ecological succession and a continued variation within well--specified, but lower, bounds. Moreover, remote sensing of millions of pixels in the boreal forest of North America show the surprisingly rapid turnover of forest stands in just ten years. Therefore, realistic estimates of carbon storage must take into account the mean and the statistical confidence interval. It is recommended that the mean minus the confidence interval becomes the standard value for carbon sequestration offset calculations. Also, carbon storage must be planned for specific time-horizons rather than indefinite futures.

These results show that a global program using straightforward, relatively simple and consistent methods could yield far more accurate carbon storage values, and greatly improve any carbon trading, carbon sequestering, and scientific information about biomass and carbon storage and exchange.

References

Ajtay G.L., Ketner P., Duvigneaud P. [1979]: Terrestrial primary production and phytomass. In: Bolin B., Degens E.T., Kempe S., Ketner P. (ed.). The Global Carbon Cycle, J Wiley & Sons, New York: 129–182

Aldred A.H., Alemdag I.S. [1988]: Guidelines for forest biomass inventory. Petawawa National Forestry Institute, Canadian Forestry Service, Information Report PI-X-77

Ashraf M.I., Bourque C.P.-A., MacLean D.A., Erdle T., Men F.-R. [2013]: Estimation of potential impacts of climate change on growth and yield of temperate tree species. Mitigation and Adaptation Strategies for Global Change 18: DOI 10.1007/s11027-013-9484-9

Ashraf M.I., Bourque C.P.-A., MacLean D.A., Erdle T., Meng F.-R. [2012]: Using JABOWA-3 for forest growth and yield predictions under diverse forest conditions of Nova Scotia, Canada. The Forestry Chronicle 88 [6]: 708–721

Baker T.R., Phillips O.L., Malhi Y., Almeida S., Arroyo L., Di Fiore A., Erwin T., Higuchi N., Killeen T.J., Laurance S.G., Laurance W.F., Lewis S.L., Monteaguado A., Neill D.A., Vargas P.N., Pitman N.C.A., Silva J.N.M., Martinez R.V. [2004]: Increasing biomass in Amazonian forest plots. Philosophical Transactions of the Royal Society of London B 359: 353–365. DOI 10.1098/rstb.2003.1422

Beetson T., Nester M., Vanclay J. [1992]: Enhancing a permanent sample plot system in natural forests. Statistician 41 [5]: 525–538

Bonnor G.M. [1985]: Inventory of forest biomass in Canada. Canadian Forestry Service. Petawawa National Forestry Institute, Petawawa, Ontario

Botkin D.B. [1993]: Forest Dynamics: An Ecological Model, Oxford University Press

Botkin D.B. [2013]: JABOWA forest growth model software [accessed: 4.10.2013]. Available from: http://www.naturestudy.org/services/jabowa/

Botkin D.B., Janak J.F., Wallis J.R. [1970]: A simulator for northeastern forest growth: a contribution of the Hubbard Brook Ecosystem Study and IBM Research, IBM Research Report 3140, Yorktown Heights, New York: 21

Botkin D.B., Janak J.F., Wallis J.R. [1972]: Some ecological consequences of a computer model of forest growth. Journal of Ecology 60 [3]: 849–872

Botkin D.B., Janak J.F., Wallis J.R. [1973]: Estimating the effects of carbon fertilization on forest composition by ecosystem simulation. In: Woodwell G.M., Pecan E.V. (eds.): Carbon and the Biosphere. Brookhaven National Laboratory Symposium No. 24, Technical Information Center, U.S.A.E.C., Oak Ridge: 328–344

Botkin D.B., Simpson L. [1990]: Biomass of the North American boreal forest: A step toward accurate global measures. Biogeochemistry 9 [2]: 161–174

Botkin D.B., Simpson L., Nisbet R.A. [1993]: Biomass and carbon storage of North American deciduous forest. Biogeochemistry 20 [1]: 1–17

Brown S., Schroeder P., Birdsey R.A. [1997]: Above-ground biomass distribution of U.S. eastern hardwood forests and the use of large trees as indicators of forest development. Forest Ecology and Management 96 [1]: 37–47

Canadell J.G., Dhakal P.C.S., Dolman H., Friedlingstein P., Gurney K.R., Held A., Jackson R.B., Le Que're C., Malone E.L., Ojima D.S., Patwardhan A., Peters G.P., Raupach M.R. [2010]: Interactions of the carbon cycle, human activity, and the climate system: A research portfolio. Current Opinion in Environmental Sustainability 2 [4]: 301–311

Canadell J.G., Mooney H.A. [1999]: Ecosystem metabolism and the global carbon cycle. Tree 14 [6]: 249

Detwiler R.R., Hall A.S. [1988]: Tropical forests and the global carbon cycle. Science 239 [4835]: 42–47

Doley D. [1967]: Water relations of *Eucalyptus marginata* Sm. under natural conditions. Journal of Ecology 55 [2]: 597–614

Evert F. [1985]: Systems of equations for estimating oven-dry mass of 18 Canadian tree species. Petawawa National Forestry Institute, Canadian Forestry Service, Information Report PI-X-59

Gibbs H.K., Brown S., Niles J.O., Foley J.A. [2007]: Monitoring and estimating tropical forest carbon stocks: Making REDD a reality. Environmental Research Letters 2 [1]: 1–13

Gifford R. [2000]: Carbon content of woody roots: Revised analysis and comparison with woody shoot components. National Carbon Accounting System, Australian Greenhouse Office, Canberra

Gregoire T.G., Valentine H.T. [2008]: Sampling Strategies for Natural Resources and the Environment. Chapman & Hall/CRC, New York, USA

Hall F.G., Botkin D.B., Strebel D.E, Woods K.D., Goetz S.J. [1991]: Large scale patterns in forest succession as determined by remote sensing. Ecology 72 [2]: 628–640

Hanson J.C., Lorimer C.G., Halpin C.R. [2011]: Predicting long-term sapling dynamics and canopy recruitment in northern hardwood forests. Canadian Journal of Forestry Research 41 [5]: 903–919

Hollinger D.Y. [2008]: Defining a landscape-scale monitoring tier for the North American Carbon Program. C.M. Hoover (ed.) Field Measurements for Forest Carbon Monitoring, pp 3–16, Springer Science + Business Media B.V.

Hoover C.M. (ed.) [2008]: Field Measurements for Forest Carbon Monitoring, Springer Science + Business Media B.V.

Hoover C.M., Leak W.B., Keel B.G. [2012]: Benchmark carbon stocks from old-growth forests in north New England, USA. Forest Ecology and Management 266 [1]:108–114

Houghton R.A. [2005]: Above-ground forest biomass and the global carbon balance. Global Change Biology 11 [6]: 945–958

Houghton R.A., Hobbie J.E., Melillo J.M., Moore B., Peterson B.J., Shaver G.R., Woodwel G.M. [1983]: Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO2, to the atmosphere. Ecological Monographs 53: 235–262

Hu H., Wang G.G. [2008]: Changes in forest biomass carbon storage in South Carolina Piedmont between 1936 and 2005. Forest Ecology and Management 255 [5–6]: 1400–1408

Huntzinger D.N., Post W.M., Wei Y., Michalak A.M., West T.O., Jacobson A.R., Baker I.T., Chen J.M., Davis K.J., Hayes D.J., Hoffman F.M., Jain A.K., Liu S., McGuire A.D., Neilson R.P., Potter C., Poulter B., Price D., Raczka B.M., Tian H.Q., Thornton P., Tomelleri E., Viovy N., Xiao J., Yuan W., Zeng N., Zhao M., Cook R. [2012]: North American Carbon Program (NACP) regional interim synthesis: Terrestrial biospheric model intercomparison. Ecological Modelling 232[1]: 144–157. DOI: 10.1016/j.ecolmodel.2012.02.004

IPCC [2006]: International Panel on Climate Change guidelines for national greenhouse gas inventories. Eggleston H.S., Buendia L., Miwa K., Ngara, T., Tababe K. (ed.), Agriculture Forestry and Other Land Use. National gas inventories, vol. 4 IGES, Japan [accessed: 4.10.2013]. Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

Keith H., Mackey B.G., Berry S.L., Lindenmayer D.B., Gibbons P. [2010]: Estimating carbon carrying capacity in natural forests ecosystems across heterogeneous landscapes: Addressing sources of error. Global Change Biology 16 [11]: 2971–2989

Keith H., Mackey B.G., Lindenmayer D.B. [2009]: Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon-dense forests. PNAS 106 [28]: 11635–11640

King D.A., Turner D.P., Ritts W.D. [2011]: Parameterization of a diagnostic carbon cycle model for continental scale application. Remote Sensing of Environment 115 [7]: 1653–1664

Larocque G.R., Archambault L., Delisle C. [2011]: Development of the gap model ZELIG--CFS to predict the dynamics of North American mixed forest types with complex structures. Ecological Modelling 222 [14]: 2570–2583

Long C.-Y., Zhao Y., Jafari H. [2014]: Mathematical models arising in the fractal forest gap via local fractional calculus. Abstract and Applied Analysis 2014: 782393. DOI: 10.1155/2014/782393

Mackey B.G., Keith H., Berry S.L., Lindenmayer D.B. [2008]: Green carbon: the role of natural forests in carbon storage. Part 1. A green carbon account of Australia's southeastern eucalypt forests, and policy implications. Australian National University, Canberra, p. 47

Mandallaz D. [2008]: Sampling Techniques for Forest Inventories. Chapman & Hall/CRC, Boca Raton, FL, USA

Monserud R.A. [2003]: Evaluating forest models in a sustainable forest management context. Forest Biometry, Modelling and Information Sciences 1 [1]: 35–47

Moroni M.T. [2012]: Aspects of forest carbon management in Australia – a discussion paper. Forest Ecology and Management 275 [1]: 111–116

Moroni M.T., Kelley T.H., McLarin M.L. [2010]: Carbon in trees in Tasmanian State forest. International Journal of Forestry Research 2010 [690462]: 1–13. DOI: 10.1155/2010/690462

Ngugi M.R., Botkin D.B. [2011]: Validation of a multispecies forest dynamics model using 50-year growth from *Eucalyptus* forests in eastern Australia. Ecological Modelling 222 [17]: 3261–3270

Ngugi M.R., Botkin D.B., Doley D., Cant M., Kelley J. [2013]: Restoration and management of callitris forest ecosystems in Eastern Australia: Simulation of attributes of growth dynamics, growth increment and biomass accumulation. Ecological Modelling 263 [1]: 152–161

Ngugi M.R., Hunt M.A., Doley D., Ryan P., Dart P. [2003]: Dry matter production and allocation in *Eucalyptus cloeziana* and *Eucalyptus argophloia* seedlings in response to soil water deficits. New Forests 26 [2]: 187–200

Ngugi M.R., Hunt M.A., Doley D., Ryan P., Dart P. [2004]: Selection of species and provenances for low-rainfall areas: Physiological responses of *Eucalyptus cloeziana* and *Eucalyptus argophloia* to seasonal conditions in subtropical Queensland. Forest Ecology Management 193 [1–-2]: 141–156

Ngugi M.R., Johnson R.W., Mc Donald W.J.F. [2011]: Restoration of ecosystems for biodiversity and carbon sequestration: Simulating growth dynamics of brigalow vegetation communities in Australia. Ecological Modelling 222 [3]: 785–794

Olson J.S., Pfuderer H.A., Chan Y.H. [1978]: Changes in the Global Carbon Cycle and the Biosphere. ORNL/EIS-109, Oak Ridge National Laboratory, Oak Ridge, Tenn

Olson J.S., Watts J.A., Allison L.J. [1983]: Carbon in Live Vegetation of Major World Ecosystems. ORNL-5862, Oak Ridge National Laboratory, Oak Ridge, Tenn

Pretzsch H., Biber P., Dursky J., von Gadow K., Hasenauer H., Kandler G., Kenk G., Kublin E., Nagel J., Pukkala T., Skovsgaard J.P., Sodtke R., Sterba H. [2002]: Recommendations for standardized documentation and further development of forest growth simulators. Forstwissenschaflicht Centralblatt 121 [3]: 138–151

R Development Core Team [2011]: R: A language and environment for statistical computing. Vienna, Austria, R Foundation for Statistical Computing

Ribe J.H. [1979]: A study of multi-stage sampling and dimensional analysis of puckerbrush stands. The Complete Tree Institute, University of Maine, Orono. Maine, Bulletin 1

Saatchi S.S., Harris N.L., Brown S., Lefsky M., Mitchard E.T.A., Salas W., Zutta B.R., Buermann W., Lewis S.L., Hagen S., Patrova S., White L., Silman M., More A. [2011]: Benchmark map of forest carbon stocks in tropical regions across three continents. PNAS 108 [24]. DOI:10.1073/pnas.1019576108 6

Sierra C.A., del Valle J.I., Orrego S.A., Moreno F.H., Harmon M.E., Zapata M., Colorado G.J., Herrera M.A., Lara W., Restrepo D.E., Berrouet L.M., Loaiza L.M., Benjumea J.F. [2007]: Total carbon stocks in a tropical forest landscape of the Porce region, Colombia. Forest Ecology and Management 243 [2–-3]: 299–309

Smith W.B., Brand G.J. [1983]: Allometric biomass equations for 98 species of herbs, shrubs, and small trees. North Central Forest Experiment Station, St. Paul, Minnesota Research Note NC-299

Stage A.R. [2003]: How forest models are connected to reality: Evaluation criteria for their use in decision support. Canadian Journal of Forest Research 33 [3]: 410–421

Stanek W., State D. [1978]: Equations predicting primary productivity (biomass) of trees, shrubs, and lesser vegetation based on current literature. Canadian Forestry Service, Pacific Forest Research Center, Victoria, British Columbia Information Report BC-X-183

Thompson A.M., Lzaurralde R.C., Smith S.J., Clarke L.E. [2007]: Integrated estimates of global terrestrial carbon sequestration. Global Environmental Change 18 [1]: 192–302

Valentine H.T., Affleck D.L.R., Gregoire T.G. [2009]: Systematic sampling of discrete and continuous populations: sample selection and the choice of estimator. Canadian Journal of Forest Research 39 [6]: 1061–1068

Valentine H.T., Mäkelä A. [2005]: Bridging process-based and empirical approaches to modeling tree growth. Tree Physiology 25 [7]: 769–779

Whittaker R. H. [1966]: Forest dimensions and production in the Great Smoky Mountains. Ecology 47 [1]: 103–121

Whittaker R.H. [1975]: Communities and Ecosystems, MacMillan Publishing, New York

Whittaker R.H., Likens G.E. [1973]: Carbon in the biota. Woodwell G.M., Pecan E.V. (ed.) Carbon and the Biosphere, pp. 281–300. National Technical Information Center, Springfield, VA, USA

Woods K.D., Feiveson A.H., Botkin D.B. [1991]: Statistical error analysis for biomass density and leaf area index estimation. Canadian Journal of Forest Research 21 [7]: 974–989

Yamane T. [1967]: Elementary Sampling Theory. Prentice Hall, Englewood, NJ

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BIOMASS DYNAMICS IN YOUNG SILVER BIRCH STANDS ON POST-AGRICULTURAL LANDS IN CENTRAL POLAND

The paper analyses the production and allocation of biomass in young, spontaneous silver birch afforestation occurring on post-agricultural lands in the Mazowsze region (central Poland). We investigated 114 sample plots of age varying from 1 to 19 years. During the first 15 years after their establishment on abandoned farmland, the naturally regenerated silver birch stands produced on average approximately 75 tons of dry biomass per hectare. The major (50–70%) part of this biomass was stored in the tree stems and this share increased with age. The fractions of biomass in the foliage and roots decreased over time, while the share of biomass in the branches remained rather constant. The significant age-dependency of the allometric relationships suggested the need to use age-sensitive biomass expansion factors to estimate the biomass from the stem volume.

Keywords: secondary succession, afforestation, biomass allocation, silver birch

Introduction

Carbon accumulation in different ecosystems has recently become a topic of great interest. Forest biomass is considered as having a large potential for the temporary and long-term storage of carbon [Lorentz, Lal 2010; Carroll et al. 2012; Hodgman et al. 2012] and estimates of the biomass that sequesters carbon have been pre-

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sented in numerous studies [Orzeł et al. 2006; Bijak, Zasada 2007; Zasada et al. 2008, 2009; Bronisz et al. 2009; Alves et al. 2010; Ribeiro et al. 2011; Wojtan et al. 2011; Jagodziński et al. 2012; Skovsgaard, Nord-Larsen 2012; Suchanek et al. 2012; Ochał et al. 2013]. Knowledge of the carbon stocks in forests is crucial for assessing the role of these biomes in global carbon budgets. In the case of many tree species, their potential for carbon sequestration and the dynamic of this process over time is still poorly understood and misquantified.

Spontaneous natural reforestation of abandoned farmland has recently been observed in Poland as well as in other central and eastern European countries on a large scale. Fast-growing pioneer species, especially silver birch (*Betula pendula* Roth.), have appeared extensively on lands, where agricultural activity had ceased [Bernadzki, Kowalski 1983; Karlsson et al. 1998; Johansson 2007; Uri et al. 2007a, b; Hynynen et al. 2010]. The phenomenon has become more and more important as the area of such lands increased as a result of socio-economic changes that took place in these regions. Moreover, the expected high-productivity of such stands seems to be a promising source of bioenergy as far as the dwindling of non--renewable natural resources is concerned. Also their potential role in the mitigation of greenhouse gas emissions should be considered, especially considering that the European Union plans to increase the share of energy generated from renewable sources to 20% by the year 2020. The production of energy from the wood of fast--growing deciduous species is one means of achieving this goal [Hodgman et al. 2012]. However, despite the ecological and economic importance of these newly--established ecosystems, our knowledge of their dynamics is relatively limited.

The majority of studies on silver birch biomass deal with the calculation of aboveground fractions of trees [Mälkönen 1977; Johanson 1999; Claesson et al. 2001; Repola 2008; Varik et al. 2009; Strub et al. 2014]. In recent years, the scope of research has broadened and belowground biomass, as well as the allocation of carbon and nutrients in the various components, have been included in analyses [Uri et al. 2007a, b, 2012; Kuznetsova et al. 2011; Bijak et al. 2013; Varik et al. 2013]. Thus far studies on silver birch biomass in Poland have been limited and have not dealt with the dynamics of biomass fractions. The main objective of the presented study was (i) to assess the biomass of various pools (stem, branch, foliage and roots) in young silver birch stands growing on abandoned farmlands in central Poland and (ii) to model the dynamics of biomass allocation over time.

Materials and methods

Measurements were carried out in pure silver birch stands on 114 sample plots located in the Mazowsze region (central Poland) (table 1). The plots were established on former arable lands that had been abandoned. Age was determined using tree-ring analyses, and the investigated stands were classified into one of the following age classes: I – trees 1–4 years of age, II – 5–8 years of age, III – 9–12 years of age and IV – trees older than 12 years of age. Each plot was more or less rectangular in shape and located in a randomly chosen position within a given area. The plots consisted of approximately 200 trees each. Because of the very diverse spacing, a single plot area varied from 2 to 731 m^2. All the trees on the plot were measured for their diameter at 0.0, 0.5 and 1.3 m above ground level, and a sample of 50 individual trees was measured for total tree height. Height-diameter curves were elaborated based on breast height diameter (DBH), or other diameters in cases where DBH was not present. Such curves were determined for each plot and used to calculate the height of each tree.

Table 1. Basic characteristics of sample plots

Age class		Plot area [m^2]	Stocking [trees/ha]	DBH [cm]	Height [m]
I n = 46	min.	2	27297	0.22	0.15
	m	18	194078	0.57	1.14
	max.	74	1555556	1.40	3.02
	SD	14	249641	0.34	0.64
II n = 30	min.	16	4680	0.20	0.34
	m	83	45695	2.02	3.50
	max.	359	165000	4.60	6.06
	SD	78	36849	0.95	1.43
III n = 22	min.	53	2926	2.01	3.81
	m	239	12047	4.72	7.65
	max.	731	31746	8.35	10.65
	SD	147	7976	1.64	1.81
IV n = 16	min.	173	3200	3.61	6.59
	m	315	7910	5.70	9.18
	max.	645	12644	7.99	12.39
	SD	151	2926	1.34	1.72

min. – minimum, m – mean, max. – maximum, SD – standard deviation, n – number of plots

We used allometric equations elaborated by Strub et al. [2014] to calculate the biomass of the basic components (stems, branches, foliage and roots) as well as aboveground and total stand biomass (table 2). Separate equations were used for the trees with a height above and below 1.3 m, i.e. equations based on the diameter and height or height alone, respectively. To assess the temporal dynamic of these attributes in the investigated stands, we determined the system of equations that describes changes in the components' biomass over time. As the power function is thought to suit allometric relationships the best [Payandeh 1981], it is used to approximate them the most often [Zianis et al. 2005]. For this reason, this concept was adhered to and a general formula was applied to all the biomass components investigated:

$$B_i = b_{i1} \cdot a^{b_{i2}} \quad (1)$$

where: B_i – biomass [Mg/ha] of i^{th} component (stems, branches, foliage, roots),
a – stand age [years],
b_{i1}, b_{i2} – parameters in equations for individual components.

Table 2. Biomass [Mg/ha] of individual components, aboveground part of trees (AGB) and total stand biomass with regard to age class (I – 1–4 years, II – 5–8 years, III – 9–12 years, IV – above 12 years)

Age class		Stem [Mg/ha]	Branches [Mg/ha]	Foliage [Mg/ha]	Roots [Mg/ha]	AGB [Mg/ha]	Total [Mg/ha]
I n = 46	min.	2.31	0.16	0.24	0.23	0.63	0.86
	m	2.67	0.78	1.12	1.38	4.56	5.94
	max.	8.52	1.88	2.79	4.98	12.86	17.47
	SD	2.38	0.44	0.58	0,90	3.27	4.03
II n = 30	min.	0.38	0.08	0.06	0.12	0.51	0.64
	m	14.98	2.70	1.87	3.95	19.56	23.51
	max.	41.09	6.66	3.47	8.90	51.23	60.12
	SD	9.78	1.58	0.84	2.10	12.02	13.94
III n = 22	min.	6.07	1.12	0.44	1.42	7.63	9.06
	m	39.44	6.79	2.38	8.18	48.61	56.79
	max.	79.22	13.84	4.11	16.54	97.18	113.72
	SD	17.92	3.04	0.75	3.53	21.58	25.02
IV n = 16	min.	14.54	2.36	1.06	2.82	17.96	20.77
	m	51.59	8.76	2.70	10.39	63.04	73.43
	max.	76.03	12.82	3.93	15.05	92.44	107.49
	SD	16.34	2.77	0.69	3.27	19.58	22.70

min. – minimum, m – mean, max. – maximum, SD – standard deviation, n – number of plots, AGB – aboveground biomass

The goodness-of-fit of the individual equations was assessed based on Akaike's Information Criterion (AIC), coefficient of determination (R^2) and residual standard error (RSE). To address the logical concept of additivity of the biomass equations on the plot level, the seemingly unrelated regression (SUR) was applied to determine parameters in the following model of total stand biomass:

$$B_{total} = B_{stem} + B_{branches} + B_{foliage} + B_{roots} = b_1 \cdot a^{b_2} + b_3 \cdot a^{b_4} + b_5 \cdot a^{b_6} + b_7 \cdot a^{b_8} \quad (2)$$

where: B_{total} – total stand biomass [Mg/ha],
a – stand age [years],
$b_1, \ldots, b_8$ – complex model parameters.

The parameters of all the components and the total stand biomass model were estimated using the systemfit package [Henningsen, Hamann 2006] of R software [Ihaka, Gentlemen 1996].

Results and discussion

Table 3 presents the parameters of the models (equation (1)) which enabled a calculation of the biomass of individual biomass pools using the stand age as a predictor. The applied power function estimated the component biomass quite well except in the case of foliage ($R^2 < 50\%$).

Table 3. Parameters (b_{i1} and b_{i2}) of equation (1) and goodness-of-fit measures for biomass of individual components

Biomass components	b_{i1}	b_{i2}	AIC	R^2	RSE
Stem	0.93890	1.53793	871.0253	0.7560	10.8474
Branches	0.20866	1.43398	466.3502	0.7429	1.8386
Foliage	0.67226	0.53456	239.8033	0.4627	0.6807
Roots	0.40890	1.24100	512.3864	0.7083	2.2499

b_{i1}, b_{i2} – parameters in equation (1) variants for individual component, AIC – Akaike's Information Criterion, R^2 – coefficient of determination, RSE – residual standard error

The total stand biomass model for young silver birch stands on post-agricultural lands, developed using the SUR approach, can be expressed in its final form derived from the equation (2):

$$B_{total} = 1.10204 \cdot a^{1.47366} + 0.25639 \cdot a^{1.35085} + 0.75334 \cdot a^{0.4864} + 0.5099 \cdot a^{1.15122} \quad (3)$$

where: a – stand age (years), and consecutive parts of the formula correspond to biomass of stems, branches, foliage and roots, respectively.

All the parameters of this model were significant. The coefficient of determination (R^2) equalled 0.6085, which means that almost 61% of the biomass variance could be explained by the diversity of the stand age. Moreover, it suggests that there are other important factors (e.g. soil conditions, climate, water availability) that are responsible for the remaining part of the biomass variability.

In general the findings concerning the production and allocation of biomass in young silver birch stands on post-agricultural lands are consistent with data presented for similar study objects in Sweden [Johansson 1999, 2007], Finland [Hytönen et al. 1995] and Estonia [Uri et al. 2007a, b, 2012; Aosaar, Uri 2008; Varik et al. 2009] as well as for other species [Vanninen et al. 1996; Helmisaari et al. 2002; Peichl, Arain 2006, 2007; Walle et al. 2007; Aosaar, Uri 2008; Varik et al. 2009; Genet et al. 2010; Kuznetsova et al. 2011]. The biomass of all the analysed components increased in the silver birch stands investigated along with stand age (fig. 1). The most rapid growth was observed for the stem biomass and, as a result, for aboveground and total biomass. The foliage constituted the smallest fraction of the total biomass of the analysed stands, while the biomass allocated to the roots and to the branches constituted rather similar fractions (fig. 2).

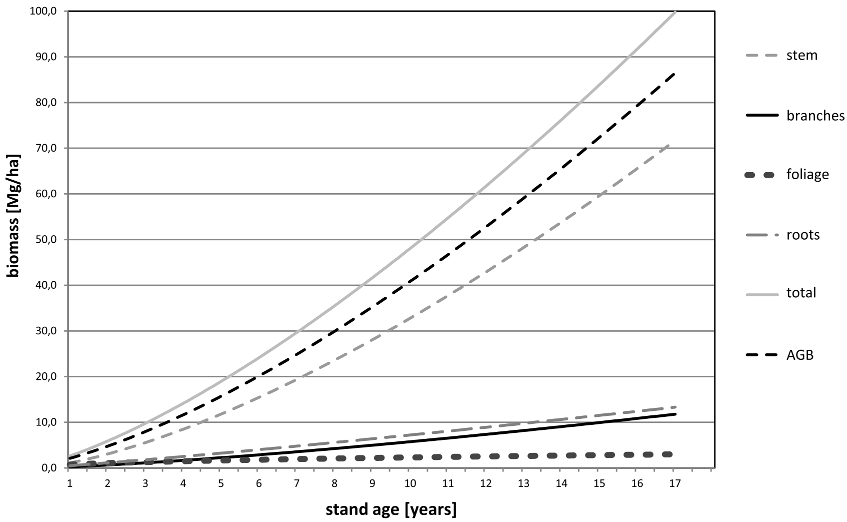

Fig. 1. Age-related changes in biomass of various pools in young silver birch stands on post-agricultural lands in central Poland

AGB – aboveground biomass

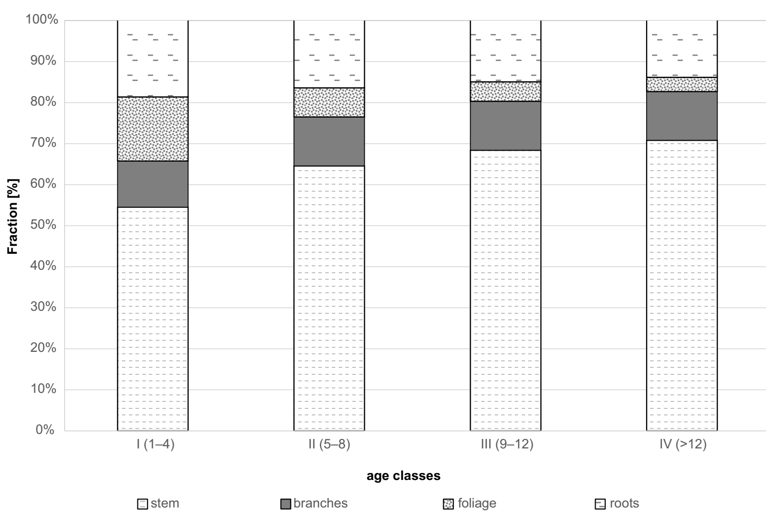

Fig. 2. Age-related changes in fraction of various pools in total stand biomass in young silver birch stands on post-agricultural lands in central Poland

The productivity of young silver birch afforestation observed in central Poland is similar to the amount of biomass found in other parts of Central and Eastern Europe. In 8-year-old natural silver birch stands growing on abandoned agricultural land in Estonia, Uri et al. [2007a] reported the aboveground biomass equal to 31.2 Mg/ha, which is very close to this study's observations, which amounted to 29.93 Mg/ha. In other studies performed in silver birch stands of that age and located in various places in Estonia, Uri et al. [2007b] showed a slightly lower biomass than found in this study. The stem biomass was reported to be from 3.79 to 15.65, the branches from 1.34 to 4.22, the leaves from 0.81 to 3.91, and the total aboveground biomass from 6.02 to 22.78 Mg/ha, while in this study the respective average values were 23.61, 4.25, 2.07 and 29.93 Mg/ha. Uri et al. [2012] investigated the allocation of aboveground biomass in a chronosequence (6, 14, 13, 18 years) of silver birch stands growing on fertile sites in Estonia. The aboveground biomass equalled 25.7, 39.9, 67.6 and 81.3 Mg/ha, respectively. These values are higher than observed in the stands analysed in Poland (table 2). The stem biomass reported by Uri et al. [2012] ranged from 18.2, to 72.3 Mg/ha, which is also relatively high compared to the amounts found in this study. The research presented in this paper, however, was performed on rather poor soils. In turn, according to Johansson [1999] the aboveground biomass of silver birch stands on post-agricultural areas in Sweden, amounted to 5.7–55.7 Mg/ha at 7–11 years of age, while the plots in this research contained from 0.51 to 97.18 Mg/ha at 5–12 years of age.

The dynamics of biomass do not only concern the absolute amount of biomass accumulated in various parts of trees, but also applies to its relative allocation, because the fractions of the various components within the total biomass also change over time (fig. 2). The age-dependence of biomass allocation has been reported for various species [Peichl, Arain 2006, 2007; Aosaar, Uri 2008; Varik et al. 2009; Genet et al. 2010; Kuznetsova et al. 2011]. In the silver birch stands investigated in central Poland, the share of stem biomass within the total stand biomass was the highest among the analysed components and increased with stand age. The fraction of roots and foliage decreased, while the amount of branch biomass remained rather constant. These findings are quite consistent with other studies regarding young silver birch afforestation from other countries. Johansson [1999] observed that stem biomass constituted 61–90% of the aboveground biomass in stands at 8–32 years of age. Uri et al. [2007b] found the production of stems accounted for 62.4% of the total biomass in 8-year-old stands. In 14-year-old birch afforestation in Estonia, Varik et al. [2009] observed 78% of aboveground biomass allocated to the stems. The significant change in the contribution of stem biomass to the aboveground or total tree biomass occurring with tree age was observed by Peichl and Arain [2006] in a white pine chronosequence in southern Ontario, Canada. These findings suggest the need to use age-sensitive biomass expansion factors in order to achieve precise estimates of total aboveground biomass from stem volume data. Biomass allocation to the roots decreases slightly over the time, which results from the shift in the "growth policy" of a plant which no longer needs to invest in spreading out and an effective root system [Bijak et al. 2013]. Johansson [2007] observed a similar pattern of biomass allocation to that found in this study, however, he also found that the total biomass of 12-year-old silver birch stands and its fractioning was greatly affected by initial spacing. Similar findings were presented by Claesson et al. [2001]. Among other factors that influence biomass production and allocation, various authors name site fertility [Peichl, Arain 2007; Uri et al. 2012], soil conditions [Johansson 1999, 2007] and nutrient content [Kuznetsova et al. 2011].

Conclusions

During the first 15 years after their establishment on abandoned farmland, naturally regenerated silver birch stands in central Poland could produce on average approximately 75 tons of dry aboveground biomass per hectare. The major (50–70%) part of this biomass was stored in the tree stems and this share increased with age. The fractions of foliage and roots decreased over time, while the share of branches remained constant. The significant age-dependency of allometric relationships suggested the necessity of using age-sensitive biomass expansion factors to estimate the biomass from stem volume data.

References

Alves L.F., Vieira S.A., Vieira M.A., Scaranello P.B., Camargo F.A.M., Santos C.A., Joly L.A. [2010]: Forest structure and live aboveground biomass variation along an elevational gradient of tropical Atlantic moist forest (Brazil). Forest Ecology and Management 260: 679–691

Aosaar J., Uri V. [2008]: Biomass production of grey alder, hybrid alder and silver birch stands on abandoned agricultural land. Forestry Studies 48: 53–66. DOI: 10.2478/v10132-011-0055-0

Bernadzki E., Kowalski M. [1983]: Brzoza na gruntach porolnych (Silver birch on post-agricultural lands). Sylwan 127 [12]: 33–42

Bijak Sz., Zasada M. [2007]. Oszacowanie biomasy korzeni w drzewostanach sosnowych Borów Lubuskich (Assessment of the belowground biomass in Scots pine stands of Bory Lubuskie). Sylwan 151 [12]: 21–29

Bijak Sz., Zasada M., Bronisz A., Bronisz K., Czajkowski M., Ludwisiak Ł., Tomusiak R., Wojtan R. [2013]: Estimating coarse roots biomass in young silver birch stands on post-agricultural lands in central Poland. Silva Fennica 47 [2] article id 963

Bronisz K., Bronisz A., Zasada M., Bijak Sz., Wojtan R., Tomusiak R., Dudek A., Michalak K., Wróblewski L. [2009]: Biomasa aparatu asymilacyjnego w drzewostanach sosnowych zachodniej Polski (Biomass of assimilation apparatus in Scots pine stands of western Poland). Sylwan 153 [11]: 758–767

Carroll M., Milakovsky B., Finkral A., Evans A., Ashton M.S. [2012]: Managing carbon sequestration and storage in temperate and boreal forests. In: Ashton M.S., Tyrrell M.L., Spalding D., Gentry B. (eds.). Managing forest carbon in a changing climate. Springer, Dordrecht, Heidelberg, London, New York: 205–226. DOI:10.1007/978-94-007-2232-3_5

Claesson S., Sahlén K., Lundmark T. [2001]: Functions for biomass estimation of young Pinus sylvestris, Picea abies and Betula spp. from stands in northern Sweden with high stand densities. Scandinavian Journal of Forest Research 16: 138–146

Genet H., Bréda N., Dufrêne E. [2010]: Age-related variation in carbon allocation at tree and stand scales in beech (*Fagus sylvatica* L.) and sessile oak (*Quercus petraea* (Matt.) Liebl.) using a chronosequence approach. Tree Physiology 30 [2]: 177–192. DOI:10.1093/treephys/tpp105

Helmisaari H.-S., Makkonen K., Kellomäki S., Valtonen E., Mälkönen E. [2002]: Below- and aboveground biomass, production and nitrogen use in Scots pine stands in eastern Finland. Forest Ecology and Management 165: 317–326

Henningsen A., Hamann J. [2006]: Systemfit: A package to estimate simultaneous equation systems in R.

Hodgman T., Munger J., Hall J.S., Ashton M.S. [2012]: Managing afforestation and reforestation for carbon sequestration: considerations for land managers and policy makers. In: Ashton M.S., Tyrrell M.L., Spalding D., Gentry B. (eds.). Managing forest carbon in a changing climate. Springer, Dordrecht, Heidelberg, London, New York: 227–256. DOI:10.1007/978-94-007-2232-3_5

Hynynen J., Niemistö P., Viherä-Aarnio A., Brunner A., Hein S., Velling P. [2010]: Silviculture of birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.) in northern Europe. Forestry 83 [1]: 103–119

Hytönen J., Saarsalmi A., Rossi P. [1995]. Biomass production and nutrient uptake of short--rotation plantations. Silva Fennica 29 [2]: 117–139

Ihaka R., Gentlemen R. [1996]: R: a language for data analysis and graphics. Journal of Computational and Graphical Statistics 5 [3]: 299–314

Jagodziński A.M., Jarosiewicz G., Karolewski P., Oleksyn J. [2012]: Zawartość węgla w biomasie pospolitych gatunków krzewów podszycia leśnego (Carbon concentration in the biomass of common species of understory shrubs). Sylwan 156 [9]: 650–662

Johansson T. [2007]: Biomass production and allometric above- and below-ground relations for young birch stands planted at four spacings on abandoned farmland. Forestry 80 [1]: 41–52. DOI:10.1093/forestry/cpl049

Johansson T. [1999]: Biomass equations for determining fractions of pendula and pubescens birches growing on abandoned farmland and some practical implications. Biomass and Bioenergy 16: 223–238

Karlsson A., Albrektson A., Forsgren A., Svensson L. [1998]: An analysis of successful natural regeneration of downy and silver birch on abandoned farmland in Sweden. Silva Fennica 32 [3]: 229–240

Kuznetsova T., Lukjanova A., Mandre M., Lõhmus K. [2011]: Aboveground biomass and nutrient accumulation dynamics in young black alder, silver birch and Scots pine plantations on reclaimed oil shale mining areas in Estonia. Forest Ecology and Management 262 [2]: 56–64. DOI:10.1016/j.foreco.2010.09.030

Lorenz K., Lal R. [2010]: Carbon sequestration in forest ecosystems. Springer, Dordrecht, Heidelberg, London, New York: 288

Mälkönen E. [1977]: Annual primary production and nutrient cycle in birch stand. Communicationes Instituti Forestalis Fenniae 91 [5]: 35

Ochał W., Grabczyński S., Orzeł S., Wertz B., Socha J. [2013]: Alokacja nadziemnej biomasy u sosen zajmujących różne pozycje biosocjalne w drzewostanie (Aboveground biomass allocation in Scots pines of different biosocial positions in the stand). Sylwan 157 [10]: 737–746

Orzeł S., Forgiel M., Ochał W., Socha J. [2006]: Nadziemna biomasa i roczna produkcja drzewostanów sosnowych Puszczy Niepołomickiej (Aboveground biomass and annual production in stands of the Niepołomicka Forest). Sylwan 150 [5]: 16–32

Payandeh B. [1981]: Choosing regression models for biomass prediction equations. Forestry Chronicles 57: 229–232

Peichl M., Arain M.A. [2006]: Above- and belowground ecosystem biomass and carbon pools in an age-sequence of temperate pine plantation forests. Agricultural and Forestry Meteorology 140: 51–63

Peichl M., Arain M.A. [2007]: Allometry and partitioning of above- and belowground tree biomass in an age-sequence of white pine forests. Forest Ecology and Management 253: 68–80

Repola J. [2008]: Biomass equations for birch in Finland. Silva Fennica 42: 605–624

Ribeiro S.C., Fehrmann L., Soares C.P.B., Jacovine L.A.G., Kleinn C., de Oliveira Gaspar R. [2011]: Above- and belowground biomass in a Brazilian Cerrado. Forest Ecology and Management 262: 491–499

Skovsgaard J.P., Nord-Larsen T. [2012]: Biomass, basic density and biomass expansion factor functions for European beech (*Fagus sylvatica* L.) in Denmark. European Journal of Forest Research 131: 1035–1053

Strub M., Cieszewski Ch. J., Bijak Sz., Bronisz K., Bronisz A., Tomusiak R., Wojtan R., Zasada M. [2014]: Equations for aboveground biomass of Betula pendula growing on former farmland in central Poland. Forest Science [in review]

Suchanek A., Socha J., Chwistek K. [2012]: Biomasa i roczna produkcja drzewostanów Ojcowskiego Parku Narodowego (Biomass and annual production of forest stands in the Ojcowski National Park). Sylwan 156 [6]: 451–462

Uri V., Lõhmus K., Ostonen I., Tullus H., Lastik R., Vildo M. [2007a]: Biomass production, foliar and root characteristics and nutrient accumulation in young silver birch (*Betula pendula* Roth.) stand growing on abandoned agricultural land. European Journal of Forest Research 126 [4]: 495–506. DOI:10.1007/s10342-007-0171-9

Uri V., Vares A., Tullus H., Kanal A. [2007b]: Above-ground biomass production and nutrient accumulation in young stands of silver birch on abandoned agricultural land. Biomass and Bioenergy 31: 195–204

Uri V., Varik M., Aosaar J., Kanal A., Kukumägi M., Lõhmus K. [2012]: Biomass production and carbon sequestration in a fertile silver birch (*Betula pendula* Roth) forest chronosequence. Forest Ecology and Management 267: 117–126. DOI:10.1016/j.foreco.2011.11.033

Vanninen P., Ylitalo H., Sievänen R., Mäkelä A. [1996]: Effects of age and site quality on the distribution of biomass in Scots pine (*Pinus sylvestris* L.). Trees 10: 231–238

Varik M., Aosaar J., Ostonen I., Lõhmus K., Uri V. [2013]: Carbon and nitrogen accumulation in belowground tree biomass in a chronosequence of silver birch stands. Forest Ecology and Management 302: 62–70. DOI:10.1016/j.foreco.2013.03.033

Varik M., Aosaar J., Uri V. [2009]: Biomass production in silver birch stands in Oxalis site type. Forestry Studies 51: 5–16. DOI: 10.2478/v10132-011-0073-y

Walle I.V., Camp N.V., Casteele L.V., Verheyen K., Lemeur R. [2007]: Short-rotation forestry of birch, maple, poplar and willow in Flanders (Belgium) I – Biomass production after 4 years of tree growth. Biomass and Bioenergy 31: 267–275

Wojtan R., Tomusiak R., Zasada M., Dudek A., Michalak K., Bijak Sz., Bronisz K. [2011]: Współczynniki przeliczeniowe suchej biomasy drzew i ich części dla sosny pospolitej (*Pinus sylvestris* L.) w zachodniej Polsce (Trees and their components biomass expansion factors for Scots pine (*Pinus sylvestris* L.) of western Poland). Sylwan 155 [4]: 236–243

Zasada M., Bronisz K., Bijak Sz., Dudek A., Bruchwald A., Wojtan R., Tomusiak R., Bronisz A., Wróblewski L., Michalak K. [2009]: Effect of the cutting age and thinning intensity on biomass and carbon sequestration–the Gubin Forest District case study. Folia Forestalia Polonica seria Forestalia 51: 138–144

Zasada M., Bronisz K., Bijak Sz., Wojtan R., Tomusiak R., Dudek A., Michalak K., Wróblewski L. [2008]: Wzory empiryczne do określania suchej biomasy nadziemnej części drzew i ich komponentów (Empirical formulae for determination of the dry biomass of aboveground parts of the tree). Sylwan 152 [3]: 27–39

Zianis D., Muukkonen P., Mäkipää R., Mencuccini M. [2005]: Biomass and stem volume equations for tree species in Europe. Silva Fennica Monographs. Finnish Society of Forest Science, Finnish Forest Research Institute

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BIOENERGY INNOVATIONS AND THEIR DETERMINANTS: A NEGATIVE BINOMINAL COUNT DATA ANALYSIS

The research employed a negative binominal count data model approach to analyse the determinants of bioenergy innovations with a special focus on the effect of energy and climate policies. A panel of 14 OECD countries were analysed using patent counts for the period 1978–2009 as a proxy for innovations. The policies examined were feed-in tariffs, quota obligations and different types of investment support schemes. The study found that feed-in tariffs affected innovation positively but quota obligations did not. The results regarding investment support programs were ambiguous since the dummy variable representing strong investment policies was statistically significant whereas the continuous variable for investment support schemes was not. Another finding was that electricity prices seemed to be an important determinant of innovation and that the accumulated stock of knowledge in the bioenergy sector also had a positive impact on bioenergy innovation.

Keywords: economics, renewable energy, energy policy, innovation, patent, bioenergy

Introduction

The use of bioenergy is not a novelty in global energy production. Wood, or its derivatives, has been one of the most important energy sources throughout human history. With the introduction of coal and, later on, petroleum products, the use of bioenergy in industrialized countries faded. However, in wake of the oil crises of 1973 and 1979, and lately growing concern about global warming, the need to find alternatives to traditional fossil fuels has become a high priority. In this context, bioenergy is an energy source many countries are becoming increasingly reliant on. The common arguments used for the growing use of bioenergy are rela-

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ted to climate issues, security-of-supply and, in some cases, to rural development [European Parliament 2009]. However, compared to many renewable energy sources, including bioenergy, fossil fuels still have cost advantages due to, for example, economies of scale, path dependencies in energy systems and a higher level of technological maturity [Neuhoff 2005]. Nevertheless, bioenergy is beneficial for energy production in the sense that it is readily available in many countries, not only in the form of wood materials or the cultivation of perennial crops, but also as by-products from forestry, agriculture and industrial processes. There is also the potential for energy extraction from municipal waste. In addition, since many of the areas of bioenergy technology are relatively immature, additional benefits might arise for first movers, for example, a country becoming an exporter of bioenergy-related technology. Thus, in addition to climate issues, security-of-supply and rural development arguments, the innovation aspect of bioenergy technologies might bring further benefits for a country.

Innovation is also a key factor in the development and deployment of bioenergy technology. Lower operating costs by continuous improvements in existing technology and the development of new technologies are results of the innovation process. Both aspects are necessary in order to increase the competitiveness of bioenergy and to make it a reliable substitute for fossil fuels. To speed up the deployment and development of bioenergy technologies, a variety of public support schemes such as feed-in tariffs, renewable energy quotas, investment support schemes, tax support schemes and guaranteed electricity purchase obligations have emerged during the last three decades. However, the purpose of most of these related policy schemes has not explicitly been to stimulate innovation, but rather to achieve goals related to energy self-reliance and the mitigation of carbon emissions. One of the first policy measures introduced was publicly financed research development and demonstration (RD&D) [IEA 2004]. This type of support for research on bioenergy started in the mid to late 1970s and has increased considerably since then. For instance, the total annual sum of bioenergy RD&D in the 14 countries included in this study rose from 75 to 611 million USD between 1978 and 2010 (USD in 2012).

The effect of different policy schemes on innovation has been theoretically and empirically investigated in a number of earlier studies [e.g. Lanjouw, Mody 1996; Jaffe, Palmer 1997; Brunnermeier, Cohen 2003; Walz et al. 2008; Johnstone et al. 2010; Noailly, Batrakova 2010; Rübbelke, Weiss 2011]. The majority of these earlier studies focused on the effect of environmental regulations, i.e., policies designed to increase the cost of economic activities that are deemed environmentally harmful. Another approach investigated commonly used support schemes and modeled the intensity of the implemented support. However, only Johnstone et al. [2010] considered the effect on bioenergy technology in particular. Thus, empirical knowledge on how specific policy schemes affect bioenergy related innovations is lacking. The purpose of this study was therefore to estimate and analyze the determinants of bioenergy innovations with a special focus on the effect of energy and climate policies. This was carried out for a sample of 14 countries and for the period between 1978 and 2009. The study specifically aimed to empirically test the hypothesis that innovation in bioenergy technology can be stimulated by appropriate policies or combinations thereof.

Research methodology

Patents as a proxy for innovation

A key issue in modeling policy-induced innovation is how to actually measure innovation. There is no direct measure; instead some sort of proxy must be used. One method to approximate innovation is to use either R&D expenditures or the number of scientific personnel employed. According to Rübbelke and Weiss [2011], these two proxies could be assumed to correlate with the level of innovation. However, they could hardly be seen as an output of the innovation process, but rather as an input.

Another approach is to use the number of patents as a proxy for the outcome of innovation activities. An explanation given by Griliches [1990] is that innovation could be seen as the change in accumulated knowledge (which is an indiscernible variable) and is proportional to research expenditures and other unobserved influences, such as, for example, random influential scientific discoveries. This accumulated knowledge, i.e., level of technological development, is in turn a determinant of the change in an output measure which could be, for example, growth, productivity or the stock market value of a firm or industry. These last quantities are also determined by other measurable factors such as capital-deepening and other unobservable influences. The notion here is that patents could be seen as an indicator of the change in accumulated knowledge; if knowledge is constant, no new patents should be applied for, but if knowledge is growing at a constant rate, patenting should increase at the same rate every year, and if the rate of technological change increases, the rate of patenting should increase as well. Among the alternative proxies at hand, patents have so far shown themselves to be the best indicator of the result of the innovation process [OECD 2009; Johnstone et al. 2010].

As with all proxies, patents also have some problematic properties. Popp [2003, 2005], commented on the quality aspect of an innovation when studying innovations in the United States before and after the SO_2 permit trading system was introduced. He found that the number of patents was actually higher before the 1990s. However, the effectiveness of the patented technologies, in terms of the amount SO_2 removed, was higher after trade began. This is counterintuitive to the idea that a high number of patents are equal to a high rate of growth in technological knowledge. Furthermore, not all innovations will be patented, therefore patents are not a complete measure of innovation activity. Moreover, patent practices across countries are likely to be heterogeneous and the propensity to patent may differ between countries [Johnstone et al. 2010].

As seen in fig. 1, the number of bioenergy patents increased at a slow rate from the late 1970s until the mid-90s, after which patent activity started to increase exponentially. However, the ratio between bioenergy patents and total number of patents is not that encouraging when the development for the first period between 1978 and 1996 is considered, since the share of total number of patents steadily decreased. This can be partly explained by the decline in energy prices that occurred in the 1980s and 1990s, which would have lowered the interest for bioenergy. This explanation could be valid despite the fact that oil prices were still quite high at the beginning of the 1980s. Findings by Popp [2002], for example, showed that the innovative effect of rising energy prices seemed to diminish relatively quickly after an initial price shock. The sharp increase in the number of bioenergy patents from the mid-90s until 2008 might be explained by the emergence during the 1990s of energy and climate policies related to renewable energy. Once again rising energy prices could also have played a role in the interest in bioenergy until they collapsed at the beginning of the 2008 crisis.

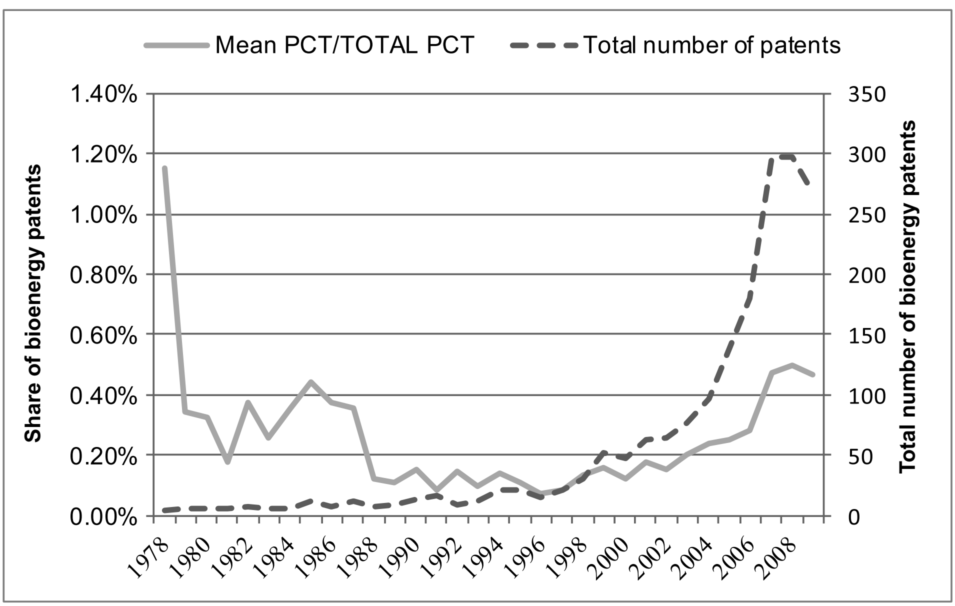

Fig. 1. Total number of patents in bioenergy technologies and its share of total number of patents between 1978 and 2009 for sample countries

Source: OECD [2013]

Determinants of innovation

In Jaffe et al. [2000], two major strands in literature were identified concerning the determinants of innovation. One was the evolutionary approach, and the other the investment-subject-to-market-failure approach. The evolutionary model builds on bounded rationality first formulated by Simon [1947]. In this paradigm, firms base their R&D decisions on rules of thumb and routines rather than on optimization. This behavior arises as a consequence of imperfect information [Simon 1947; Nelson, Winter 1982; Jaffe et al. 2000]. A theoretical framework that could be attributed to the latter approach (from now on called the investment approach), and used in this study, is what has been named price-induced technical change [Hicks 1932]. In this paradigm, as well as in the investment approach in general, R&D decisions are based on firms' efforts to maximize their profits. Accordingly, changes (or expected changes) in relative prices should stimulate inventions towards the reduced use of the more expensive factor of production [Newell et al. 1999; Popp 2002]. The notion of price-induced technical change can be further incorporated into a three-dimensional innovation space, where innovation is a function of what Jaffe [1986] and Popp [2002] called supply and demand-side factors.

Supply-side factors in induced innovation were defined by Popp [2002] as those factors that constitute the technological opportunity for innovators to succeed in creating new knowledge. Technological change is not only seen as a function of changes in relative prices for inputs, but also of previous investment in R&D and the accumulated knowledge stock. This serves as a proxy for earlier scientific advancements, making further discoveries easier (in absolute numbers). An early formulation of the concept was made by Scherer [1965] and Schmookler [1966]. Early R&D policies in the 1970s were designed using this understanding.

In a similar way to supply-side factors, Popp used the concept of demand-side factors, or market variables, to represent factors that will induce innovation by increasing the value of new innovations [Popp 2002]. Thus, price-induced innovation is embraced by this definition of input prices and market demand of output. The role of policy here is to change the relative prices of the output from renewable energy sources with regard to conventional fossil-based energy generation.

Energy and climate policy determinants

The policy areas of renewable energy and climate change are relatively new, even though interest in the latter was originally awakened after the oil crisis in the 1970s. In order to understand the fundamentals of policy areas and their connection to bioenergy, a short description of the technological properties with economic relevance for renewable energy production is needed. Neuhoff [2005] argued that network externalities are one of the major obstacles to restructuring energy production in the industrialized world. An example of such could be the infrastructure built around petrol- and oil use, where the value of having a petrol-driven car or any other type of oil-consuming technical devise increases if many other people are also using the same type of technology. The necessary technological support and infrastructure will be more widespread as a consequence. Energy systems also exhibit a strong characteristic of lock-in[1] to established technologies, caused by factors such as economies of scale, market-place barriers, accumulated learning--by-doing and learning-by-using of established technologies. Finally, energy systems tend to involve large-scale products and investments which last decades. For all these reasons energy systems themselves may be highly path dependent – future economic possibilities depend on previous decisions and patterns of investment. According to Neuhoff [2005], the abovementioned properties are the theoretical justification for many of the renewable energy policy measures that have been in use in the last 25 years. Up-front capital subsidies or investment tax deductions provide public financial support for the initial investment which otherwise would not be undertaken since investors discount rates are too high for renewable energy projects to break even. Contracts ensuring stable energy prices guaranteed at the level of retail tariffs (feed-in tariffs) also remove or alleviate some uncertainty bias. Public funding or subsidizing also mitigate the disproportionately high transaction costs for risk management tools which result from small-scale properties that often signify renewable energy projects. Neuhoff [2005] also emphasized that as technologies improve and the scale of deployment increases, it is of importance to support the actual power produced rather than the investments, in order to reward performance instead of simply installed capacity.

Different categories of implemented policies have been identified, e.g., general framework policies, direct short-term investment subsidies or R&D support. Some are designed to target renewable energy in general while others are aimed specifically at bioenergy. Empirically, there are only a few studies that have analysed the impact of energy and climate policies on the innovative performance of renewable energy [e.g. Walz et al. 2008; Johnstone et al. 2010; Noailly, Batrakova 2010; Rübbelke, Weiss 2011]. The general finding is that certain policies are more effective than others depending on energy technology. Targeted subsidies such as feed--in tariffs are more efficient in stimulating innovations in newly-emerged and less developed technologies with high operating costs, while more general policies such as quota obligations with tradable green certificates stimulate innovations in mature technologies that have already been subject to innovation and learning-by-doing cost improvements [Johnstone et al. 2010] – the latter in particular as producers always seek to comply with a regulation in the cheapest possible way. Since bio-

[1] Lock-in is closely related to path dependence. See for example Arthur et al. [1987] or David [2001] for a detailed explanation of the concept.

energy comprises many different technologies with varying degrees of maturity, it could be argued that both feed-in tariffs as well as quotas might be determinants of innovation for this energy field.

Feed-in tariffs (FIT) in this study were defined as they were by Sijm [2002] as "the regulatory, minimum guaranteed price per kWh that an electricity utility has to pay to a private, independent producer of renewable power fed into the grid"[2]. The extra cost of the guaranteed price is in most policy regimes passed on to consumers via the electricity bill. Fig. 2 depicts the development of the average feed-in tariff for the sample countries and for the time period 1978–2010. The first feed-in tariff was introduced in 1991 in Germany, Switzerland and the UK, and had an average value of 0.021 USD per kWh (at 2005 prices). By 2010, the average feed-in tariff had risen by 319% to 0.088 USD per kWh (at 2005 prices) [Cerveny, Resch 1998; IEA 2011, 2013].

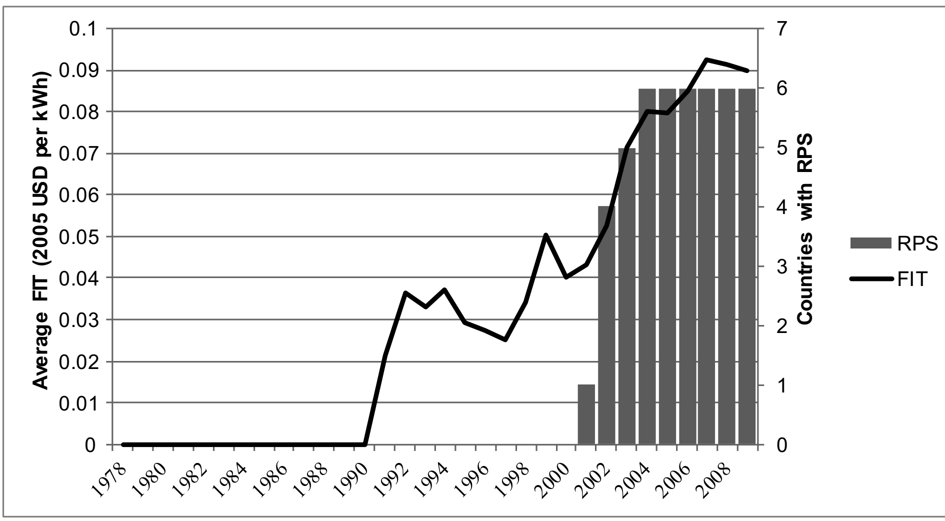

Fig. 2. Average feed-in tariffs and countries with RPS schemes between 1978 and 2009 for sample countries

Source: IEA [2011]

Two countries where feed-in tariffs have been used intensively are Germany and Spain. These countries are also representative of the different ways to im-

[2] The levels of feed-in tariffs are sometimes based on avoided costs of using non-renewable power when generating electricity and sometimes the feed-in tariffs may be fixed without any direct relation to the avoided costs. Feed-in tariffs may be guaranteed for certain time periods and are sometimes differentiated with respect to renewable energy technologies such as solar photovoltaic, biomass and wind [Sijm 2002; Campoccia et al. 2009]. Moreover, sometimes the tariffs may also be differentiated on the basis of when (time or season) the electricity is fed into the grid.

plement feed-in tariffs. In Germany, the fixed price tariff has mainly been used. Under this design, the renewable energy producer is guaranteed a settled remuneration per kWh fed into the grid. Fixed tariffs can be adjusted to inflation or have a fixed nominal value. The latter suggests that the value of the tariff will be reduced over time. This diminution could be further increased by an annual discount off the tariffs, the so-called front-end loaded tariff, which is the system that was used in Germany between 2000 and 2009 [Busch et al. 2010; Couture, Gagnon 2010; IEA 2011, 2013]. In Spain, the premium price tariff has been a commonly used mechanism to reward renewable energy production. Under this policy, a premium is paid in addition to the market price for electricity. These market-dependent feed-in tariff schemes come with a set of different features. The simplest form is the premium price model which offers a constant premium on top of the market price. A more modern tariff construction used in Spain today is the variable premium tariff where the premium varies within certain boundaries according to the market price. The purpose of this construction is to avoid windfall profits in the case of sharply increasing market prices, but also to reduce risk in the event that the market price drops heavily [Couture, Gagnon 2010]. A feed-in tariff does not necessarily mean that the guaranteed payment to a renewable energy producer has to be higher than the prevailing market price at every single moment in time. The first feed-in tariff in Germany, the electricity feed-in tariff law 1991, based its level of remuneration on a percentage of the mean market price of electricity for the previous year. Denmark and Spain also used this type of policy construction earlier. Due to the great element of randomness in this remuneration scheme, it has today been abandoned in favor of other more up-to-date tariff designs [Couture, Gagnon 2010].

Quota policies are often deployed in the form of renewable portfolio standards (RPS). A quota is set for the amount of renewable energy within the total energy production, which energy distributors are obliged to fulfill. This policy is sometimes combined with a certificate trading regime called tradable green certificates (TGC). In a TGC scheme, the quota can be fulfilled either through renewable energy production (in cases where utilities produce their own energy) or by buying certificates from an external accredited generator [IEA 2004]. As with the feed-in tariffs, the cost of certificates (in the instance of non-renewable energy generation) is ultimately born by the electricity consumers. Often a TGC regime guarantees a minimum buy-back price of the certificates if an excessive amount of renewable energy were to be produced for the regular market. In fig. 2 the number of countries within the sample using quota policies is presented. Renewable portfolio standards and quota policies were introduced later than feed-in tariffs. They were first implemented in Austria in 2001 and nine years later RPSs were also implemented in Belgium, Italy, Japan, Sweden and the UK [IEA 2011].

Investment support policies could for example be grants or low-interest loans provided to cover the investment costs of bioenergy production capacity. In some instances, investment support schemes cover the whole investment cost. However, it is more usual that the support only covers a certain percentage of the total investment cost [IEA 2004, 2011]. Investment support programs could also be directed towards research and demonstration facilities with the purpose of helping immature technology become commercially viable. These schemes are an older type of subsidy than feed-in tariffs and RPS, and are quite common in the bioenergy sector. Investment support programs are not a feature of liberalized energy markets in the same way as feed-in tariffs or RPS policies, even if an investment policy by definition does not exclude a design targeted towards production efficiency instead of pure installation. A distinction between R&D policies and investment support should also be made. Public subsidies of R&D activities without investment in physical production capital were not defined as investment support policies in this study. The first investment policies were implemented (among the sample countries) in Denmark with its Act on support for the utilization of renewable energy sources starting in 1981, and shortly after in Italy in 1982 with the 308/82 law (1982–1989). The Italian 308/82 law enabled public investment of 113 million USD in 295 different renewable energy projects between 1982 and 1989. The support scheme did not have a big impact on renewable energy markets due to the modest scale of the financial resources and the highly bureaucratic management of the programs [IEA 2004]. Germany started its Support of the federal states scheme in 1985. This program is managed by the federal states (Länder) in Germany and regional differences could be large. Regional support in Germany is often sector specific, e.g. it could be targeted towards the agricultural sector or a specific industry. Solar PV and biogas systems have been prioritized technologies in these regional support programs [IEA 2011]. By the late 90s, different support schemes were in use in most of the sample countries. Until the middle of the first decade of the 2000s, countries such as Canada and Finland relied entirely on investment support schemes for the bioenergy sector [IEA 2004]. In Canada, a prominent support scheme for bioenergy is the ecoEnergy program and in Finland the Biorefine technology programme for new biomass products. The Canadian ecoEnergy program is a compilation of various support schemes, targeted towards different types of bioenergy such as biomass use in power generation or biofuels for the transportation sector. The Finnish Biorefine technology programme for new biomass products was introduced in 2007 and supports pilot and demonstration plants, the development of innovative new products and co-operation between companies from different industrial clusters for innovation in biomass technology [IEA 2011].

Empirically, investment support schemes have not shown any significant impact on innovation in bioenergy but were a significant determinant for waste-to-energy technology in the study by Johnstone et al. [2010], a technological field which to some extent is included in the definition of bioenergy in this study by the inclusion of e.g. landfill gas-technology.

Model specification

In order to model innovation, a distinction has to be made between technological innovation and economically useful innovations in general [Jaffe et al. 2000]. The latter need not necessarily implicate new technology, but could be new organisational forms or even more efficient societal planning. In this study, the former definition was used.

A cornerstone of the modern theory of technological change is the trichotomy defined by Schumpeter [1934] where the process of technological change consists of three stages: (1) Invention which is the actual development of a new product or process and is normally what is intended when the word innovation is used in its more general sense. Some of the inventions may be patented while some are not; (2) Innovation is the commercialization of the new product i.e., it is made available for sale on the market and; (3) Diffusion is when an innovation becomes widely adopted by various economic agents.

The model specification, represented by equation (1), included three vectors of different types of determinants, quantified either as discrete or continuous:

$$I_{i,t} = f\,(A_{i,t}, D_{i,t}, P_{i,t}) \tag{1}$$

The specification stipulated that the count of bioenergy patents (I) in country i and time period t could be explained by a vector of policy variables (A), vector of supply-side R&D variables related to technical opportunity (D) and a vector containing the demand-side market variables (P).

The policy vector (A) included three major policy groups: feed-in tariffs (FIT), renewable portfolio standards (RPS) (i.e. renewable energy quotas) and investment subsidies. Tax policies were not explicitly included in the specification even though they are a fairly common policy instrument. The reason for that was the lack of reliable disaggregated data on tax policies used in the sample countries. The vector of RD&D variables (D) included two variables checking for the propensity to patent and the technical opportunity for bioenergy innovation. The vector of market variables (P) contained total energy consumption, the market price of electricity and the relative price between roundwood and light fuel oil.

For a proper estimation of the number of occurrences of an event, count data models such as the Poisson or negative binomial model have been suggested [Cameron, Trivedi 1998]. An event count is formally defined as a realization of a non-negative integer-valued random variable. In this model, an event count is the number of patent applications for each country respectively each year. It is assumed that the patent counts ($I_{i,t}$) follow a negative binomial distribution. Since it was quite likely that the countries investigated would differ substantially in their country-specific characteristics, the fixed-effects negative binomial model sug gested by Allison and Waterman [2002] was used in this study. That is, a negative binomial model with country-fixed effects was used for an estimation of equation (1). The downside was that it was not ruled out that the estimates would suffer from an incidental parameters problem[3]. The alternative was to use the fixed effects-model by Hausman et al. [1984], but since the conditional mean function would still be homogeneous in that model, instead there would have been what Greene [2007] names a "left-out variable problem".

The specification of the negative binominal model is given by equation (2) and (3). $E(I_{it})$ was the expected value (i.e. the mean) of the patent counts and β was a vector of coefficients. A, D and P were the vectors of determinants of innovation in the model and C was the country-fixed effects.

$$E(I_{it}) = u exp(\mathrm{x}'_{it}\beta) \tag{2}$$

where:

$$\mathrm{x}'_{it}\beta = \alpha + \beta_1 A_{it} + \beta_2 D_{it} + \beta_3 P_{it} + \delta C_i \tag{3}$$

The error term $u = \exp(\varepsilon_{it})$ was assumed to be gamma distributed.

Data

Fourteen countries in total were included in the sample (Austria, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Japan, Netherlands, Spain, Sweden, Switzerland and the United Kingdom) constituting an unbalanced panel dataset for the time period 1978–2009. The data on patents and the control variables was obtained from the OECD. The data used in the construction of the policy vector was collected from IEA [2004, 2011, 2013] and Cerveny and Resch [1998]. Moreover, various international governmental organizations and websites were consulted to extend and control the accuracy of the data used to construct the policy vector. Information on feed-in tariff levels and renewable energy quotas for specific years and countries was gathered from the latter sources in the case of missing information in the IEA database.

Patents filed under the Patent Cooperation Treaty (PCT)[4] were used as the PCT does not have the same problem of home bias as a simple count of applications made at the national patent offices might have. Furthermore, it does not have the same problems with weak timeliness, i.e., a very long delay between application and publishing that could prevail under other filings [OECD 2009]. The PCT also contains longer time-series without structural breaks than other comparable filings. Patents filed under the PCT are defined as applications sorted according to

[3] The incidental parameters problem arises in cases where the number of parameters increases with the number of observations, e.g. in short panels and n is increased by adding more cross-sectional units using individual fixed effects. This could make the estimator inconsistent [Neyman, Scott 1948].

[4] An alternative filing is the Triadic patent families.

the inventor's country of residence and priority date (earliest date in the application process). This chosen definition of included patents is based on recommendations made by OECD [2009]. The patent sample consisted of biofuel- and fuel from waste technologies given by the ECLA-classification system created by the European patent office (ECLA Y02E50/10 up to Y02E50/346 classes) and was obtained from the OECD Statistics database [2013]. In cases where total patents for a country and year were reported as a fraction (when several countries share the credit for a patent), it was rounded off to the nearest integer.

Following Moore and Ihle [1999], that a program for financial assistance must remain stable for at least ten years, two feed-in tariff variables were therefore constructed for this study: one for contracts of a minimum of 10 years or longer, and another for contracts shorter than 10 years. The feed-in tariffs were measured as continuous variables defined as USD per kWh (2005 value). The FIT variables were defined annually after an enactment or change in level. In instances when a policy was in use at the beginning of the year that it was first enacted, it was considered enabled the following year. This was based on the assumption that inventors react to active policies actually in use. In order to construct the FIT variables in a symmetric manner, policies abolished before the end of a given year were still counted as in use for that year. In most countries there was no uniform tariff level even within the same technology group. For instance, remuneration levels differed depending on the biofuel technology type and on the size of plant and policy design in use in a certain year. To account for this, the feed-in tariffs were calculated as a weighted average of the different relevant and comparable tariffs in use in each year. If the technology base eligible for support was broadened or narrowed over time, in a sense that would change the mean level of tariffs to a non-comparable measurement unit, these specific technologies were not included. An example of this was the British NonFossil Fuel Obligation scheme (NFFO) where the fuel base eligible for support has been redefined several times during the existence of the program. As in the research by Rübbelke and Weiss [2011], tariff levels were also discounted with the stated yearly percentage if tariffs were constructed as descending by the regulator (e.g., in Germany).

The RPS variable was continuous, defined as the percentage of obliged renewable energy within total energy production while a RPS policy was active. The RPS was counted as active if they were in use before 1st July of a given year.

Investment subsidies were measured as annual total funding (2005 USD value) of a specific program. In the instances where the data on the annual budget was not available, it was assumed that the total initial funding of a certain program was exhausted within five years. The reason for choosing a 5-year limit was that when time limits are explicitly mentioned in policy descriptions, five years is usually the timeframe used [IEA 2011]. Due to a lack of information, it was not possible to include some policies in the continuous investment variable, however these policies were taken into account by a cardinal interval variable which measured the total number of investment support policies in use for a specific year and country. Since these programs could target different sectors of the economy and could be more or less effective, they were divided into three separate variables; strong policies, weak policies and policies directly aimed at the household or residential sector. Cardinal investment policies were assessed as strong if they were directly targeted towards renewable energy production, either in power generation or the production of bioenergy. On the other hand, if a policy only provided a little support, e.g. soft loans to renewable energy projects but with risk-adjusted high rents close to what should have been the level if negotiated on the open market, it was categorized as weak. Furthermore, if it was unclear whether an explicit renewable energy policy was relevant at all for bioenergy, it was also classified as weak. The latter also applied to policies otherwise categorized as residential sector policies. When an investment policy overlapped two categories, it was then recorded as a fraction for each group. Table 1 summarizes the process in which the policy variables were constructed.

Table 1. Description and sources of data used

Type of variable	Data	Source	Processing by authors
Dependent variable	Patent data	OECD [2013]	None, compiled at the OECD. Originally data originates from the European Patent Office
Policy variables (independent variables)	Policy description	IEA [2004], IEA IRENA database [2011, 2013]. Cerveny and Resch [1998]. Governmental and bioenergy organizational websites*	Quantification of investment support data and computation of yearly mean feed-in tariff levels made by authors. In some cases (i.e. Japan) computation of effective quota levels for the RPS have also been made by the authors since explicit information regarding these have not been available
Control variables (independent variables)	Prices on energy, biomass and electricity. Total numbers of patents and yearly bioenergy RD&D. Total energy consumption	FAO [2013], OECD [2013]	Accumulated RD&D stock computed by summation of yearly expenses on bioenergy research

* France: FOGIME – http://www.muredatabase.org/
Belgium: Res Regulation – http://www.resregulation.gr/bibliography/
Canada: CBSA – http://www.cbsa-asfc.gc.ca
The Netherlands: SDE – http://www.energy.eu/
Japan: MoE – http://www.meti.go.jp/english/policy/energy_environment/renewable/index.html
General: http://fxtop.com/en/; http://faostat3.fao.org/

In the RD&D vector (D), the propensity to patent was measured by the total number of patent counts under the PCT, aggregated over all technological areas. Thus the bioenergy patent was related to the overall trend in patenting in a given country. It also checked for differences in size and research capacity of the countries. This variable was expected to have a positive sign in the regression. Technological opportunity was approximated by the accumulated knowledge stock constructed using a country`s aggregated (public) RD&D expenditures on bioenergy technology. RD&D expenditures were measured in 2012 USD and retrieved from the OECD [2013]. The accumulated knowledge stock was built in a similar way to the work by Söderholm and Klaasen [2007] and was defined as:

$$STOCK_{\mathrm{i,t}} = (1 - \delta)STOCK_{\mathrm{i,t-1}} + RD\&D_{i,t-x} \tag{2}$$

where: *STOCK* – the accumulated knowledge stock,

δ – the rate of depreciation,

x – the time lag before R&D expenditures was added to the knowledge stock.

According to Klaasen et al. [2005] a time lag of two years ($x = 2$) and a depreciation rate of 3% ($\delta = 0.03$) is reasonable.

The data for national RD&D expenditures had some missing observations which could not be omitted since it would have made construction of the knowledge stock impossible. In those instances, the methodology of linear interpolation employed in Jaunky [2009] using the mean of the observations before and after the missing observation was used to complete the series.

The demand-side factors included in vector (P), contained the electricity prices and the relative price between roundwood and light fuel oil. This price ratio served as a proxy for the relative price between biomass and other important fossil fuel prices. The reason for the choice of light fuel oil as proxy and not a broad index on oil prices was due to the limited data availability. Moreover, a variable on total energy consumption was included to check for the size of the energy market – higher energy consumption meant that there were greater potential sales for energy technology and therefore larger incentives to innovate. The electricity price was retrieved from IEA [2013] and was expressed in USD per kWh (2005 value). Total energy consumption was measured in TWh and originated from the OECD Statistics Database [2013]. In order to account for the aforementioned heterogeneity amongst the sample countries, 13 dummy variables[5] were added to the regression equation. This was in line with the methodology of the Allison and Waterman [2002] fixed-effects model.

Finally, in 1994 the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS) was negotiated which was expected to have had an impact on the patenting behaviour in the countries included in the sample. With TRIPS, intellectual property law was first introduced to the international trading system

[5] The dummy for Austria was excluded to avoid perfect multicollinearity.

and is still the most extensive international agreement on intellectual property so far introduced. An additional dummy was included in the regression to distinguish between pre- and post-TRIPS patenting activity. This dummy took the value of 1 from 1995 onwards.

Results and discussion

Theoretically, it was possible that patenting was affected by a time lag, therefore several model specifications containing lagged independent variables were tested in order to decide upon a feasible first specification of the model. One variable did improve the model when it was lagged – the relative price between roundwood and light fuel oil. To test if the binomial count model was appropriate, a dispersion test was conducted. The test indicated that the data was overdispersed, and therefore the negative binomial model was appropriate. The regressions were conducted using bootstrapping since normal robust standard errors could have been unreliable in the presence of outliers; moreover, these are more likely to influence the standard errors in smaller samples [Cameron, Trivedi 1998].

The econometric results were deemed statistically-reliable and nothing in the chosen estimation technique or model specification warranted further scrutiny. The patent data reliability was, however, harder to validate. This was not in terms of its source, but rather since it was difficult to validate that each patent was exclusively related to bioenergy technologies. The results were applicable to several issues and areas. Since the focus was on the effect energy and climate policies had on bioenergy innovation activity, the foremost area of applicability was in policy formulation. That is, based on the results, policy-makers could better assess different policy options if they desired to stimulate bioenergy innovation in their climate agenda.

The result of the regression is given in table 2. The results regarding the policy variables were diverse. Both variants of feed-in tariffs were statistically significant, with a positive impact on innovation. In addition, the cardinal variable for the strong investment policies was statistically significant with a positive sign. The other policy variables, such as quota obligations (RPS) or other different measures of investment support schemes were not statistically significant.

The demand-side variables (total energy consumption, electricity prices and the relative prices for roundwood versus light fuel oil) were all statistically significant. The supply-side variables measuring total research capacity, propensity to patent and technological opportunity for innovation were statistically significant with an expected positive sign. The time period after the negotiation of the TRIPS agreement also had a significant impact on patenting in biofuel technology, indicating that it could lead to biased conclusions regarding policies if this variable were omitted. A variety of interaction variables checking for interaction effects between the independent variables were also tested, none of them being statistically significant.

Table 2. Estimated coefficients of the negative binomial model with country fixed effects

Variable	Elasticity	P > z	Elasticity lower bound	Elasticity higher bound
Total PCT	0.150**	0.033	0.012	0.288
Investment support (continous)	0.010	0.494	-0.019	0.039
Strong investment policies	0.127**	0.029	0.013	0.241
Weak investment policies	0.009	0.696	-0.037	0.056
Household investment p.	0.019	0.467	-0.031	0.068
RPS	0.025	0.152	-0.009	0.059
Feed-in tariffs A (longer agreement)	0.172***	0.000	0.101	0.242
Feed-in tariffs B	0.072***	0.003	0.024	0.119
Energy consumption (market size)	2.394***	0.002	0.868	3.921
Accumulated bioenergy knowledge stock	0.439**	0.014	0.087	0.790
Electricity price	0.871***	0.001	0.365	1.378
Lagged relative price: roundwood/ light fuel oil	-0.332***	0.003	-0.549	-0.115
TRIPS	0.284***	0.004	0.089	0.479
Country dummies	14 DV			
Log-likelihood	-619.705			
Chi-squared (prob)	52.40	(0.000)		
n = 373				

* 10% significance, ** 5% significance, *** 1% significance

The correlation between the independent variables was also inspected in order to check for multicollinearity. In the first specification, the correlation between the weak investment policy variable and total PCTs was 0.63 and therefore a regression was estimated where it was omitted, but the significance and sign of the other independent variables remained robust.

However, the assumption that the various investment support programs contained in the three cardinal interval variables had the same impact on innovation could be called into question. Therefore, a set of binary dummy variables for each of the three cardinal investment support variables was constructed and substituted for the cardinal variables. This represented other relevant investment policy support which, however, was impossible to quantify in the continuous variable. The results from that regression coincided with those of the first specification. Finally, a single dummy variable was constructed substituting all the cardinal variables. The dummy was significant with a positive sign and once again the same results were obtained regarding the other independent variables. Arguably, this confirmed the robustness of the result from the first specification.

It was possible that the ambiguous effect of the investment support schemes could have been a result of the method used in the quantification of the investment support variable. The continuous variable consisted of many different types of investment support programs, such as measures aimed directly at bioenergy investment, but also at renewables in general. Therefore, a further disaggregated continuous investment support variable was constructed in order to investigate whether a smaller subset of the policies had an impact on innovation in bioenergy. The new categories were: bioenergy investment support (mainly in power and large-scale heat generation), investment support against renewables in general, and support for renewable energy in the household and residential sector. It should be mentioned that the categorization was not analogous to the classification of the cardinal interval variable for the investment support programs impossible to quantify continuously. However, in the regressions using these new classifications, it was found that none of them was statistically significant and, therefore, the result from the first specification remained unchanged.

Another reason why RPS schemes and investment support programs did not show any significant effect could have been the somewhat broad definition of the dependent variable; bioenergy is a fairly diversified energy field and consists of many types of technology. Some of the policy programs might have affected innovation in a narrow field of bioenergy technology, but the patent classes used in the study were too diversified to enable the detection of such an effect in the regressions. Information on the policies in the IEA database was also in some cases quite vague regarding the scope and magnitude of the support targeted to bioenergy specifically, which made it harder to assess the relevance of the investment support schemes than in the case of the levels of feed-in tariffs. The investment support variable may therefore have contained a higher share of noise than the other policy variables.

The strongest impact on patenting in biofuel technology was given by total energy consumption with an elasticity of 2.39, which means that if energy consumption rose by 1%, patenting would increase by 2.39%. Other demand-side factors, such as the electricity price and the lagged relative price between roundwood and light fuel oil, had an elasticity of 0.87 and -0.33, respectively. Regarding supply-side factors, the accumulated knowledge stock had quite a strong effect, with an elasticity of 0.44. The feed-in tariffs had an elasticity of 0.17 and 0.072, respectively. The tariff associated with a contractual agreement longer than 10 years had more than double the impact of the feed-in tariff negotiated on shorter terms, which was in line with the theoretical assumptions regarding feed-in tariffs. The elasticity for the strong investment policies was 0.127; the finding that only the strong investment support variable was statistically significant supported the division of the cardinal investment variable into several variables of different relevance.

The results were to some extent contradictory to the earlier assessments by Johnstone et al. [2010] who did not find any effect of feed-in tariffs on innovation in the bioenergy field. Investment support schemes had a significant impact in that study but the support was only measured as a binary dummy, which is consistent with the statistically-significant and positive effect of the strong investment policies in this study. Quota obligations did not have a statistically significant effect in either of the studies.

In order to test how sensitive the results were to the assumed depreciation rate (3%) and lag structure (2 years) for the knowledge stock variable, a sensitivity analysis was carried out. Table 3 presents the regression results based on 2% and 4% depreciation rate and a one and 3-year lag structure. The sensitivity analysis is presented as a percentage change to the results in table 2. As table 3 indicates, the results were relatively robust to minor changes in the parameters used to construct the knowledge stock variable. No important change in the sign or significance of the variables used was detected.

Table 3. Sensitivity analysis of depreciation rates and lags in the construction of the knowledge capital stock. Change in estimated coefficients compared to the base model in percentage points

Variable	2% depreciation rate	4% depreciation rate	2-year lag	4-year lag
Total PCT	-0.5**	-0.5**	-9.5**	8.6**
Investment support (continous)	-1.2	-1.2	-23.8	14.3
Strong investment policies	0.4**	0.0**	-5.7**	3.1**
Weak investment policies	-5.0	12.7	7.9	4.2
Household investment p.	-6.3	-1.7	-45.1	3.1
RPS	-9.8	13.3	-1.6	7.6
Feed-in tariffs A (longer agreement)	0.1***	0.6***	-1.9***	2.5***
Feed-in tariffs B	2.6***	4.4***	-3.4***	7.4***
Energy consumption (market size)	-3.4***	4.5***	-0.8***	0.3***
Accumulated bioenergy knowledge stock	-4.3**	6.7**	17.3***	-6.1**
Lagged relative price: roundwood/light fuel oil	-0.5***	-0.1***	-5.9***	2.8***
Electricity price	-3.4***	-1.7***	-12.2***	0.6***
TRIPS	-1.7***	0.3***	-1.4***	-1.5***
Country dummies	14 DV	14 DV	14 DV	14 DV

Significance of estimated coefficients: * 10% significance, ** 5% significance, *** 1% significance

Conclusions

This study investigated the determinants of bioenergy innovations with a special focus on the effect of energy and climate policies, within a sample of 14 countries between 1978 and 2009. Innovation was approximated by patent counts, and a vector of different disaggregated policy measures was included, together with a set of market and R&D variables in order to assess their impact on innovation. An inspection of the development of the number of patents and the amount of support targeted towards renewable energy during the investigated time period suggested that these programs played an important role in technological change in the biofuel sector.

The econometric results indicated that policies such as feed-in tariffs and investment support programs had a statistically-significant and positive impact on innovation in bioenergy technology. Renewable energy quotas failed to have a significant effect on innovation in this study. Market variables such as total energy consumption and electricity prices also had a significant, positive effect on innovation. Higher roundwood prices relative to light fuel oil had a negative effect. The variables representing technological opportunity for innovators and over-all research capacity of a given country (measured by accumulated RD&D expenditure on biofuel technology and total patent counts over all technology groups), did show a positive and significant effect on innovation as well, which was in line with the theoretical assumptions of the model.

The economically most noteworthy result of the study relevant for policy--makers was that innovation was significantly driven by electricity prices. Policy measures such as feed-in tariffs and certain investment support schemes also played a role in the development of bioenergy technology. Thus, these findings suggest a combination of measures that internalize the negative external effects of power production and properly designed support programs in order to further increase the rate of innovation in biofuels, which will hopefully make bioenergy a fully cost-competitive substitute for traditional fossil fuels.

References

Allison P., Waterman R. [2002]: Fixed-Effects Negative Binomial Regression Models. Sociological Methodology 32 [1]: 247–265

Arthur W.B., Ermoliev Y.M., Kaniovski Y.M. [1987]: Path dependence processes and the emergence of macro-structure. European Journal of Operational Research 30: 294–303

Brunnermeier S., Cohen A. [2003]: Determinants of environmental innovation in US manufacturing industries. Journal of Environmental Economics and Management 45 [2]: 278–293

Busch S., Held A., Klein A., Merkel E., Pfluger B., Ragwitz M., Resch G. [2010]: Evaluation of different feed-in tariff design options – Best practice paper for the International Feed-in cooperation. 3rd edition, update by December 2010. Energy Economics Group, Fraunhofer ISI

Cameron A., Trivedi P. [1998]: Regression Analysis of Count Data. Cambridge University Press, New York, USA

Campoccia A., Dusonchet L., Telaretti E., Zizzo G. [2009]: Comparative analysis of different supporting measures for the production of electrical energy by solar PV and Wind systems: Four representative European cases. Solar Energy 83 [3]: 287–297

Cerveny M., Resch G. [1998]: Feed-in tariffs and regulations concerning renewable energy electricity generation in European countries. Energieverwertungsagentur [E.V.A.], Vienna, Austria

Couture T., Gagnon Y. [2010]: An analysis of feed-in tariff remuneration models: Implications for renewable energy investment. Energy Policy 38: 955–965

David P.A. [2001]: Path dependence: Its critics and the quest for historical economics. In Garrouste P. and Ioannides S. (ed), Evolution and Path Dependence in Economic Ideas: Past and Present, Edward Elgar Publishing, Cheltenham, UK

European Parliament [2009]: Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009

FAOStat [2013]: FAOStat forestry database [accessed 16.08.2013]. Available from: http://faostat3.fao.org/faostat-gateway/go/to/download/F/*/E

Greene W. [2007]: Fixed and Random Effects Models for Count Data. Leonard N. Stern School of Business Paper No. ISSN 1547-3651

Griliches Z. [1990]: Patent Statistics as Economic Indicators: A Survey. Journal of Economic Literature 28 [4]: 1661–1707

Hausman J., Hall B., Griliches Z. [1984]: Economic Models for Count Data with an Application to the Patents–R&D Relationship. Econometrica 52: 909–938

Hicks J. [1932]: The theory of wages. Macmillan, London, UK

International Energy Agency [2004]: Renewable Energy – Market & Policy Trends in IEA Countries. IEA, Paris

International Energy Agency [2011]. Global Renewable Energy Policies and Measures database [accessed 1.10.2011]. Available from: http://www.iea.org/textbase/pm/?mode=re

International Energy Agency [2013]: IEA/IRENA Joint Policies and Measures database [accessed 1.08.13]. Available from: http://www.iea.org/policiesandmeasures/renewableenergy

Jaffe A.B. [1986]: Technological Opportunity and Spillovers of R&D: Evidence from Firms` Patents, Profits and Market Value. The American Economic Review 76 [5]: 984–1001

Jaffe A.B., Palmer K. [1997]: Environmental Regulation and Innovation: A Panel Data Study. Review of Economics & Statistics 79 [4]: 610–619

Jaffe A., Newell R., Stavins R. [2000]: Technological Change and the Environment. NBER Working Paper 7970

Jaunky V.C. [2009]: Human capital in Africa: Technical change, efficiency and productivity. Applied Econometrics and International Development 9–2

Johnstone N., Haščič I., Popp D. [2010]: Renewable Energy Policies and Technological Innovation: Evidence Based on Patent Counts. Environmental and Resource Economics 45 [1]: 133–155

Klaasen G., Miketa A., Larsen K., and Sundqvist T. [2005]: The impact of R&D on Innovation for Wind Energy in Denmark, Germany and the United Kingdom. Ecological Economics 54 [2–3]: 227–240

Lanjouw J., Mody A. [1996]: Innovation and the international diffusion of environmentally responsive technology. Research Policy 25 [4]: 549–571

Moore C., Ihle J. [1999]: Renewable energy policy outside the United States. Renewable Energy Policy Project, October 1999, No. 14

Nelson R.R., Winter S.G. [1982]: An Evolutionary Theory of Economic Change. Harvard University Press, Cambridge, USA

Neuhoff K. [2005]: Large Scale Deployment of Renewables for Electricity Generation. Oxford Review of Economic Policy 21 [1]: 88–110

Newell R., Jaffe A., Stavins R. [1999]: The Induced Innovation Hypothesis and Energy-Saving Technological Change. The Quarterly Journal of Economics 114 [3]: 941–975

Neyman J., Scott E. [1948]: Consistent Estimates Based on Partially Consistent Observations. Econometrica 16 [1]: 1–31

Noailly J., Batrakova S. [2010]: Stimulating energy-efficient innovations in the Dutch building sector: Empirical evidence from patent counts and policy lessons. Energy Policy 38 [12]: 7803–7817

Organisation for Economic Cooperation and Development [2009]: OECD Patent Statistics Manual. OECD Publishing, Paris, France

Organisation for Economic Cooperation and Development [2013]: OECD.Stat (database) [accessed 25.09.2013]. Available from: http://stats.oecd.org/Index.aspx.

Popp D. [2002]: Induced innovation and energy prices. The American Economic Review 92 [1]: 160–180

Popp D. [2003]: Pollution control innovations and the Clean Air Act of 1990. Journal of Policy Analysis and Management 22 [4]: 641–660

Popp D. [2005]: Lessons from Patents: Using Patents to Measure Technological Change in Environmental Models. Ecological Economics 54 [2–3]: 209–226

Popp D. [2007]: Using the Triadic Patent Family Database to Study Environmental Innovation. Methodological paper, OECD

Rübbelke D., Weiss P. [2011]: Environmental Regulations, Market Structure and Technological Progress in Renewable Energy Technology – A Panel Data Study on Wind Turbines. FEEM Working Paper No. 581.2011

Scherer F.M. [1965]: Firm Size, Market Structure, Opportunity, and the Output of Patented Inventions. The American Economic Review 55 [5]: 1097–125

Schmookler J. [1966]: Invention and economic growth. Harvard University Press, Cambridge, USA

Schumpeter A.J. [1934]: The theory of economic development. Harvard University Press, Cambridge, USA. Published in German in 1911 as Theorie der wirtschaftlichen Entwicklung. Verlag von Dunker & Humblot, Leipzig, Germany

Sijm J. [2002]: The Performance of Feed-in Tariffs to Promote Renewable Electricity in European Countries. ECN-C-02-083

Simon H.A. [1947]: Administrative Behavior: A Study of Decision-making Processes in Administrative Organization, Macmillan Company, New York

Söderholm P., Klaassen G. [2007]: Wind Power in Europe: A Simultaneous Innovation-Diffusion Model. Environmental & Resource Economics, 36[2]:163–190

Walz R., Ragwitz M., and Schleich J. [2008]: Regulation and innovation: the case of renewable energy technologies. DIME Working Papers: Working Paper No. 2

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FOREST BIOMASS FOR BIOENERGY: OPPORTUNITIES AND CONSTRAINTS FOR GOOD GOVERNANCE. A CASE STUDY FROM ITALY

Interest in the use of biomass for energy has increased significantly in the last few years. The latest report by the Intergovernmental Panel on Climate Change highlights the influence mankind has had on the climate: an unprecedented increase in GHG levels in the last 800,000 years and a rise of 40% in CO_2 concentrations since pre-industrial times. The challenge now is to find energy alternatives, and in this context, one important option is bioenergy, one of the most important energy sources of the future. In light of this, the goal of this paper was to assess the sustainable potential of woodfuel resources in Italy using WISDOM methodology. WISDOM, developed by the FAO, has been applied in many countries around the world. From this study, at national level, household consumption was at 19.3 Mt in 2003 (average value), while the potential supply of woody biomass (productivity) was 24.9 Mt (average value), with a surplus of almost 6 million tons between household consumption and productivity. This study represents an advance in knowledge of the biomass potential for energy use in Italy, and, as such, is subject to possible future improvement. Forest bioenergy development creates good opportunities to mobilize the production potential of European forests, and to contribute to a more climate-friendly, bio-based economy.

Keywords: Biomass estimation, WISDOM, SFM, climate change, GHG

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Introduction

Over the last few years, the interest in climate-policy-related questions and the use of biomass for energy has increased greatly, due to its potential for fossil fuel replacement and for forest product diversification [Lamers et al. 2013]. The forest biomass also has a very important role within the global carbon balance, and its utilization is influential in the mitigation of climate change [Fiorese, Guariso 2013].

The latest report by the Intergovernmental Panel on Climate Change [IPCC 2013] gives prominence to human influence on the climate system and highlights how the atmospheric concentration of carbon dioxide, methane, and nitrous oxide has increased to unprecedented levels in the last 800,000 years. In this report, four scenarios for future emissions and projections of climate change have been generated, namely RCP8.5, RCP6, RCP4.5 and RCP2.6. The RCP8.5 scenario corresponds to the baseline where no direct action for the mitigation of climate change has been set, while the other scenarios have targets for mitigation that should be reached by the end of the century, with forcing levels of 6, 4.5 and 2.6 W/m^2 [Masui et al. 2011; Thomson et al. 2011; van Vuuren et al. 2011]. The baseline scenario is of a continuously increasing global population to the tune of approx. 12 billion by 2100, with slow economic development and little progress in terms of efficiency. This context would lead to high-energy demands. The RCP 8.5 represents the highest RCP scenario in terms of Greenhouse Gas (GHG) emissions [Riahi et al. 2011] and would lead to a temperature increase from 4 to 6.1 degrees with respect to the pre-industrial era.

Mitigation scenario RCP2.6 would need to decrease substantially in order to demonstrate a considerable improvement in energy efficiency, fossil fuel replacement and an increase in renewable energy and nuclear power [van Vuuren et al. 2011]. RCP2.6 is the scenario virtuous of "green" conversion where the temperature should increase within a range of 1.3–1.9 degrees from the pre-industrial era. Between these, there are two other scenarios (RCP4.5 and RCP 6.0) with an intermediate hypothesis. According to the above-mentioned scenarios, the goal is to remain below 420 ppt of CO_2 by the end of the century, although the Global Monitoring Division of NOAA/Earth System Research Laboratory describes the target as ambitious.

Presently, the mean carbon dioxide concentration is more than 390 ppt with respect to 280 ppt in the pre-industrial era [NOAA]. The source of anthropogenic emissions has increased by 40% from 1920 until the present day, both for fossil fuel emissions and for net land use change emissions [Quéré et al. 2012].

Land Cover and Land Use Changes (LCLUC) are an important factor in environmental alterations [García-Ruiz et al. 2011], they are significant both within the global carbon budget [Houghton et al. 2012] and in the supply of/demand for biomass for bioenergy. From 2000 to 2009, anthropogenic carbon emissions due to LULCC were 12.5% of the total [Friedlingstein et al. 2010], taking into account the switch from fossil fuels to renewable energy such as wind, hydropower, biomass and solar power.

This high percentage challenges humankind to enhance the use of renewable energy, especially bioenergy from forests [Schulze et al. 2012].

Globally, forests represent a significant carbon stock and their management influences the carbon cycle, although according to Nabuurs et al. [2013] the first signs are visible of carbon sink saturation in European forests.

However, managed forests can provide valuable feedstock for energy production, though harvesting operations produce a variety of changes to the forest structure and ultimately to biodiversity [Fiorese, Guariso 2013].

The forest biomass is considered a renewable energy source, which is almost carbon-neutral, as the carbon balance is approx. zero between the atmospheric carbon sequestered during growth and its release to produce energy while burning [Lattimore et al. 2009]. Within the carbon balance, it is essential to consider the whole Life Cycle Assessment (LCA) of biomass, as fossil fuels are needed for harvesting operations and a decrease in the standing volume of the forest should be taken into account [Schulze et al. 2012]. The substitution of fossil fuels for biomass avoids GHG emissions to the atmosphere, in addition to the creation of carbon stock in wood products [Fiorese, Guariso 2013].

In Europe, the Renewable Energy Directive (RED) established a target of 20% renewable energy to be reached by 2020 through the adoption of national action plans for renewable energy, which are compulsory for Member States [EU]. Bioenergy represents a great opportunity to mitigate GHG emissions in the short and medium term. Beringer et al. [2011] estimate that 15–25% of global primary energy could come from bioenergy in the year 2050.

Furthermore, the RED directives define sustainability criteria for liquid bio-fuels, which in turn could be linked to criteria for solid bio-fuels.

Considering the biomass potential available, biomass from forests will be among the most important energy sources of the future [Ciccarese, Oriani 2013] and it will be the largest fuel used in Europe in its various forms with various advantages, one being that it is continuous energy and always available [Economist, 6th April 2013].

The question and the challenge nowadays is to understand if biomass is carbon neutral, what its impact on climate change and the environment is, and, above all, how to mobilize the biomass from our forests [Muys et al. 2013].

Forest bioenergy development creates a good opportunity to mobilize the production potential of European forests, and to contribute to a more climate-friendly, bio-based economy. However, this development also holds risks, such as the possible competition for feedstock with the traditional forest industry [Muys 2013].

In light of this, the aim of this paper was to assess the sustainable potential of woodfuel resources in Italy, to improve the understanding of the role currently played by Italian forests and other woody biomass sources, and of their potential as a renewable energy source and in GHG emission reduction. The study was based on the information available throughout the country, using WISDOM methodology.

Materials and methods

In this study, WISDOM (Woodfuels Integrated Supply/ Demand Overview Mapping) methodology was applied. The WISDOM approach has already been applied in Slovenia [Drigo 2004a], Senegal [Drigo 2004b], East Africa [Drigo 2006], Southeast Asia [Drigo 2007], and Mexico [Ghilardi et al. 2007] and was developed by the FAO, in cooperation with the Center for Ecosystem Research at the National Autonomous University of Mexico (UNAM). This methodology combines a geo-database with statistical data on woodfuel production and consumption, integrating forestry, energy and socio-economic data and information.

The study area was analyzed using a Geographic Information System (GIS), producing an estimate of net balance between supply and geographically-localized demand.

The method to estimate the potential of woodfuel resources in Italy comprised the following five steps:

1. Definition of the cartographic base for analysis and data collection of the necessary layers.
2. Development of the demand module.
3. Development of the supply module (potential and current).
4. Development of the integration module between supply and demand for production of the geo-referenced net balance.
5. Identification of priority woodfuel hotspots.

The analyses were carried out at the lowest administrative level for which demographic, social and economic parameters were available, namely the municipality.

The data sources used for this constituted a layer of 8,095 municipalities, 103 provinces, 20 regions and, for some variables, it was necessary to use a raster approach on a 300 × 300 meter grid (pixels). The national territory was covered by 3,356,451 pixels in this resolution.

Demand module

In this study, the demand for woodfuel was related to household use only. The two sources of information taken into account in the demand estimation were from ISTAT (the Italian National Institute of Statistics) and ENEA (the Italian National

Agency for New Technologies, Energy and Sustainable Economic Development). ISTAT publishes statistical data on forestry related to wood harvested for energy purposes, while in 1997 and 1999 ENEA published data on biomass consumption for energy use, based on sample surveys by telephone interviews (6,000 interviews per year) [as cited in Gerardi et al. 1998; Gerardi, Perella 2001].

The consumption of household wood fuel estimated by the two information sources is very different: ISTAT's data reported approx. 4.4 million m^3 (equal to 3.26 Mt considering an average humidity of 20% and an average wood basal density of 600 kg m^{-3}), while ENEA's data reported 21.6 Mt in 1997 and 14.7 Mt in 1999. Hellrigl [2002] reported that the real value of consumption between 1997 and 1999 was between 16 and 20 Mt per year.

Consumption in the residential and industrial sectors was estimated according to three different scenarios: 1) an estimate of the maximum values extracted by ENEA data [1997]; 2) an estimate of the minimum values extracted by ENEA data [as cited in Gerardi, Perella 2001]; 3) an estimate of the intermediate values extracted from the average of the previous values.

For each municipality the degree of urbanization, the altitude zone according to the Statistical Atlas of Municipalities [ISTAT 2006] and the number of households were determined. Based on these data, the annual average consumption per household was identified for the three scenarios (fig. 1).

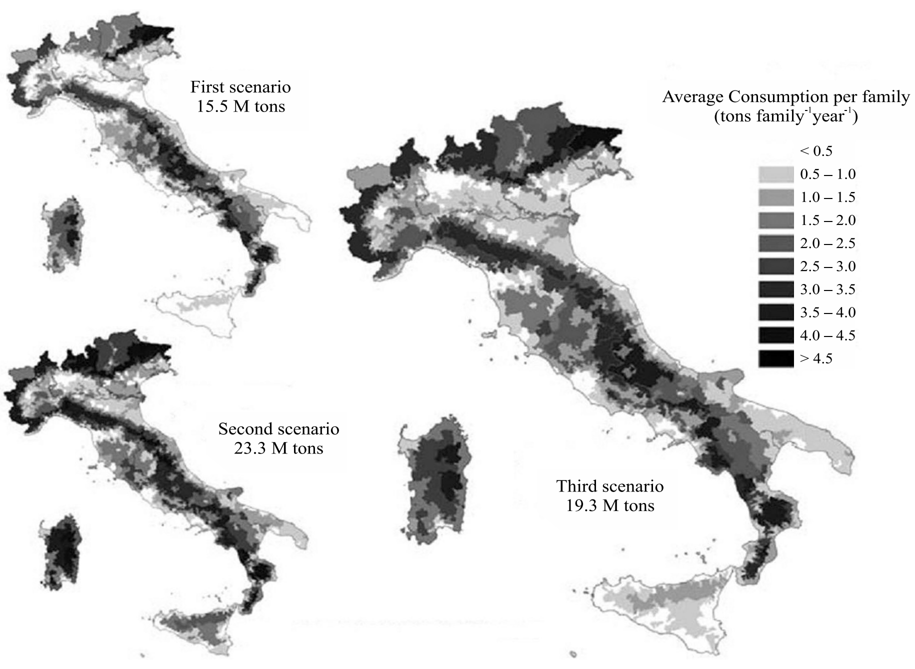

Fig. 1. Average annual household consumption of woody biomass for energy use per family in Italian municipalities within the three scenarios defined

Supply module

The estimated supply of woodfuel for each of the 8,095 municipalities considered was calculated from the potential total productivity of woodfuel for categories of land cover weighted attentively considered the accessibility level of the area under analysis. This land cover dataset was derived from the Corine Land Cover level-IV Map (CLC2000). For each forest polygon in CLC2000, woody biomass productivity for energy use was estimated. The 1985 National Forest Inventory data were used to estimate the stock and productivity (min, med and max), as well as a literature review on biomass productivity [APAT 2003], and a yield table for coppice by Ciancio and Nocentini [2004].

The branch and crown volumes were taken into consideration for high forests and standard trees found in coppice stands, and they were estimated as a fraction of total dendrometric volume, equal to a range of values between 15 and 35% of the total [APAT 2003].

In the coppice forests, productivity was estimated on the basis of the coppice shoots present, while the biomass for energy use in chestnut coppices was estimated as a value equal to 50% of the total volume (for the production of poles). The coppice shoot productivity was estimated according to the national average volumes by species and forest inventory types [IFNI 1985]. The coppice rotation cycle was considered between 20 and 25 years.

In the productivity assessment, for biomass outside forests, reference values associated to the CLC2000 classes for crops and for poplars [APAT 2003] were used.

The productivity values for land use and land cover classes (CLC2000) used for the analysis, according to the MAF-ISAFA [1988], are shown in fig.1.

Fig.1 only shows the main forest classes (CLC codes) that as a whole, they cover globally more than 80% of the national forest area. The CLC forestry classes not shown within the graph have an average potential productivity between 1.7 and 4 tons per hectare per year. Non-forest classes, such as urban forestry and urban greening, heterogeneous agricultural areas and shrub vegetation areas, have an average potential productivity between 0.5 and 1.6 tons per hectare per year.

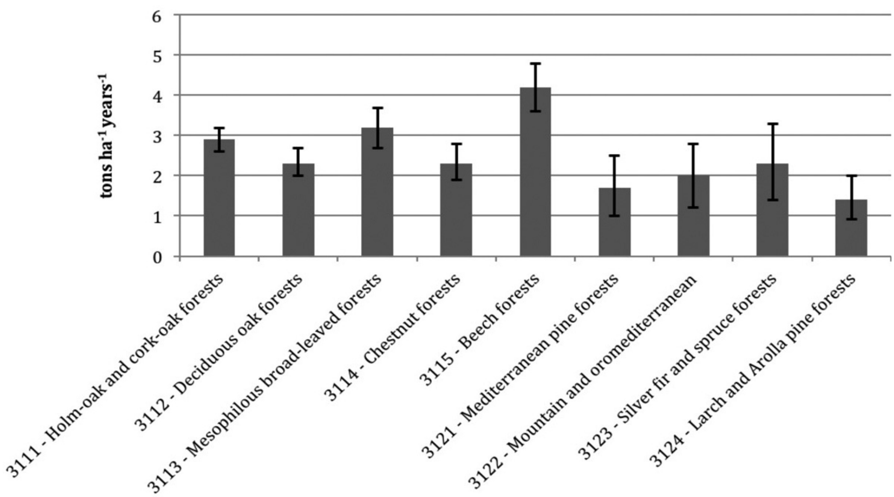

Fig. 1. Estimation of potential productivity at national level (minimum, average and maximum) of woody biomass for energy purposes according to the main forest CLC classes (tons ha^{-1} years^{-1})

Estimate of the limitations

The woodfuel supply capacity is dependent on physical factors limiting accessibility. The main aim of accessibility analyses is to relate woody biomass supply to population distribution [Millington et al. 1994; Top et al. 2006]. An estimate of accessibility was reached through an algorithm of cost distance [Eastman 1989] based on the distance from roads, distance from main residential areas and the slope of the land [Chirici et al. 2003].

The roads were derived from a vectorial geographical database containing a total of 168,499 km of different types of roads. In the model, road network was only related to asphalt roads and was therefore only a part of the road network [Hippoliti, Piegai 2000] useful for forestry purposes. Urban centers were derived from a vectorial database containing 59,700 units. The slopes map was derived from a Digital Terrain Model (DTM) with a 75 m grid.

Estimate of potential supply considering limitations

A supply and demand balance was estimated at municipality level through a raster data analysis. The vectorial data layer, with the values of potential productivity gross, was rasterized based on the raster grid reference with a 300 m resolution. At raster layer, the limitations map multiplied potential gross productivity. The result of this process was a raster map containing an estimate of the net potential productivity (fig. 3). This map was associated with the vectorial boundaries layer of the municipalities.

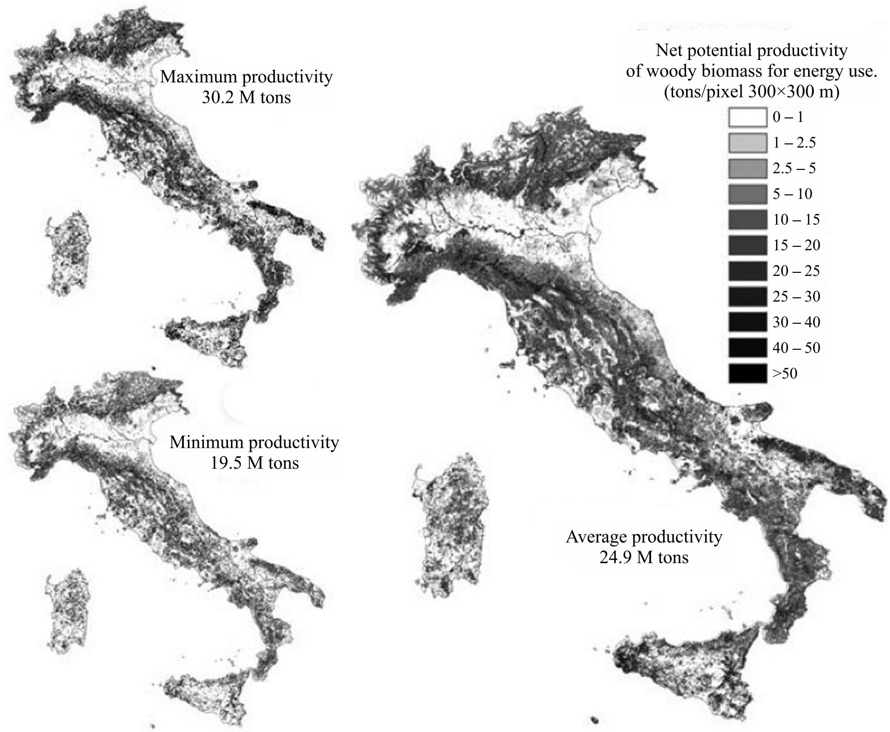

Fig. 3. Annual productivity potential of woody biomass for energy use. Minimum, maximum and average values for 300 × 300 m pixels

Results and discussion

At national level, the estimated demand for woodfuel for household consumption was between a minimum of 15 Mt and a maximum of 23.3 Mt, with an average value of 19.3 Mt in 2003. At regional level, the aggregate data showed a great variability of consumption with values from a minimum of 0.06 Mt to 3.25 Mt maximum. These variations can be ascribed to several factors, such as regional extension, the availability of other energy sources (i.e. methane), the population density and the local customs and traditions.

The data analysis highlighted the largest consumption in the Alpine and Alpine foothill areas, along the Apennine ridge up to the Calabria mountains, and in the mountainous areas of Sardinia, with values generally higher than 3.5 tons per family^{-1} per year^{-1} (fig. 1).

At national level, the potential supply of physically accessible woody biomass (productivity) for energy use ranged from a minimum of 19.5 Mt and a maximum of 30.2 Mt, with an average value of 24.9 Mt. Approx. 82% of woodfuel supply was provided by forestry production. At regional level, the aggregate data varied from a minimum of 0.11 Mt and a maximum of 2.9 Mt. In this case, the variability of the potential productivity was mainly due to regional extension, the forest coverage in the region and the biomass availability, bearing in mind limiting factors (i.e. accessibility). Fig. 3 shows the spatial distribution of potential productivity across the country. The figure identifies a large area called the Po Valley characterized by low productivity values due to the presence of arable land, currently unsuitable for biomass production for energy purposes.

At municipality level, by combining the values of the potential productivity and household consumption, the first maps on supply and demand balance were produced. Three different scenarios were produced, with the aim of highlighting the uncertainty level in the available data: 1) a minimum balance, given by the minimum productivity and maximum consumption; 2) a maximum balance, given by the maximum productivity and minimum consumption; 3) an average balance, given by the average productivity and consumption (fig. 4).

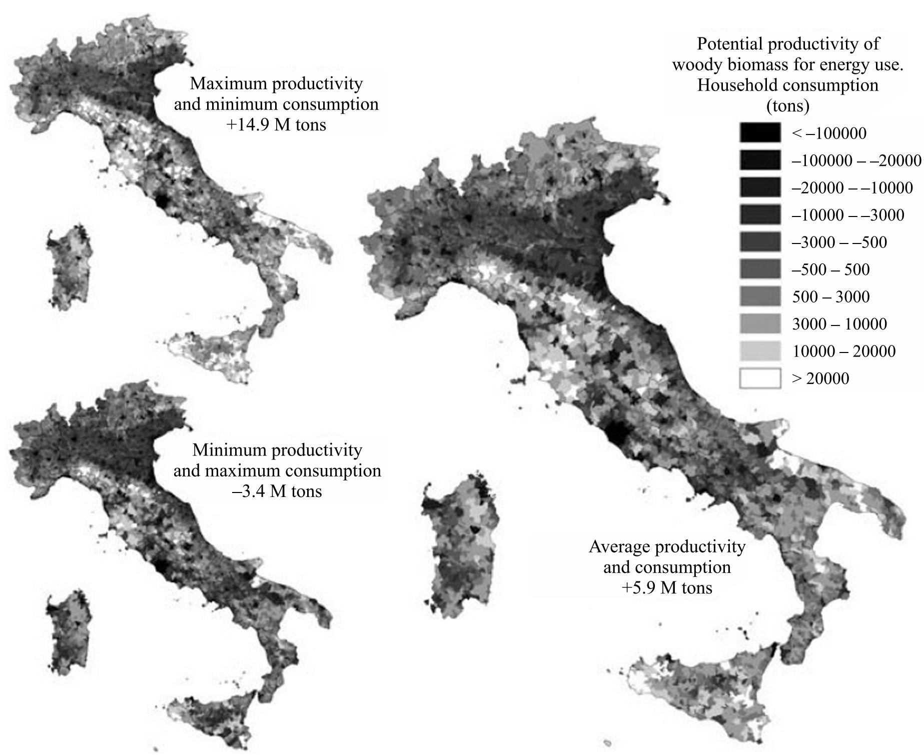

Fig. 4. Net balance between the potential productivity and household consumption of woody biomass for energy purposes

The balance at municipality level was divided based on elevation and urbanization zones allowing characterization of the supply and demand balance in Italy. Fig. 5 shows the regional values for the average scenario balance while Table 1 shows the balance between the average productivity potential and average household consumption at national level, according to elevation and urbanization zones.

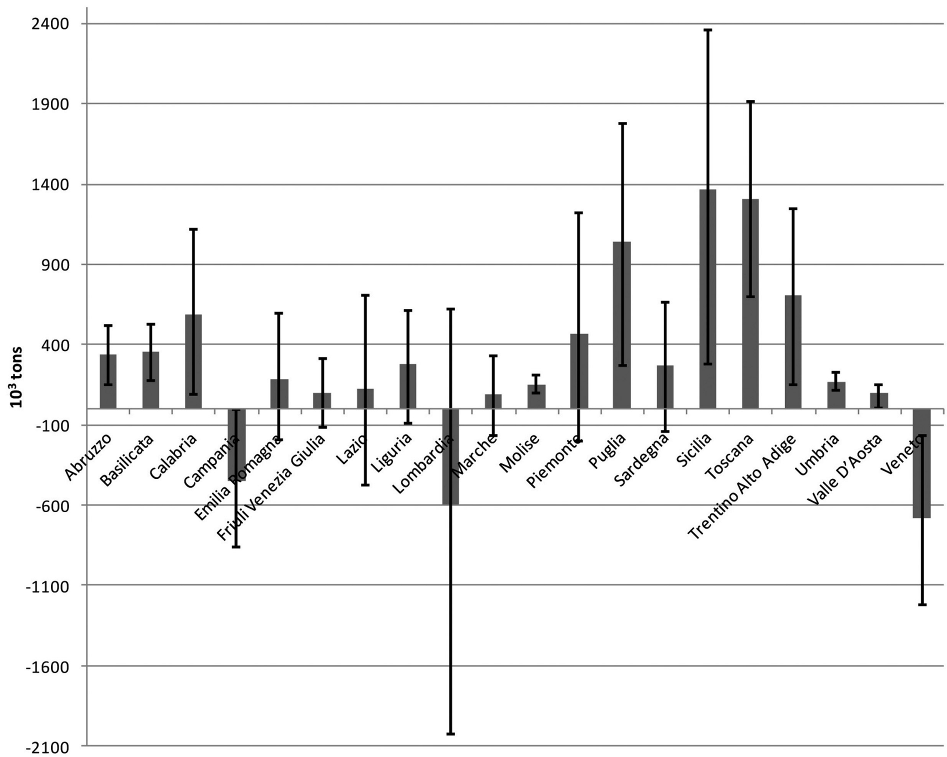

Fig. 5. Minimum, maximum and average values per district of annual balance between average potential productivity and average household consumption

In Italy, in average conditions of consumption and productivity, there was a surplus of almost 6 million tons localized predominantly in the inland mountainous and hilly areas with low urbanization (table 1), while in the minimum scenario there was a deficit of 3.4 Mt and in the maximum, a surplus of almost 15 Mt (Fig. 3).

Table 1. Balance between the average productivity potential of sustainable biomass for energy and average household consumption per degree of urbanization and elevation (10^3 tons)

Urbanization	Inland mountain	Coast mountain	Inland hill	Coast hill	Flatland	Total
Low	5740	122	2000	741	-39	8565
Average	-169	-3		210	-318	-280
High	-89	-201	-506	-593	-980	-2368
Italy	5483	-81	1493	358	-1337	5916

The analysis of the regional totals in the average scenario showed that all the regions were potentially self-sufficient with the exception of Veneto, Lombardy and Campania, which had a negative balance, equaling 0.7, 0.6 and 0.45 Mt, respectively.

Conclusions

The Methodology applied on a national scale should not replace studies and investigations on woodfuel demand and supply on a local scale but should support a higher level of planning by directing policy in the bioenergy sector. Combined with other energy planning tools, the WISDOM approach could help in the design of robust policies and actions that are more effective.

The main goal of the WISDOM approach is to evaluate the use of woody fuel for energy production in a sustainable manner, and to be a point of departure for strategic planning and policy [Masera et al. 2006].

This study represents an advance in knowledge of the biomass potential for energy use in Italy, and, as such, is subject to possible future improvements. The woody biomass chain can contribute to local development in terms of environmental benefits, in employment opportunities [Lasserre et al. 2011] and in the creation of products for local trade. Wood harvesting for energy purposes can be integrated into forest management activities (residues from others activities in forests e.g. thinning, logging) or can be the main objective of management activities (Short Rotation Coppice), although this could have some impact on the local ecosystem according to the scale, intensity and type of management system used [Lattimore et al. 2009]. The adoption of site-specific best management practices (or counter measures) can help reduce risks connected to soil productivity and biodiversity [Lamers et al. 2013].

Even the new 2013 EU forest strategy defines the importance of the products from forests, encouraging a cascading use of wood, LULUCF carbon accounting, the promotion of energy efficiency measures and biodiversity safeguards [Muys et al. 2013]. These are challenges for the whole forestry sector.

References

APAT [2003]: Le biomasse legnose. Un'indagine delle potenzialità del settore forestale italiano nell'offerta di fonti di energia (The woody biomass. An investigation of the potential of the forestry sector in the provision of Italian energy sources). Report APAT 30/2003

Beringer T., Lucht W., Schaphoff S. [2011]: Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. Global Change Biology Bionenergy 3: 299–312. DOI: 10.1111/j.1757-1707.2010.01088.x

Chirici G, Marchi E., Rossi V., Sscotti R. [2003]: Analisi e valorizzazione della viabilità forestale tramite G.I.S.: la foresta di Badia Prataglia (AR) (Analysis and enhancement of forest roads using GIS: the forest of Badia Prataglia (AR)). L'Italia Forestale e Montana 6: 460–481

Ciancio O., Nocentini S. [2004]: Il bosco ceduo. Selvicoltura, assestamento, gestione (The coppice. Forestry inventory and management). Accademia Italiana di Scienze Forestali, Firenze

Ciccarese L., Oriani A. [2013]: Is all bio energy neutral for the atmosphere? A bug to be corrected. ProForBioMed report. Available from: http://www.proforbiomed.eu

Drigo R. [2004a]: WISDOM Slovenia: analysis of spatial woodfuel production–consumption patterns in Slovenia. Consultancy report FAO/Government of Slovenia project "Supply and utilization of bioenergy to promote sustainable forest management" TCP/SVN/2901. Rome: FAO

Drigo R. [2004b]: WISDOM Senegal: Analysis of woodfuel production–consumption patterns in Senegal. Consultancy report, FAO wood energy programme. Rome

Drigo R. [2006]: East Africa WISDOM - Woodfuel Integrated Supply/Demand Overview Mapping (WISDOM) methodology - spatial woodfuel production and consumption analysis of selected African countries. FAO Wood Energy Programme. Rome

Drigo R. [2007]: Wood-energy supply/demand scenarios in the context of poverty mapping. A WISDOM case study in Southeast Asia for the years 2000 and 2015. FAO Wood Energy Programme (FOPP) and Poverty Mapping Project (SDRN). Rome

Eastman J.R. [1989]: Pushbroom algorithms for calculating distances in raster grids. Proceeding, AUTOCARTO 9: 288-297

Economist [2013]: The fuel of the future [accessed 6.04.2013]. Available from: http://www.economist.com/news/business/21575771-environmental-lunacy-europe-fuel-future

EU: http://ec.europa.eu [accesed 10.09.2013]

Fiorese G., Guariso G. [2013]: Modeling the Role of Forests in a Regional Carbon Mitigation Plan. Renewable Energy 52: 175–82. DOI: 10.1016/j.renene.2012.09.060

Friedlingstein P., Houghton R.A., Marland G., Hackler J., Boden T.A., Conway T.J., Canadell J.G., Raupach M.R., Ciais P., Le Quéré C [2010]: Update on CO_2 emissions. Nature Geoscience 3: 811–812. DOI: 10.1038/ngeo1022

García-Ruiz J.M., López-Moreno J.I., Vicente Serrano S.M., Lasanta-Martínez T., Beguería S. [2011]: Mediterranean Water Resources in a Global Change Scenario. Earth-Science Reviews 105 [3]: 121–139. DOI: 10.1016/j.earscirev.2011.01.006

Gerardi V., Perella G., Masia F. [1998]: Il consumo di biomassa a fini energetici nel settore domestico (The consumption of biomass for energy in the domestic sector). ENEA, Roma

Gerardi V., Perella G. [2001]: I consumi energetici di biomassa nel settore residenziale in Italia nel 1999 (The energy consumption of biomass in the residential sector in Italy in 1999). ENEA, Roma

Ghilardi A., Guerrero G., Masera O. [2007]: Spatial analysis of residential fuelwood supply and demand patterns in Mexico using the WISDOM approach. Biomass and Bioenergy 31 [7]: 475–491. DOI: 10.1016/j.biombioe.2007.02.003

Hellrigl B. [2000]: L'uso energetico del legno nelle abitazioni in Italia (The use of wood energy in homes in Italy). Sherwood [75]: 15–26

Hippoliti G., Piegai F. [2000]: Tecniche e sistemi di lavoro. La raccolta del legno (Techniques and work systems. The harvesting of wood). Compagnia delle Foreste, Arezzo

Houghton R.A., House J.I., Pongratz J, van der Werf G.R., DeFries R.S., Hansen M.C., Le Quéré C., Ramankutty N. [2012]: Carbon Emissions from Land Use and Land-Cover Change. Biogeosciences 9: 5125–42. DOI:10.5194/bg-9-5125-2012

IPCC [2013]: Climate change 2013. The Physical Science Basis. Available from: http://www.ipcc.ch/report/ar5/wg1/#.UntbVyeFc1N

ISTAT [2006]: Atlante Statistico dei Comuni (Statistical Atlas of municipalities). Versione 1.0 del 19/07/2006. Progetto interdipartimentale «Informazione statistica territoriale e settoriale per le politiche strutturali 2001–2008». Available from: http://www.istat.it/dati/catalogo/20061102_00/

Lasserre B., Chirici G., Chiavetta U., Garfì V., Tognetti R., Drigo R., Di Martino P, Marchetti M. [2011]: Assessment of Potential Bioenergy from Coppice Forests Trough the Integration of Remote Sensing and Field Surveys. Biomass and Bioenergy 35: 716–24. DOI:10.1016/j.biombioe.2010.10.013

Lamers P., Thiffault E., Paré D., Junginger M. [2013]: Feedstock specific environmental risk levels related to biomass extraction for energy from boreal and temperate forests. Biomass and Bioenergy 55: 212–226. DOI: 10.1016/j.biombioe.2013.02.002

Lattimore B., Smith C.T., Titus B.D., Stupak I., Egnell G. [2009]: Environmental factors in woodfuel production: opportunities, risks, and criteria and indicators for sustainable practices. Biomass and Bioenergy 33 [10]: 1321–1342. DOI: 10.1016/j.biombioe.2009.06.005

Masera O., Ghilardia A., Drigo R., Trossero M.A. [2006]: WISDOM: A GIS-based supply demand mapping tool for woodfuel management. Biomass and Bioenergy 30 [7]: 618–637. DOI: 10.1016/j.biombioe.2006.01.006

Millington A.C., Ryan P., Douglas, Critchley R.W. [1994]: Estimating woody biomass in Sub-Saharan Africa. Washington DC

MAF-ISAFA [1988]: Inventario Forestale Nazionale. Sintesi metodologica e risultati (National Forest Inventory. Synthesis methodology and results). ISAFA, Trento

Masui T., Matsumoto K., Hijioka Y., Kinoshita T., Nozawa T., Ishiwatari S., Kato E., Shukla P.R., Yamagata Y., Kainuma M. [2011]: An emission pathway to stabilize at 6 W/m2 of radiative forcing. Climatic Change 109 [1–2]: 59–76. DOI: 10.1007/s10584-011-0150-5

Muys B. [2013]: Forest Biomass is key to meet EU renewable energy targets. In EFINEWS 1 [21]: 10–11

Muys B., Hetemäki L., Palahi M. [2013]: Sustainable wood mobilization for EU renewable energy targets. Biofuels, Bioproducts and Biorefining 7: 359–360. DOI: 10.1002/bbb.1421

Nabuurs G.J., Lindner M., Verkerk P.J., Gunia K., Deda P., Michalak R., Grassi G. [2013]: First Signs of Carbon Sink Saturation in European Forest Biomass. Nature Climate Change 3: 792–96. DOI:10.1038/nclimate1853

NOAA: http://www.esrl.noaa.gov [accesed 03.09.2013]

Quéré C.L., Andres R.J., Boden T., Conway T., Houghton R.A., House J.I., Marland G, Peters G.P., van der Werf G., Ahlstrom A., Andrew R.M., Bopp L., Canadell J.G., Ciais P., Doney S.C., Enright C., Friedlingstein P., Huntingford C., Jain A.K., Jourdain C., Kato E., Keeling R.F., Goldewijk K., Levis S., Levy P., Lomas M., Poulter P., Raupach M.R., Schwinger J., Sitch S., Stocker B.D., Viovy N., Zaehle S., Zeng N. [2012]: The global carbon budget 1959–2011. Earth System Science Data Discussions 5 [2]: 1107–1157. DOI: 10.5194/essdd-5-1107-2012

Riahi K., Rao S., Krey V., Cho C., Chirkov V., Fischer G., Kindermann G., Nakicenovic N., Rafaj P. [2011]: RCP 8.5-A scenario of comparatively high greenhouse gas emissions. Climatic Change 109: 33–57. DOI: 10.1007/s10584-011-0149-y

Schulze E.D., Körner C., Law B.E., Haberl H., Luyssaert S. [2012]: Large-Scale Bioenergy from Additional Harvest of Forest Biomass Is Neither Sustainable nor Greenhouse Gas Neutral. GCB Bioenergy 4: 611–16. DOI: 10.1111/j.1757-1707.2012.01169.x

Thomson A.M., Calvin K.V., Smith S.J., Kyle G.P., Volke A., Patel P., Delgado-Arias S., Bond-Lamberty B., Wise M.A., Clarke L.E., Edmonds J.A. [2011]: RCP4.5: a pathway for stabilization of radiative forcing by 2100. Climatic Change 109 [1–2]: 77–94. DOI: 10.1007/s10584-011-0151-4

Top N., Mizoue N., Ito S., Kai S., Nakao T., Ty S. [2006]: Re-assessment of woodfuel supply and demand relationships in Kampong Thom Province Cambodia. Biomass and Bioenergy 30: 134–143. DOI: 10.1016/j.biombioe.2005.11.008

Van Vuuren D.P., Stehfest E., Den Elzen M.G.J., Deetman S., Hof A., Isaac M., Klein Goldewijk K., Kram T., Mendoza Beltran A., Oostenrijk R., van Ruijven B. [2011]: RCP2.6: Exploring the possibility of keeping global mean temperature change below 2°C. Climatic Change 109 [1-2]: 95–116. DOI: 10.1007/s10584-011-0152-3

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ELEMENT CONTENT OF SCOTS PINE (*PINUS SYLVESTRIS* L.) STANDS OF DIFFERENT DENSITIES

Modern forestry management should be based on the principle of sustainability. In order to preserve habitat productivity, the amount of nutrients removed from the environment along with forestry products must be taken into consideration. This study shows the exact concentrations of chemical elements in different tree parts of Scots pine, growing on poor soils in north-western Poland. The observed values were compared to the values found in literature. In addition, the relationship between the concentrations of elements and stem diameter or stand density was researched. The highest concentration of chemical elements was observed in the needles (C, N, P, K, Mg, S, Mn, Na, Fe) and the lowest (C, N, P, S, Cu, Na, Ni, Pb, Zn, Fe) in the stem wood. Most of the macronutrients (P, K, Ca, Mg and S) reached optimal values, with the exception of N showing a deficiency, especially in the needles. The relationship between the content of elements and DBH or stand density was rather weak, and in both cases, negative.

Keywords: Scots pine, chemical diversity, nutrients, heavy metals, wood biomass, bark, branches, needles

Introduction

The proper growth and development of plants can be disrupted by inadequate nutrient content or the wrong proportions of elements in the soil. Nutrients are used repeatedly by plants, as they return to the environment with foliage and other

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parts of plants which fall and form litter and then humus. The circulation of elements is to some degree disrupted by the utilization of timber and other parts of plant biomass, which results in a decrease in the pool of elements available for the next generation of living organisms. Pine stands, which usually grow on poor soils, are especially exposed to element shortages. In order to preserve habitat productivity, sustainable forest management should be based on a thorough knowledge of the chemical composition of different tree parts in the Scots pine biomass.

Studies on the content of chemical elements in parts of Scots pine trees have been conducted by many authors. Most studies have focused on the chemical composition of the needles, where most of the elements reached their highest concentrations. The element content in the needles were often studied as part of wider studies concerning various issues, e.g. air and soil pollution [Dmochowski, Bytnerowicz 1995; Giertych et al. 1997; Kurczyńska et al. 1997; Rautio et al. 1998; Lamppu, Huttunen 2003; Rautio, Huttunen 2003; Luyssaert et al. 2005; Merilä, Derome 2008], the influence of various final felling methods on nutrient withdrawal from the forest environment [Jacobson et al. 2000; Olsson et al. 2000; Gornowicz 2002; Palviainen et al. 2004; Luiro et al. 2010; Saarsalmi et al. 2010; Palviainen, Finér 2012], an evaluation of the effects of fertilization [Bramryd 2001; Nilsen, Abrahamsen 2003; Røsberg et al. 2006; Saarsalmi et al. 2006; Prietzel et al. 2008; Moilanen et al. 2013] and other issues [Raitio 1990; Helmisaari 1992; Migaszewski 1997; Reimann et al. 2001, Hytönen, Wall 2006; Baumann et al. 2006; Pensa et al. 2007; Blanco et al. 2008; Mandre et al. 2010; Kuznetsova et al. 2011; Armolaitis et al. 2013; Pietrzykowski et al. 2014].

The chemical composition of other aboveground parts of the tree (stem wood, bark and branches) has been studied significantly less often [Fober 1993; Finer, Kaunisto 2000; Gornowicz 2002; Meerts 2002; Palviainen et al. 2004; Saarela et al. 2005; Kuznetsova et al. 2011; Armolaitis et al. 2013].

The aim of this study was to determine the concentrations of selected elements in different parts of Scots pine trees and to test the relationship between the element content in different tree parts and tree diameter or stand density.

Materials and methods

The research material was collected on experimental plots (0.5 ha) in 82-year old Scots pine (*Pinus sylvestris* L.) stands, located in Drawno Forest District, north-western Poland (longitude from E 15°50’ to E 16°00’, latitude from N 53°10’ to N 53°13’). This area is characterized by poor habitats on sandy soils, where the dominant tree species is Scots pine. It mostly forms single-species and even-aged stands with a small admixture of other tree species, usually birch.

The chemical analysis was carried out for trees growing in 5 single-species and even-aged stands with different stand densities (table 1). On each 0.5 ha sample plot, 3 model trees, representing the entire range of tree diameters, were chosen (fig. 1). The 15 model trees selected were then cut down, divided into tree parts – the stem, branches, needles and cones – and immediately weighed. In order to establish the dry weight and element content, samples were taken from each part of each tree. Every sample was first weighed fresh, and then again after drying at a temperature of 65°C to constant mass.

Table 1. Main characteristics of sampled Scots pine stands [area 0.5 ha and age 82 years]

Sample plot	Density, [tree ha^{-1}]	Mean DBH, cm]	Mean height, [m]	Basal area, [m^2 ha^{-1}]	Volume, [m^3 ha^{-1}]
1	476	28.2	22.9	30.5	319
2	570	25.7	20.8	31.5	302
3	672	23.6	19.6	30.3	275
4	756	23.9	20.1	35.6	337
5	824	21.8	19.3	31.7	286

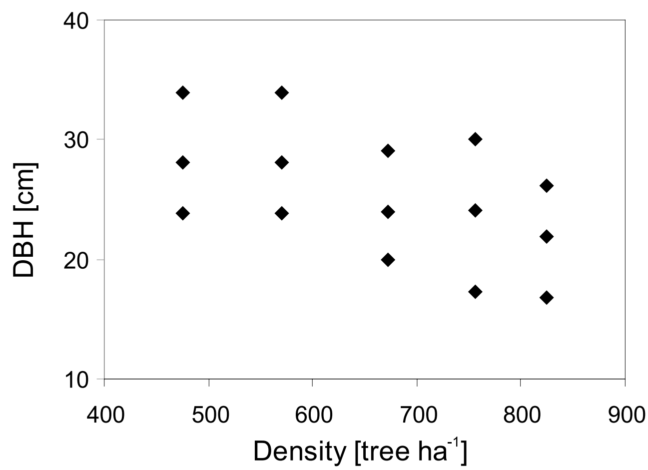

Fig. 1. Stand densities and diameters (DBH) of model trees (N = 15) from which samples were taken for analysis of mineral content

The samples were taken from the tree trunks in the form of two discs. The tree trunks were divided into two parts: one section of more than 14 cm in diameter and the rest of the trunk. The discs were cut out from the middle of each section. The discs had various diameters – corresponding to the trunk diameter – and a length of 10 cm. After drying, the bark and wood were separated. From the cross-sectional area of the discs, shavings were collected using a mechanical planer. Bark and wood shavings were milled and samples for chemical analysis were collected.

The branches were divided into living and dead. The living branches were cut with secateurs into two parts – twigs covered with needles and the rest of the branch. The needles and cones were separated from the twigs. From each of the aforementioned parts samples were milled and taken to determine element content.

Chemical analyses were performed in the Laboratory of Environmental and Soil Remediation Geochemistry, the Department of Forest Ecology and Department of Forest Soil Science, the Faculty of Forestry at the University of Agriculture in Kraków. The samples were mineralized in HNO_3 and by using an ICP-OES device, the content of the following elements was determined: P, K, Ca, Mg, Mn, Cd, Cr, Cu, Na, Ni, Pb, Zn and Fe. Without mineralization, by using a LECO TruMac CNS device, the content of C, N and S was determined.

Statistical analyses were performed using the "Multivariate Platform" tool in JMP 10.0 statistical software (SAS Institute Inc., Cary, NC, USA). From these Pearson correlation coefficients (r) and the corresponding levels of significance were obtained. On this basis, an assessment of the correlations between the element content and tree diameter and density of the stands was performed. The diameter at breast height (DBH) was measured 1.3 m above the ground.

Results and discussion

The average concentrations of 16 elements in individual parts of the aboveground part of the Scots pine trees are shown in table 2. The highest concentrations were usually found in the needles and thin branches. In these parts, the N, P and K content significantly decreased with the increase in trunk diameter (fig. 2, table 3). Such a correlation was not observed regarding the stand density (fig. 3, table 4). In contrast to the other elements – the highest concentration of Ca was found in the bark (fig. 2, fig. 3). For all the other analysed elements, the lowest concentrations were found in the wood and dead branches (table 2).

Table 2. Mean (±SD) concentrations of elements in different tree parts of sampled Scots pine stands

Element [mg g^{-1}]	Stem wood	Stem bark	Thick branches	Thin branches	Dead branches	Needles	Cones
1	2	3	4	5	6	7	8
C	470±4.9	471±9.5	488±9.6	502±5.7	496±9.9	503±2.9	495±20.7
N	0.83±0.21	4.91±1.06	2.53±0.96	7.08±1.01	1.89±0.54	12.3±1.19	4.78±5.15
P	0.07±0.04	0.62±0.18	0.33±0.08	0.78±0.10	0.09±0.02	1.15±0.14	0.75±0.57
K	0.27±0.15	1.53±0.52	1.15±0.24	2.65±0.44	0.18±0.16	4.45±0.61	3.31±1.51
Ca	0.65±0.13	7.89±1.85	2.05±0.27	2.26±0.28	1.49±0.42	3.16±0.38	0.31±0.17
Mg	0.27±0.10	0.99±0.31	0.42±0.07	0.63±0.09	0.17±0.05	0,65±0.11	0.48±0.20

Table 2. Continued

1	2	3	4	5	6	7	8
S	0.03±0.02	0.43±0.10	0.25±0.16	0.73±0.12	0.21±0.07	1.28±0.10	0.65±0.37
Mn	0.15±0.05	0.65±0.15	0.32±0.06	0.34±0.06	0.22±0.07	1.13±0.21	0.12±0.09
Cd	0.24±0.07	0.97±0.28	0.47±0.11	0.41±0.08	0.36±0.11	0.10±0.03	0.05±0.04
Cr	0.99±0.91	0.00±0.0	1.06±0.73	1.27±0.77	0.74±0.86	1.10±1.78	0.17±0.23
Cu	0.94±0.92	2.39±0.84	1.48±0.76	3.60±1.30	1.44±1.23	2.67±0.93	2.51±1.57
Na	7.33±3.1	10.5±4.2	49.1±9.2	58.9±21.5	26.0±13.8	59.1±20.9	16.8±11.9
Ni	0.25±0.09	0.76±0.42	0.46±0.11	1.21±0.32	0.52±0.26	2.89±2.33	4.30±2.09
Pb	0.79±0.72	1.41±0.87	2.59±0.57	2.80±0.85	1.70±0.65	2.10±1.54	4.01±3.56
Zn	11.7±3.1	66.6±18.7	34.7±6.4	45.0±13.1	25.7±7.5	47.4±6.9	21.5±10.7
Fe	13.4±10.7	22.2±6.8	23.3±19.2	32.7±15.8	21.9±11.1	34.2±15.7	21.9±6.0

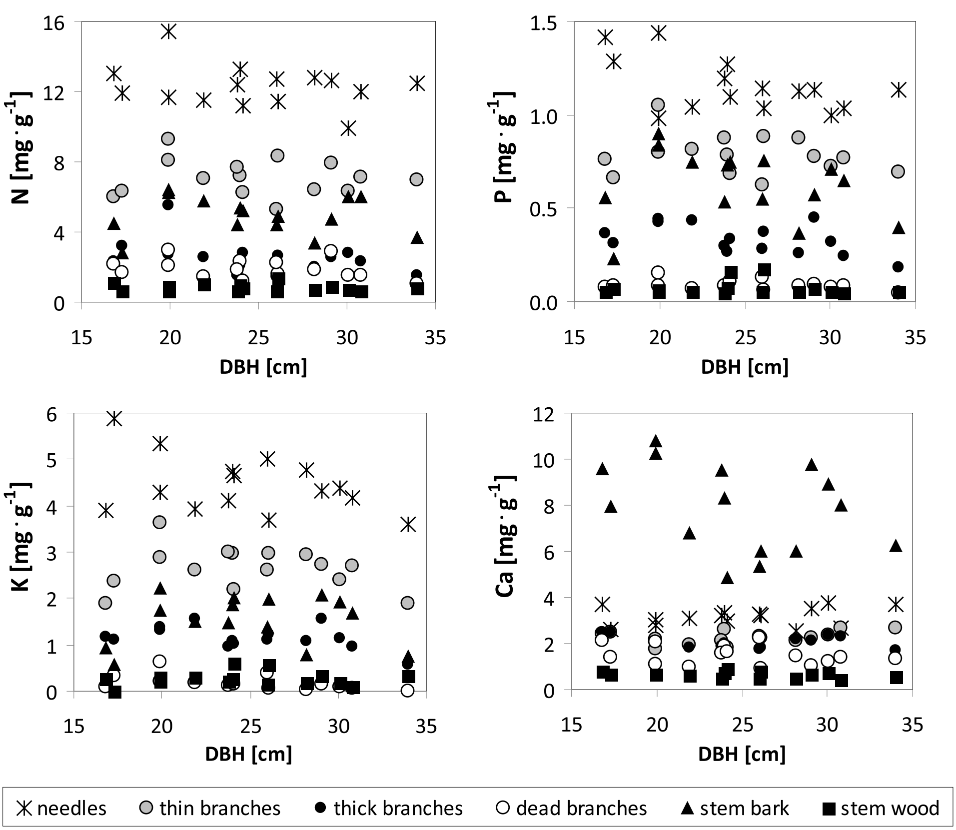

Fig. 2. Concentration of N, P, K and Ca in given parts of Scots pine trees of different stem diameter (DBH)

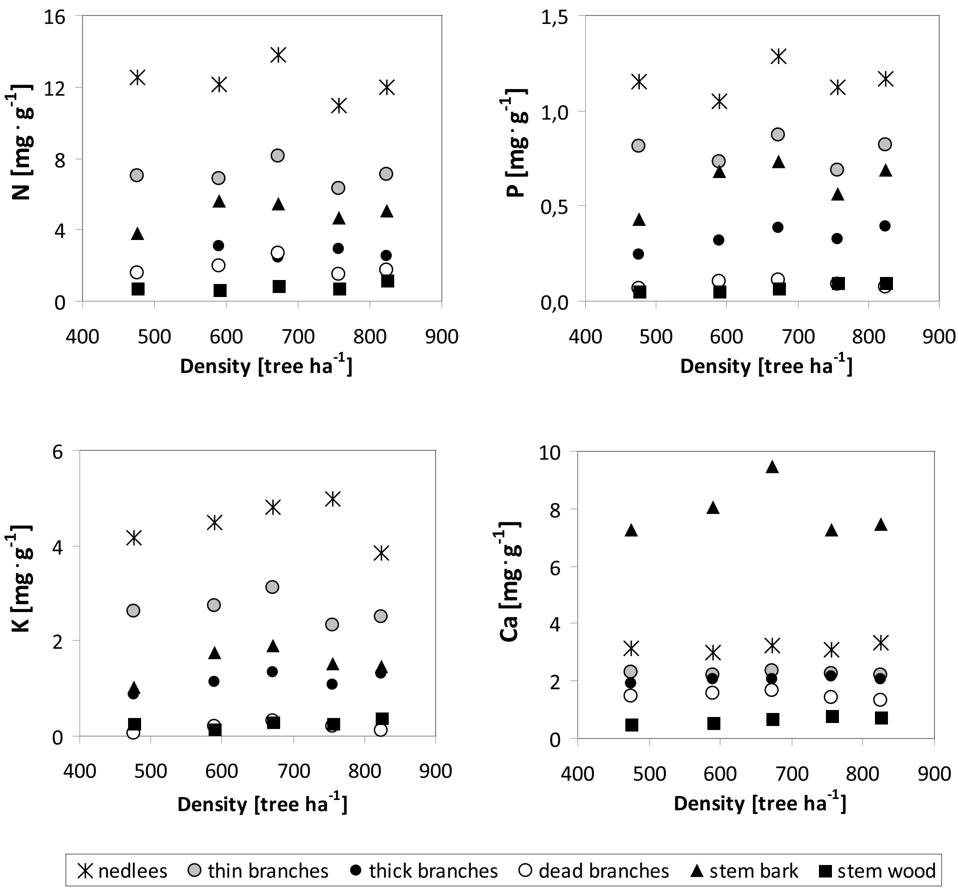

Fig. 3. Concentration of N, P, K and Ca in given parts of Scots pine trees from stands of different densities

For 9 of the studied elements (C, N, P, K, Mg, S, Mn, Na and Fe), the highest concentration was found in the needles, for 3 (Ca, Cd, Zn) in the bark, for 2 (Cu, Cr) in the twigs and for 2 in the cones (Ni, Pb). The lowest concentrations for 9 of the studied elements were found in the stem wood (C, N, P, S, Cu, Na, Ni, Pb, Zn and Fe), for 3 in the cones (Ca, Mn, Cd), for 2 in the dead branches (K, Mg) and for 1 (Cr) in the bark.

In most of the analysed cases, an inverse relationship between the concentration of elements in the individual parts of the tree and the diameter at breast height (DBH) of the particular tree was found (table 3). A statistically significant relationship was observed in six cases for Cd and in five cases for Zn. The relationship between the concentration of elements and the stand density was much weaker (table 4). Nevertheless, in those cases where it was statistically significant, the correlation coefficient was of a negative value, as it was for DBH.

Table 3. Correlation between tree diameter (DBH) and concentrations of elements in different tree parts of Scots pine trees

Element	Stem wood	Stem bark	Thick branches	Thin branches	Dead branches	Needles
C	-0.449*	0.254	0.150	0.013	-0.123	-0.232*
N	-0.128	-0.032	-0.437*	-0.070	-0.315	-0.270*
P	0.002	-0.141	-0.523*	-0.190	-0.331	-0.543*
K	0.083	0.085	-0.428*	-0.133	-0.498*	-0.405*
Ca	-0.347*	-0.365*	-0.292	0.365	-0.316	0.266
Mg	-0.211	-0.196	-0.257	-0.023	-0.227	-0.145
S	0.010	-0.210	-0.389*	-0.188	-0.284	-0.316*
Mn	-0.287*	-0.419*	-0.356*	-0.063	-0.261	-0.331*
Cd	-0.500*	-0.689*	-0.631*	-0.555*	-0.550*	-0.236*
Cr	-0.656*	0.000	-0.200	-0.135	-0.630*	0.241
Cu	0.221	0.313	-0.314	-0.224	-0.116	-0.255*
Na	0.092	0.014	0.008	-0.060	-0.404*	-0.043
Ni	-0.173	-0.181	-0.575*	-0.306*	-0.432*	0.311
Pb	-0.395*	-0.018	-0.255	-0.333*	-0.282	-0.003
Zn	-0.086	-0.333*	-0.619*	-0.350*	-0.549*	-0.377*
Fe	0.574	0.254	-0.385	-0.168	-0.081	-0.066

* Significant at $p < 0.05$

Table 4. Correlation between stand density and concentrations of elements in different tree parts of sampled Scots pine stands

Element	Stem wood	Stem bark	Thick branches	Thin branches	Dead branches	Needles
C	-0.064	-0.170	0.146	0.096	0.107	0.528
N	0.670	0.463	0.409	-0.010	-0.038	0.043
P	0.812	0.683	0.849	0.048	-0.132	0.591
K	0.659	0.439	0.789	0.263	-0.264*	0.235
Ca	0.804	-0.191	0.301	-0.460*	-0.052	0.769
Mg	0.655	0.620	0.781	0.055	-0.283*	-0.246
S	0.553	0.374	-0.020	-0.044	-0.432*	0.186
Mn	0.486	0.042	0.468	0.130	-0.019	0.656
Cd	0.991	0.745	0.565	0.522	0.472	-0.484*
Cr	0.830	0.000	0.822	0.591	-0.026	0.508
Cu	-0.090	-0.153	0.288	-0.697*	-0.321*	0.972
Na	-0.966*	-0.630*	0.092	0.581	0.221	0.389
Ni	-0.471*	-0.355*	0.639	0.616	0.486	-0.409*
Pb	0.905	0.209	0.098	0.848	0.809	0.455
Zn	0.043	-0.300*	0.932	0.641	0.588	0.268
Fe	-0.888*	-0.511*	0.158	-0.092	0.261	0.580

* Significant at $p < 0.05$

From all the analysed macronutrients, only N showed a deficiency. In the needles, an N content lower than 12 g·kg^{-1} is considered insufficient [Fober 1993; Kurczyńska et al. 1997; Moilanen et al. 2013]. From the five analysed sample plots, only one had an optimal N concentration, on three it was at the limit of the range, and on one it was below the optimal range. Similarly low N concentrations were found in the other tree parts.

The other analysed macronutrients (P, K, Ca, Mg and S) reached concentrations within the acceptable range and close to the values quoted by other authors [Raitio 1990; Johansson 1995; Kurczyńska et al. 1997; Giertych et al. 1997; Migaszewski 1997; Rautio et al. 1998; Olsson et al. 2000; Reimann et al. 2001; Gornowicz 2002; Luyssaert et al. 2005; Saarela et al. 2005; Hytönen, Wall 2006; Saarsalmi et al. 2006; Merilä, Derome 2008; Prietzel et al. 2008; Saarsalmi et al. 2010; Luiro et al. 2010; Kuznetsova et al. 2011; Armolaitis et al. 2013; Moilanen et al. 2013].

With regard to the micronutrients and heavy metals, the one deviating most from the accepted ranges was Mn. According to Fober [1993], the correct content of Mn in Scots pine needles should not exceed 1000 mg·kg^{-1}. Among the 5 sample plots studied, the concentration of Mn in the needles exceeded on 4 sample plots and was close to the upper limit on one. The concentration of Mn in the wood and bark, however, did not differ from the values given by Fober [1993] and Saarela et al. [2005]. The Fe content in the needles was lower than the range quoted by Fober [1993], but did not differ from the results obtained by other authors. However, the concentration of Fe in the branches and bark was lower than quoted by other authors [Fober 1993; Palviainen et al. 2004; Saarela et al. 2005]. The concentration of Cr had a wider range, compared to literature [Rautio et al. 1998; Bramryd 2001; Reimann et al. 2001; Saarsalmi et al. 2006]. The concentration of Cu, Zn, Ni and Pb was within the range given by other authors [Raitio 1990; Helmisaari 1992; Dmochowski, Bytnerowicz 1995; Giertych et al. 1997; Rautio et al. 1998; Bramryd 2001; Reimann et al. 2001; Saarsalmi et al. 2010; Moilanen et al. 2013].

Conclusions

The highest concentration of chemical elements was observed in the needles and the lowest in the stem wood. For C, N, P, K, Mg, S, Mn, Na and Fe, the highest concentration was found in the needles, for Ca, Cd and Zn in the bark, for Cu and Cr in the twigs and for Ni and Pb in the cones. The lowest concentrations were observed for C, N, P, S, Cu, Na, Ni, Pb, Zn and Fe in the stem wood, for Ca, Mn and Cd in the cones, for K and Mg in the dead branches and for Cr in the bark.

Among all the studied macronutrients, only N showed a deficiency, especially in the needles. Similarly, low concentrations of N were found in the other tree parts. The rest of the macronutrients (P, K, Ca, Mg and S) reached optimal values.

From the microelements and heavy metals, the one deviating the most from the accepted ranges was Mn, with the exception of its concentration in the stem wood and bark, where it was within the optimal range.

In most of the analysed cases, the inverse relationship between the element content of the various tree parts and the DBH of these trees was found. A statistically significant relationship was observed in all six cases for Cd and in five cases for Zn.

The relationship between the mineral content and stand density was much weaker. Nevertheless, whenever it was statistically significant, the correlation coefficient was always negative.

References

Armolaitis K., Varnagirytė-Kabašinskienė I., Stupak I., Kukkola M., Mikšys V., Wójcik J. [2013]: Carbon and nutrients of Scots pine stands on sandy soils in Lithuania in relation to bioenergy sustainability. Biomass and Bioenergy 54: 250–259

Baumann K., Rumpelt A., Schneider B.U., Marschner P., Hüttl R.F. [2006]: Seedling biomass and element content of *Pinus sylvestris* and *Pinus nigra* grown in sandy substrates with lignite. Geoderma 136 [3–4]: 573–578

Blanco J.A., Imbert J.B., Castillo F.J. [2008]: Nutrient return via litterfall in two contrasting *Pinus sylvestris* forests in the Pyrenees under different thinning intensities. Forest Ecology and Management 256 [11]: 1840–1852

Bramryd T. [2001]: Effects of liquid and dewatered sewage sludge applied to a Scots pine stand (*Pinus sylvestris* L.) in central Sweden. Forest Ecology and Management 147 [2–3]: 197–216

Dmochowski W., Bytnerowicz A. [1995]: Monitoring environmental pollution in Poland by chemical analysis of Scots pine (*Pinus sylvestris* L.) needles. Environmental Pollution 87 [1]: 87–104

Finer L., Kaunisto S. [2000]: Variation in stemwood nutrient concentrations in Scots pine growing on peatland. Scandinavian Journal of Forest Research 15 [4]: 424–432

Fober H. [1993]: Żywienie mineralne (Mineral Nutrition). In: Białobok S., Boratyński A., Bugała W. (ed.) Biologia sosny zwyczajnej (Biology of Scots Pine). Sorus, Poznań – Kórnik: 182–193

Giertych M.J., De Temmerman L.O., Rachwał L. [1997]: Distribution of chemical elements along the length of Scots pine needles in a heavily polluted and a control environment. Tree Physiology 17 [11]: 697–703

Gornowicz R. [2002]: Wpływ pozyskania biomasy sosny zwyczajnej (*Pinus sylvestris* L.) na wycofywanie pierwiastków biogennych ze środowiska leśnego (Effects of Scots Pine *Pinus sylvestris* L. harvesting on nutrient losses in forest environment). Roczniki Akademii Rolniczej w Poznaniu 331: 1–96

Helmisaari H.-S. [1992]: Spatial and age-related variation in nutrient concentrations of *Pinus sylvestris* needles. Silva Fennica 26 [3]: 145–153

Hytönen J., Wall A. [2006]: Foliar colour as indicator of nutrient status of Scots pine (*Pinus sylvestris* L.) on peatlands. Forest Ecology and Management 237 [1–3]: 156–163

Jacobson S., Kukkola M., Mälkönen E., Tveite B. [2000]: Impact of whole-tree harvesting and compensatory fertilization on growth of coniferous thinning stands. Forest Ecology and Management 129 [1–3]: 41–51

Johansson M.B. [1995]: The chemical composition of needle and leaf litter from Scots pine, Norway spruce and White birch in Scandinavian forests. Forestry 68 [1]: 49–62

Kurczyńska E.U., Dmochowski W., Włoch W., Bytnerowicz A. [1997]: The influence of air pollution on needles and stems of Scots pine (*Pinus sylvestris* L.) trees. Environmental Pollution 98 [3]: 325–334

Kuznetsova T., Lukjanova A., Mandre M., Lõhmus K. [2010]: Aboveground biomass and nutrient accumulation dynamics in young black alder, silver birch and Scots pine plantations on reclaimed oil shale mining areas in Estonia. Forest Ecology and Management 262 [2]: 56–64

Lamppu J., Huttunen S. [2003]: Relations between Scots pine needle element concentrations and decreased needle longevity along pollution gradients. Environmental Pollution 122 [1]: 119–126

Luiro J., Kukkola M., Saarsalmi A., Tamminen P., Helmisaari, H.-S. [2010]: Logging residue removal after thinning in boreal forests: long-term impact on the nutrient status of Norway spruce and Scots pine needles. Tree Physiology 30 [1]: 78–88

Luyssaert S., Sulkava M., Raitio H., Hollmén J. [2005]: Are N and S deposition altering the chemical composition of Norway spruce and Scots pine needles in Finland? Environmental Pollution 138 [1]: 5–17

Mandre M., Lukjanova A., Pärn H., Kõresaar K. [2010]: State of Scots pine (*Pinus sylvestris* L.) under nutrient and water deficit on coastal dunes of the Baltic Sea. Trees 24 [6]: 1073–1085

Meerts P. [2002]: Mineral nutrient concentrations in sapwood and heartwood: a literature review. Annals of Forest Science 59 [7]: 713–722

Merilä P., Derome J. [2008]: Relationships between needle nutrient composition in Scots pine and Norway spruce stands and the respective concentrations in the organic layer and in percolation water. Boreal Environment Research 13 [suppl. B]: 35–47

Migaszewski Z.M. [1997]: Skład chemiczny igieł sosny zwyczajnej *Pinus sylvestris* L. w Regionie Świętokrzyskim (Chemistry of Scots pine *Pinus sylvestris* L. needles in Holy Cross Mountains region). Wiadomości Botaniczne 42 [3/4]: 79–91

Moilanen M., Saarsalmi A., Kukkola M., Issakainen J. [2013]: Effects of stabilized wood ash on nutrient status and growth of Scots pine – Comparison between uplands and peatlands. Forest Ecology and Management 295: 136–144

Nilsen P., Abrahamsen G. [2003]: Scots pine and Norway spruce stand responses to annual N, P and Mg fertilization. Forest Ecology and Management 174 [1–3]: 221–232

Olsson B.A., Lundkvist H., Staaf H. [2000]: Nutrient status in needles of Norway spruce and Scots pine following harvesting of logging residues. Plant and Soil 223 [1–2]: 163–175

Palviainen M., Finér L. [2012]: Estimation of nutrient removals in stem-only and whole-tree harvesting of Scots pine, Norway spruce, and birch stands with generalized nutrient equations. European Journal of Forest Research 131 [4]: 945–964

Palviainen M., Finér L., Kurka A., Mannerkoski H., Piirainen S., Starr M. [2004]: Release of potassium, calcium, iron, and aluminium from Norway spruce, Scots pine and silver birch logging residues. Plant and Soil 259 [1–2]: 123–136

Pensa M., Jalkanen R., Liblik V. [2007]: Variation in Scots pine needle longevity and nutrient conservation in different habitats and latitudes. Canadian Journal of Forest Research 37 [9]: 1599–1604

Pietrzykowski M, Socha J, van Doorn N.S. [2014]: Linking heavy metal bioavailability (Cd, Cu, Zn and Pb) in Scots pine needles to soil properties in reclaimed mine areas. Science of the Total Environment 470–471: 501–510

Prietzel J., Rehfuess K.E., Stetter U., Pretzsch H. [2008]: Changes of soil chemistry, stand nutrition, and stand growth at two Scots pine (*Pinus sylvestris* L.) sites in Central Europe during 40 years after fertilization, liming, and lupine introduction. European Journal of Forest Research 127 [1]: 43–61

Raitio H. [1990]: The foliar chemical composition of young pines (*Pinus sylvestris* L.) with or without decline. In: Acidification in Finland. Eds. P. Kauppi, P. Anttila and K. Kenttämies. Springer-Verlag, Berlin, p. 701–715

Rautio P., Huttunen S. [2003]: Total vs. internal element concentrations in Scots pine needles along a sulphur and metal pollution gradient. Environmental Pollution 122 [2]: 273–289

Rautio P., Huttunen S. Lamppu J. [1998]: Element concentrations in Scots pine needles on radial transects across a subarctic area. Water, Air and Soil Pollution 102 [3–4]: 389–405

Reimann C., Koller F., Frengstad B., Kashulina G., Niskavaara H., Englmaier P. [2001]: Comparison of the element composition in several plant species and their substrate from a 1500000-km^2 area in Northern Europe. The Science of the Total Environment 278 [1–3]: 87–112

Røsberg I., Frank J., Stuanes A.O. [2006]: Effects of liming and fertilization on tree growth and nutrient cycling in a Scots pine ecosystem in Norway. Forest Ecology and Management 237 [1–3]: 191–207

Saarela K.-E., Harju L., Rajander J., Lill J.O., Heselius S.J., Lindroos A., Mattsson, K. [2005]: Elemental analyses of pine bark and wood in an environmental study. The Science of the Total Environment 343 [1–3]: 231–241

Saarsalmi A., Kukkola M., Moilanen M., Arola M. [2006]: Long-term effects of ash and N fertilization on stand growth, tree nutrient status and soil chemistry in a Scots pine stand. Forest Ecology and Management 235 [1–3]: 116–128

Saarsalmi A., Tamminen P., Kukkola M., Hautajärvi R. [2010]: Whole-tree harvesting at clear-felling: impact on soil chemistry, needle nutrient concentrations and growth of Scots pine. Scandinavian Journal of Forest Research 25 [2]: 148–156

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BIOMASS OF THE XEROTHERMIC OAK ECOSYSTEM ON A SITE OF COMMUNITY IMPORTANCE, BG0001040 "ZAPADNA STARA PLANINA I PREDBALKAN", BULGARIA

The belowground and aboveground biomass was estimated for the tree story, sprouts and seedling regeneration in a representative Quercus frainetto – Quercus cerris ecosystem on "Zapadna Stara planina i Predbalkan", a Site of Community Importance (SCI). The biomass was measured by destructive sampling (on sample or "model trees" representing three calculated density classes for each species and cut at the stump) of leaves, annual and perennial branches, wood, bark and root components. The belowground (root) biomass was also calculated from a subsample. The data obtained were compared to the results of previous studies and the values on the Bazilevich and Rodin [1971] scale. The ecological status of the forest ecosystem studied and its functional efficiency are discussed based on the study results and specific climate data.

Keywords: *Quercus frainetto – Q. cerris* ecosystem, biomass, SCI, Bulgaria

Introduction

Quercus frainetto-Quercus cerris ecosystems are elements of potential vegetation in Bulgaria and thus contribute to the biological (structural and functional) diversity of Bulgarian forest vegetation, a part of the Illyrian (Balkan) province of the European deciduous forest region. Xerothermic forests belonging to habi-

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tat 91M0 Pannonian – Balkanic turkey oak-sessile oak forests [Kavrakova et al. 2009], which occupy 5% (11042 ha) of the whole territory of the Natura 2000 site: BG0001040 "Zapadna Stara planina i Predbalkan", were studied. This site is the second largest Natura site in Bulgaria, of 219753.26 ha, and it preserves deciduous forest ecosystems a part of beech and oak forests. This habitat is mainly distributed in low mountain and foothill areas and is intensively exploited in Bulgaria; therefore the forests mostly originate from sprouts (coppice reproduction) with impaired ecological and economic functions.

Basic investigations on the aboveground primary production of forest ecosystems in Bulgaria and the Balkan region have been carried out by Melovski et al. [1994]; Grupche et al. [1995] and others. The published data about oak ecosystems functioning in Bulgaria for the period 1985–2009 are cited by Lyubenova [2009].

Studies on the belowground biomass of oak ecosystems in Bulgaria have been published by Lyubenova and Bondev [1987] and Lyubenova [1992]. Mihov [1979] considered the root system biomass of white pine plantations in Bulgaria. Other research has been conducted by Hristovski et al. [2008] in Macedonia; Brumme and Khanna [2009] in European beech ecosystems; and Le Goff and Ottorini [2001] in beech communities in North-East France. Bolte et al. [2004] investigated the belowground plant mass of coarse roots in mixed stands of beech communities. Puhe [2002] studied the plant mass of spruce trees in central Europe. Kurz et al. [1996] obtained data on the root biomass as a considerable carbon depot in the Canadian forest sector. Brunner and Godbold [2007] carried out general research on all aspects of root biomass.

Despite the aforementioned research, the information available on total belowground biomass and on its accumulation of carbon is insufficient. Existing methods for studying belowground biomass are very labor-intensive and often do not provide sufficiently accurate data. For this reason, such data have often been unpublished.

The aim of this study was to estimate the belowground and aboveground biomasses of xerothermic oak ecosystems in the SCI[1] Zapadna Stara planina i Predbalkan, as well as to collect and compare existing data for the ecosystems of interest and to evaluate the habitat function in order to augment previous European investigations, which mainly focused on structure.

[1] SCI (Site of Community Importance) – this is a protected area in European countries which is part of the Natura 2000 network of nature protection areas established by the European Union (EU).

Materials and methods

Inventory of Study Sites

Xerothermic (hot dry) oak ecosystems occupy an elevation range of 0 to 650 m and a slope range from 0 to 40 degrees within the SCI. The largest extent of these ecosystems occurs at an altitude of approx. 300 m and on 15 degree slopes. The *Quercus frainetto-Quercus cerris* (Hungarian or Italian oak – Turkey oak) ecosystems in the study area are of mixed (seed or coppice) origin; only 2% are tall seminal (seed-grown) forests. Using the forest management plan and map for the SCI, polygons in the largest oak forest massifs of the SCI were differentiated, which met the average geographical conditions for distribution (described above). These marked polygons covered 0.6% (1415.4 ha) of the habitat area in the SCI. Four rectangular sampling areas (SAs) or plots of 0.25 ha were then randomly selected from these polygons. All the trees in the tree layer on the four SAs were inventoried. The understory (bush and herb) layers of small trees (at the height of bushes 3–8 m and diameter <10 cm) and different bush species as well as herb species and seedlings of trees and bushes were inventoried on subplots. The site description results and observations describing the SAs are given below.

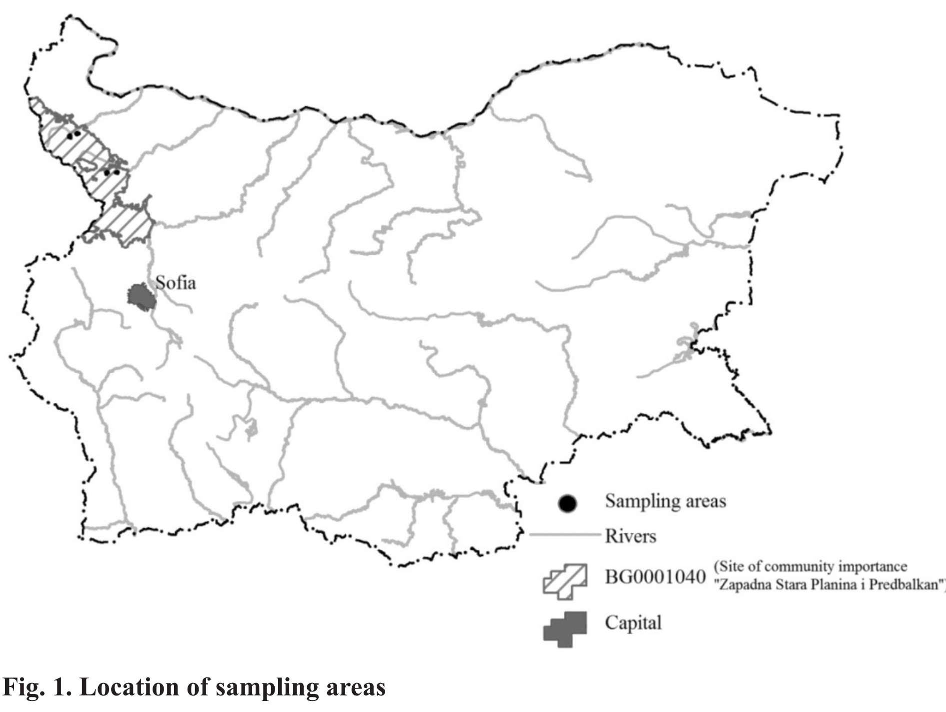

Fig. 1. Location of sampling areas

SA1 was dominated by *Quercus frainetto* Ten. (96.8%). The number of trees in the tree layer was 836 per ha and the total canopy ranged from 0.6 to 0.8 (ocular estimation). The bush layer (less than 10% ocular estimated cover and approx. 3–4 m in height) included four tree species (*Carpinus orientalis* Mill., *Q. frainetto* Ten., *Tilia plathyphyllos* Scop., and *Fraxinus ornus* L.) and eight shrub species. The herb layer had 40–50% coverage and was formed of 29 species, including *Helleborus odorus* Waldst. & Kit., *Carex caryophyllea* Latourr, *Dactylis glomerata* L., *Poa nemoralis* L., and *Lathyrus niger* (L.) Bernh. etc. Dominant tree reproduction from seeds was very good.

SA2 was dominated by *Quercus cerris* L. (58.67% of the total) and *Quercus frainetto* Ten. The total number of trees amounted to 600 per ha. The canopy of tree layer ranged from 0.6–0.9. The bush layer (20% coverage and 7–8 m in height) included 4 trees (*Carpinus betulus* L., *Q. cerris* L., *Sorbus torminalis* (L.) Crantz., *Acer campestre* L.) and nine shrubs. The herb layer had a coverage of 30–40% and included 33 species. The seed regeneration for the dominant oak species was poor but some seedlings such as *Fraxinus ornus* L., *Carpinus orientalis* Miller., and *Sorbus torminalis* (L.) Crantz. were described.

SA3 was dominated by *Quercus cerris* L. and *Quercus frainetto* Ten. with 596 trees per ha, of which 66% were Turkey oak. The canopy of tree layer was 0.6–0.7. The bush layer coverage (average height 7–8 m) was 40% and included six species of tree sprouts – *Crataegus monogyna* Jacq., *Cornus mas* L., *Carpinus orientalis* Miller., *Fraxinus ornus* L., and *Acer campestre* L., and six species of shrubs. The herb layer coverage was 40% and included 31 species. Oak seedling reproduction was poor.

SA4 was dominated by *Quercus frainetto* Ten. There were 668 trees per ha in the tree layer, of which 86% were Turkey oak. The canopy of tree layer ranged from 0.6–0.7. The bush layer coverage was 30% (height 3–4 m) and included tree sprouts of *Q. frainetto* Ten., *Q. cerris* L. and *Fraxinus ornus* L., as well as *Crataegus monogyna* Jacq. and *Cornus mas* L. bushes and 14 other species. The herb layer covered 30–50%, including 33 species with a predominance of *Primula veris* L. and *Astragalus glycyphyllos* L. The dominant trees had good seed reproduction.

Tree biomass measurement

The measurements of the aboveground biomass were carried out using traditional methods from Scandinavian-Russian scientific literature for calculating forest biomass and production [Molchanov et al. 1967; Rodin et al. 1968; Dimitrov 2000; adapted by Lyubenova 2009]. Instead of using biomass equations, this method destructively samples biomass from 1 or more trees of mean species/dimensions, from each of several diameter classes determined by dividing the measured values of the diameters of all the trees in the tree layer of each plot at 4 cm intervals, or by dividing the sum of the cross-sectional areas of the trees (calculated using DBH) in 3 equal sums for three classes of thickness. The total biomass for each diameter class was then obtained by multiplying the biomass of the "mean tree" (according to DBH, height, diameter of crown and habitus), henceforth called the model tree, by the number of trees in each diameter class. This method is presumed more accurate than calculations using biomass equations.

The diameter (DBH) of all the oak trees in the tree layer, their average height and the diameter of their crowns were measured in each SA. Diameter classes for each SA were based on a calculation of the sum of the stem cross-section at 1.3 m (the level of DBH) for *Q. cerris* L. and for *Q. frainetto* Ten. or basal area calculated as $\Sigma[(DBH/2)^2 \cdot 3.14]$. Three diameter classes were defined for each SA by dividing the total basal area of each SA into thirds. This was done by successively summing the single basal area to provide one-third of the total basal area for each thickness class, and the number of trees from the first, second and third classes of thickness was obtained (n1, n2, and n3, where n1 > n2 > n3). The diameter of the first class model tree (DBH1) was calculated as: $\sqrt{[(\Sigma S/3) / (n1 \cdot 3.14)]} \cdot 2$ and likewise for the other two classes. The average height and crown area were also calculated for the trees in each class. Table 1 summarizes these results.

Trees with the average dimension for each diameter class (summarized in table 1) were used to identify a "model tree" or tree of average size for each class and oak species on each SA. There were 18 model trees (the number of Turkey oak trees was under 10% of the total number of all the trees in SA1 and SA4, therefore models were not taken) harvested for their destructive biomass measurement at the end of the growing season (October 2013), when the accumulation of biomass was complete.

The stem of each model tree was divided into 2-m sections. Discs from the middle of the sections were taken to determine the absolute dry weight, and perform a chemical analysis and stem analysis of the growth in height, diameter, volume and weight for the whole period of forest existence. The stem volume was calculated using Huber's formula ($V = \Sigma S \cdot L + V_{is}$, where ΣS is the sum of the circular area of the stem discs, L = 200 cm, and V_{is} – the volume of the last section under 2 m, calculated using the formula for the volume of a cone) [Iliev et al. 1980]. The volume of the bark was calculated as the difference between the volume of the stem with bark and without bark based on the measured diameters of the discs with and without bark. The biomass was calculated using the volumetric (specific gravity conversion) weight of the respective wood and bark samples [Lyubenova 2009]. The wood and bark samples were dried for 48 h at 105°C. The dynamics of the biomass accumulation and stem growth in height during 5-year periods were analysed on the basis of the data obtained through the model trees in the third class of thickness to cover the largest possible period of time. Therefore, the volume and height of the stems were calculated for every 5-year period and then values were averaged for the 3rd class models of Turkish and Italian oak. The resulting diagrams outline the current and future trends in the growth of the forests [Dimitrov 2000; Lyubenova 2009].

Table 1. Summary of inventory data by model trees in sampling areas

SA	No.	Species	DBH Class	QMD [cm]	Mean H [m]	Mean crown D [cm]	Mean crown H [m]	Number of trees per class [n]	Stem [kg]	Annual branches [kg]	Perennial branches [kg]	Acorns [kg]	Leaves [kg]
1	1	Q. frainetto Ten.	1	16.04	15.60	4.60	10.15	117	80.342	0.329	12.928	–	3.459
	2		2	22.55	20.20	6.15	14.42	59	205.214	0.592	65.264	–	5.562
	3		3	30.02	24.00	8.75	16.23	33	576.034	1.549	159.111	–	16.045
2	4	Q. frainetto Ten.	1	17.90	15.80	4.85	11.10	22	95.161	0.299	17.955	–	3.235
	5		2	18.46	18.00	4.30	10.50	21	108.975	0.443	22.681	–	4.470
	6		3	19.43	17.80	5.00	10.95	19	115.521	0.459	22.662	–	4.775
	7	Q. cerris L.	1	18.08	18.80	3.25	12.75	42	143.462	0.194	26.466	0.115	2.212
	8		2	22.46	20.30	4.95	14.50	27	198.552	0.294	37.705	0.075	3.217
	9		3	26.77	21.00	5.70	12.00	19	260.761	0.564	63.604	0.353	4.775
3	10	Q. frainetto Ten.	1	14.66	16.10	3.40	9.10	30	81.869	0.212	12.360	–	3.284
	11		2	24.99	20.75	5.70	12.50	13	276.450	0.783	84.753	–	7.058
	12		3	32.27	24.60	8.25	15.80	8	698.357	1.654	167.930	–	14.134
	13	Q. cerris L.	1	20.02	19.20	5.35	14.70	51	125.822	0.238	20.912	–	1.693
	14		2	27.06	20.80	7.10	13.95	28	253.612	0.516	53.560	0.504	2.529
	15		3	32.75	25.30	9.40	13.15	19	437.585	1.480	161.275	1.061	12.170
4	16	Q. frainetto Ten.	1	17.53	16.00	4.80	9.75	91	82.051	0.364	9.374	–	4.039
	17		2	24.98	20.75	5.95	12.90	45	211.022	0.572	70.895	–	5.704
	18		3	30.03	24.35	7.90	15.00	31	552.702	1.483	161.366	–	14.132

SA – sampling area
DBH – diameter at breast height
QMD – quadratic mean diameter
D – diameter
H – height

The biomass of canopy for each model tree was separated into different fractions for weighing: the perennial branches with different intervals of diameter in the middle, annual branches, and leaves and acorns. These fractions were weighed fresh and subsamples selected to determine the absolute dry weight. The subsamples were dried at 85°C for 48 h (leaves and annual branches) and at 105°C for 48 h (perennial branches and acorns) [Rodin et al. 1968; Lyubenova 2004]. The summary of biomass for all the fractions of each tree is given in table 1.

Understory biomass sampling

For the tree-sprout biomass measurements, 20 stems averaging 6 years of age, having a 2.6 mm diameter in the middle and a height of 14.9 cm were collected for weighing. Age was determined by counting the number of annual rings. The average biomass per stem was multiplied by the number of stems per ha in each SA. The plant number was found using 5 counting plots of 1 m^2.

The herb layer was subsampled in July 2013 by using 10 rectangular 0.25 m^2 subplots in each SA. The herb biomass was fractionated into agro biological groups and seedlings. The same plots were used to count the number of seedlings [Lyubenova 2004].

Belowground biomass sampling

The belowground plant mass (roots) of the tree layer was calculated using a method devised by Rodin et al. [1968] and Winrhizo [2009]. The nutritional area of the tree layer (16 m^2) in SA1 was sampled around the "model tree" in the first class of thickness which was the most numerous in all plots. The average nutritional area was calculated as a ratio of the SA area and number of trees in it. This calculated area did not include the whole root system of the model tree. It was assumed that the share of roots going out from the nutritional area was equal to the roots share entering from the nearby trees [Rodin et al. 1968].

One third of the model nutritional area (3.2 m^2) was separated and fractionated. A pit with a width of 0.5 m and depth of 1.5 m was excavated. The soil horizons were separately collected on tarpaulins; live and dead roots in each horizon were mechanically separated. Live and dead roots were distinguished by color and structure [Vogt et al. 1983]. The live roots were weighed in fractions by diameter classes. The coarse roots were defined in classes of 0.2–1 cm, 1–2 cm, 2–5 cm, 5–10 cm in diameter. No roots were larger than 10 cm in diameter. The root stump and above ground stump were not in nutrition area and so not included in biomass. However the whole oak stump was weighed at 15.90 kg.

The fine roots (under 2 mm in diameter) were not measured. The roots were excavated at a depth of 85 cm (soil horizons: A 0–25 cm, AB 25–60 cm and BC 60–85 cm). The overstory tree and understory plant roots were distinguished according to size, structure and colour.

The root biomass of sprouts was calculated by applying the method of Rodin et al. [1968]. For each of the 20 sprouts, the whole root system was collected, washed and scanned. The images were analysed using the Winrhizo [2009] computer program. Data on the length, mean diameter, and volume of the root system were obtained. The data of root biomass (dried at 85°C and 105°C, the wood parts only, for 48 h) were presented as absolutely dry mass in t ha^{-1} (table 5).

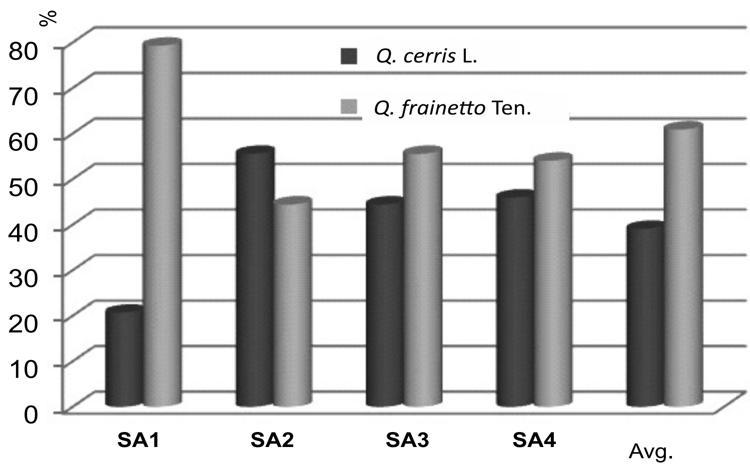

Fig. 2. Ratio between the seedlings of two dominant species by sample areas [%]

Results and discussion

Biomass Per Area Estimates

Based on calculations from the data in table 1 as described above, the average aboveground plant mass of the tree layer was 168 t·ha^{-1}. It varied from approx. 112 t·ha^{-1} for SA2 to 210 t·ha^{-1} for SA1 depending on tree age and total numbers. The percentage of different plant mass in the investigated sample areas is shown in table 2.

Table 2. Aboveground plant mass of the tree layer (t·ha^{-1} absolute dry weight and % of the total mass)

SA №	Trees n·ha-1	Stem			Branches					Branch totals			Leaves	Acorns	Total
		Sum	wood	bark	<1 cm	1–2 cm	2–5 cm	5–10 cm	>10 cm	Peren-nual sum	Annual sum	Sum			
		1	2	3	4	5	6	7	8	9	10	11	12	13	15
1	836	162.067	157.191	4.876	4.428	7.848	19.743	10.435	0.000	42.455	0.498	42.953	5.049	0.000	210.069
%		77.15	74.83	2.32	2.11	3.74	9.40	4.97	0.00	20.21	0.24	20.45	2.40	0.00	100.00
2	600	91.671	89.845	1.826	1.767	3.824	8.123	3.857	0.989	18.560	0.206	18.766	2.105	0.054	112.596
%		81.42	79.79	1.62	1.57	3.40	7.21	3.43	0.88	16.48	0.18	16.67	1.87	0.05	100.00
3	596	133.876	131.325	2.552	3.070	5.892	11.527	8.726	4.571	33.786	0.338	34.124	2.767	0.137	170.905
%		78.33	76.84	1.49	1.80	3.45	6.74	5.11	2.67	19.77	0.20	19.97	1.62	0.08	100.00
4	688	136.386	132.283	4.104	3.808	6.639	16.410	9.325	0.000	36.183	0.419	36.601	4.249	0.000	177.237
%		76.95	74.64	2.32	2.15	3.75	9.26	5.26	0.00	20.41	0.24	20.65	2.40	0.00	100.00
Avg.		131.000	127.661	3.339	3.268	6.051	13.951	8.086	1.390	32.746	0.365	33.111	3.542	0.048	167.702
%		78.12	76.12	1.99	1.95	3.61	8.32	4.82	0.83	19.53	0.22	19.74	2.11	0.03	100.00

SA – sampling area

The average total biomass in the herb layer was approx. 48.6 g·m^{-2} varying from lower values in SA1 and SA3 to higher ones in SA2 and SA3 when compared to the average value (table 3). The average share of grasses within the total herb biomass was 36.7%, even in the two of sample areas (SA3 and SA2) it was 57% and 47% respectively, which showed the turfing tendency of these forests. This has had a negative impact on the number of seedlings and their survival. The mean number of seedlings for all the sample areas was 91 per m^{-2} with an average age of 2 years. It varied among the SAs from 148 and 116 (for SA4 and SA1) to 36 per m^2 (SA2 and SA3). In three SAs, seedlings of *Q. frainetto* dominated, most strongly in SA1, and *Q. cerris* seedlings dominated only in SA2 (fig. 2). The average biomass of the seedlings was 8.5 g·m^{-2} or 17.6% of the total biomass of the herb layer and was largest in SA3 (11.3 g·m^{-2} or 29.6% of the total herb layer mass in SA3), followed by SA1 (9.5 g·m^{-2}, 28.2%). The biomass of the seedlings in SA2 was only 3 g·m^{-2} or 6% of the total mass in the herb layer, which was the lowest obtained value (table 3). As a whole, seedlings in the four sample areas were in a good ecological state: no withering or yellowing at an average age of 2 years was observed.

All the average values (X) obtained for the herb layer biomass fractions were representative as ratio X/Sx was larger than the Student's coefficient (t) at α = 0.05 for the 4 sampled areas (t = 2.132 for n = 4).

Table 3. Aboveground herb layer plant mass (g·m^{-2} absolute dry weight and % of the total mass)

SA/Groups	Grasses	Legumes	Mixed herbs	Seedlings of trees	Dead mass	Total
1	2.976	17.158	3.521	9.544	0.676	33.875
%	8.8	50.7	10.4	28.2	2.0	100.0
2	23.471	2.768	11.432	3.009	8.880	49.560
%	47.4	5.6	23.1	6.1	17.9	100.0
3	21.704	0.000	4.668	11.269	0.417	38.058
%	57.0	0.0	12.3	29.6	1,1	100.0
4	22.119	0.000	32.533	10.326	7.762	72.740
%	30.4	0.0	44.7	14.2	10.7	100.0
Average, X	17.568	4.982	13.039	8.537	4.434	48.558
%	36.2	10.3	26.9	17.6	9.1	100.0
St.Dev., S	9.757	8.222	13.457	3.752	4.513	17.432
Error of X, Sx	2.439	2.055	3.364	0.938	1.128	4.358
*X/Sx > **t	7.202	2.424	3.876	9.101	3.930	11.142

*Representativeness of X - X/Sx > 2.132 for all fractions
**Student's coefficient, t = 2.132 for α = 0.05 and n = 4
SA – sampling area
X – mean value
St.Dev. – standart deviation

The average number of sprouts was 22.4 per m^2; 85% of the sprouts were Italian oak. The mean biomass of the sprouts was calculated as 50.938 g·m^{-2} (table 4). It was distributed in 40% of the overground biomass and 60% of the belowground (root) system. The annual (new) growth of the three layer was approx. 15% and the perennial (remaining) comprised approx. 25%. The average root diameter equaled 0.828 mm, the length was 2908.774 cm·m^{-3}, and the volume was 14.784 cm^3.

Table 4. Mass of tree sprouts (g·m^{-2} absolute dry weight and % of the total mass)

Fraction	Aboveground			Belowground						Total [g·m^{-2}]
	stem and perenual branches [g·m^{-2}]	leaves and annual branches [g·m^{-2}]	sum [g·m^{-2}]	roots [g·m^{-2}]	S [cm^2]	S roots [cm^2]	d aveg. [mm]	l/V [cm·m^3]	V [cm^3]	
	12.902	7.549	20.429	30.509	117.239	742.941	0.828	2908.774	14.784	50.938
%	25.33	14.82	40.15	59.85	–	–	–	–	–	100.00

S – area
d – diameter
V – volume

Table 5. Belowground plant mass (t·ha^{-1} absolute dry weight)

Soil horizon	Living roots, d [cm]					Dead roots	Total
	0.2–1	1–2	2–5	5–10	Sum		
A	16.640	12.190	28.430	7.810	65.070	5.430	70.500
AB	7.290	1.250	24.060	0.000	32.600	3.460	36.060
BC	2.190	3.130	4.370	0.000	9.690	0.010	9.690
Total	26.120	16.560	56.870	7.810	107,36	8.900	116.250

d – diameter

The root biomass was equal to 116 t·ha^{-1} (table 5, fig. 3). Of the root system, 7.7% was dead mass. In the distribution of belowground biomass, the largest amount (60.65%) of the total was located in the upper (0–25 cm) layer of the soil. The largest amount of the root mass (48.92%) was at a diameter of 2–5 cm. The smallest amount (6.72%.) was at a diameter of 5–10 cm.

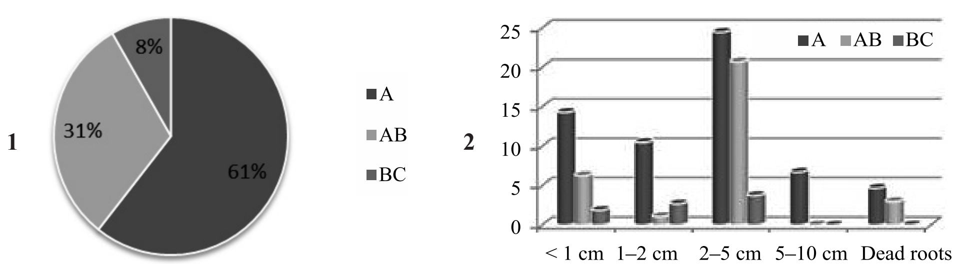

Fig. 3. Ratio of root biomass [%]: 1 – by soil horizons; 2 – by fractions

Comparison to Other Studies

The results for coarse root stocks obtained in the present study were compared to those reported by other authors for the same tree species and other forest ecosystems. The differences are probably due to variations in the ecological conditions and stand characteristics of the SAs and in the methodologies. Biomass numbers in this study are greater than those presented by Lyubenova and Bondev [1987] who reported a coarse root biomass of 68 t·ha^{-1} for *Quercus frainetto* + *Quercus cerris – Festuca heterophylla* + *Poa nemoralis community* in Sofia region, Bulgaria.

The root biomass results were also compared to other forest ecosystems. For example, the established coarse root biomass from beech communities in Macedonia, with a mean diameter 16 cm [Hristovski et al. 2008], developed on *Distric Cambisols*, at an elevation of 1400 m and with a stand density of 1200 trees per ha was 45 t·ha^{-1}. The coarse root biomass for beech communities in Germany aged 40–79 years was estimated at 54–48 t·ha^{-1} [Brumme, Khanna 2009]. The coarse root biomass of Scot's pine forest stands in Yundola (Bulgaria) studied by Mihov [1979] at 110 years of age, with a diameter of 28 cm, a height of 26 m and a density of 600 trees per ha was 26–105 kg per model tree.

The total plant mass of the oak ecosystems studied equaled from 301 to 477 t·ha^{-1}. The largest part of the plant mass was in the aboveground component and equaled 170.985 t·ha^{-1} (fig. 4). Some (98%) of the aboveground plant mass was in the over story. Very small amounts (1.42 and 0.50%, respectively) were in the sprout and seedling biomass.

Fig. 4. Average distribution [%] of total plant mass: A – by spheres of community; B – by plant mass fractions

The data on plant mass for the investigated xerothermic forest vegetation were close to those published by other researchers (table 6). The cited references give information about the amount of biomass of xerothermic forest vegetation in terms of the respective geographical coordinates, soils, species composition, age of forests and husbandry practices.

Table 6. Published data for xerothermic oak vegetation plant mass

№ of publ.	Avg. Temp., [°C]	Avg. Precip., [mm]	Altitude, [m]	Aspect	Elevation, 0	Soil	Origin	Avg. age, Y	Canopy	Avg. DBH, [cm]	Avg. H, [m]	Overgr. BM, [t·ha^{-1}]	Tree storey BM, [t·ha^{-1}]	Undergr. BM, [t·ha^{-1}]
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Lyubenova, Bondev [1998]*	10.2	603	150	E	3.0	Umbric cambisols	shoots	52.3	0.7	13.0	15.3	–	343.5	–
Bondev et al. [1998]*	12.5	650	50	NW	5.0	Chromic Luvisols	shoots	48.0	0.7	15.4	13.7	349.1	91.6	–
	12.5	650	50	NW	1.0	Chromic Luvisols	shoots	48.0	0.7	13.1	13.8	–	112.5	–
Lyubenova [1996]*	12.0	567	300	NW	–	Chromic lLuvisols	shoots	56.5	0.9	15.7	13.5	–	181.0	–
Lyubenova, Bondev [1998]*	11.1	615	400	NE	–	District planosols	shoots	53.0	0.7	17.0	19.0	119.9	–	–
	11.1	688	400	NE	–	District planosols	shoots	43.0	0.8	18.0	18.0	431.3	–	–
	11.1	578	400	W	–	District planosols	shoots	65.0	0.8	20.0	20.0	233.0	–	1.2
	11.1	–	400	W	–	District planosols	seminal	125.0	0.7	25.0	25.0	342.0	–	68.3
Bondev, Lyubenova [1992]*	8.0	627	950	W	–	Alisols	–	45.0	–	–	–	–	–	–
Lyubenova, Bondev [1987]*	–	–	–	S	–	Planosols	–	53.0	0.8	–	–	–	–	–
Meshinev, Nikolov [1986]	10.0	700	300	S	18.0	Planosols	shoots	–	0.7	–	–	13.5	8.0	–
Lyubenova, Sazdov [1995]*	11.3	615	–	SW	–	Planosols	shoots	65.0	0.7	–	–	–	3.6	–
Lyubenova [1996]*	11.3	578	150	W	–	Chromic cambisols	seminal	43.0	0.8	25.0	25.0	341.9	341.7	–
	11.3	578	150	N	–	Luvisols	shoots	41.0	0.8	20.0	20.0	233.0	232.6	–

Table 6. Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Lyubenova [1995b]*	10.6	644	1040	E	8.0	Luvisols	shoots	95.0	0.8	14.0	12.0	–	–	–
Lyubenova [1995]*	10.9	688	290	E	2.0	Cambisols	shoots	–	0.8	18.0	18.0	430.2	451.3	–
Lyubenova, Dimova [2000]*	10.0	882	1500	E	27.5	Chromic Luvisols	seminal	45.0	–	50.0	35.0	–	–	–
Grupche et al. [1993]	10.0	753	900	–	–	Gray Luvisols	–	53.0	0.7	–	–	229.9	451.4	–
Lyubenova et al. [1996]*	10.4	–	475	–	–	–	–	9.0	0.7	13.0	15.0	121.6	119.7	–
Lyubenova [1995]	12.9	832		–	–	–	–	10.0	–	16.5	19.0	119.7	102.2	–
Melovski et al. [1994]	12.9	467	350	–	10.0	–	–	15.0	–	3.0	2.5	8.5	2.3	–
	12.9	467	350	–	10.0	–	–	42.0	–	5.0	3.5	4.8	1.7	–
	–	467	350	–	10.0	–	–	42.0	0.7	3.5	2.0	7.9	2.4	–
Lalova [1994]	–	–	480	–	–	–	shoots	42.0	0.7	21.0	19.4	47.0	–	–
	–	–	480	–	–	Luvisols	shoots	42.0	0.7	21.4	19.6	–	–	–
	–	–	200	–	–	Planosol	shoots	30.0	0.7	28.4	22.7	231.5	–	47.6
	–	–	–	–	–	Chrom. Cambisol	shoots	40.0	0.9	35.0	20.9	279.0	–	85.4
Ninov [1995]	–	–	–	–	–	Umbric Leptosol	shoots	31.0	0.9	–	7.0	157.6	–	56.7
	–	–	–	–	–	Lithic Leptosol	shoots	34.0	0.9	–	13.0	190.6	–	51.2
	–	–	–	–	–	Luvisols	shoots	32.0	0.8	–	8.0	113.8	1.8	20.9
	–	–	480	NE	–	–	shoots	42.5	0.5	–	7.0	90.7	4.1	–
	–	–	–	W	–	–	shoots	–	–	–	4.0	51.3	–	–
Lalova [1994]	–	–	–	S	–	–	shoots	–	–	–	–	279.0	–	–
Gateva [1994]	–	–	–	N	–	–	shoots	–	–	–	–	–	401.0	–

* by Lyubenova [2009]; DBH – diameter at breast height; H – height; BM – biomass

The analysis of tree growth (using data collected from the 2-m stem wood sections) for the 3rd diameter class at 70 years of age showed that the growth accumulation of the stem biomass of Italian oak and Turkey oak was still intensive, i.e. the curves had not plateaued (fig. 5A, 5B). Since the trees examined from the third density class were only approx.16% of the total trees in the tree layer, and those from the first and second density classes were younger, it may be concluded that the forest has not exhausted its productive possibilities in spite of its coppice character and intensive exploitation in the recent past. The wood accumulation was sufficiently described with 2nd and 3rd degree polynomials and with respective mathematical equations for Italian and Turkish oak, which could be used for approximate evaluations because the productive behaviour of coppice forests is different from that of seminal ones. The stem growth in height (fig. 5C, 5D) could be described by 4th and 6th degree polynomials and respective mathematical equations. Height growth plateaued at approx. 30–35 years of age.

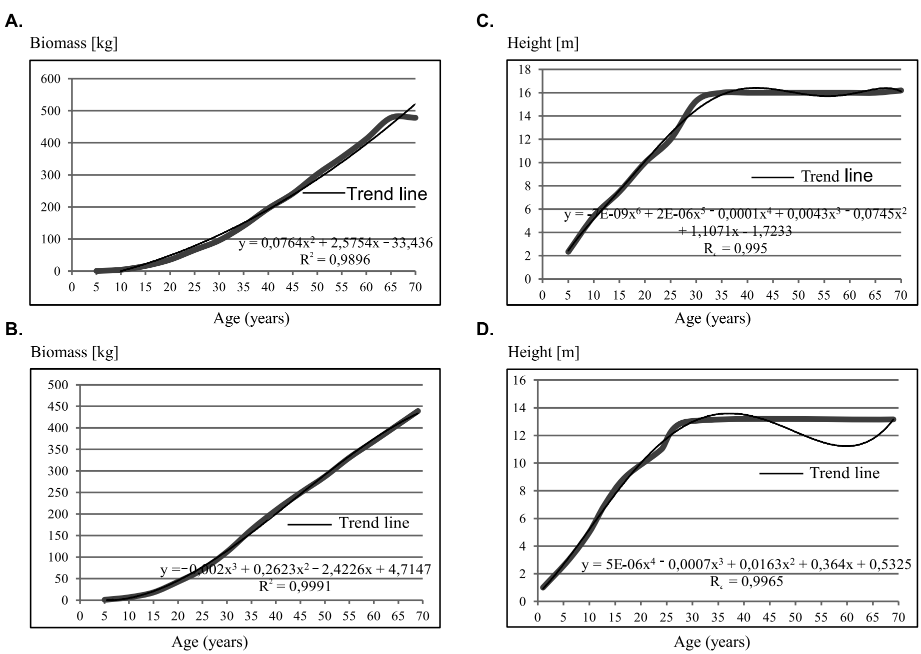

Fig. 5. Dynamics of stem growth: biomass accumulation (kg) for Italian oak (A) / Turkey oak (B); growth in height (m) for Italian oak (C) / Turkey oak (D)

Conclusion

According to the biomass data collected, the studied xerothermic forest vegetation would be given a rating of 8 (300.1–400 t·ha^{-1}) on the Bazilevich and Rodin scale [1971] for broad-leaved forest ecosystems. The plant mass distribution of the aboveground perennial stems and leaves were in the range of other cited data: 60–81% and 1–3%. The estimated percentage of the belowground biomass was higher than the cited data (17–29%). This could be due to the coppice character of the forests. Offshoots utilize the powerful maternal root systems. Although the majority of the roots die because young shoots cannot produce enough assimilates, it is assumed that in coppice forests the quantities of belowground plant mass is higher compared to seminal forests of the same species. But the differences may be due to the efforts of the authors to more accurately measure the belowground biomass with existing labour-intensive methods. The amount of bush and herb layer biomass, belowground biomass and the change of soil status probably exerted an influence on the seed regrowth of these communities. The study area was experiencing having some problems transforming from coppice tree communities into seed-produced forest, despite the large number of seedlings. Because of the high death-rate of seedlings at young and middle age, the number of sprouts was low as shown by the differences in age and number of seedlings and sprouts, and the existing tendency of tuffing in the herb layer. The changed soil characteristics from a possibly higher rate of dead root mass in the initial stages of coppice forest development may also have caused the high death-rate of seedlings at young and middle age. Nevertheless, these forests have vital potential for biomass production and seedling reproduction. Under good management, these communities should improve their health as well as their ecological, social and economic importance. This new data has helped to complete the biomass database for these human-influenced forests in southern Europe, may be used for management, future comparisons and conclusions, and may contribute to an understanding of the real productive capacity of oak forest-habitats and their potential contribution to European habitat diversity.

References

Bolte A., Rahmann T., Kuhr M., Pogoda P., Murach D., Gadow Kv. [2004]: Relationships between tree dimension and coarse root biomass in mixed stands of European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* [L.] Karst.). Journal Plant and Soil 264 [1/2]: 1–11

Brumme R., Khanna P. [2009]: Functioning and Management of European Beech Ecosystems. Ecological Studies, vol. 208, ISSN 0070-339-4, p. 479

Brunner I., Godbold D. [2007]: Tree roots in a changing world. Journal Forest Research 12: 78–82

Davies C., Moss D., Hill M. [2004]: EUNIS habitat classification revised. Final report to EA and ETC on Nature Protection and Biodiversity: 74–75. Available from: http://eunis.eea.europa.eu/upload/EUNIS_2004_report.pdf

Dimitrov E. [2000]: Производствена таксация и минджмънт на горите (Industrial forestry taxation and forest management). Publishing House Forestry University, Sofia: 262

Gateva R. [1994]: Изследване на акумулацията на микроелементи от видове дървета в индустриален район Девня (Studies on accumulation of microelements of tree species in Devnya industrial area). Journal of Forest Science 1: 8–15

Helmisaari H-S., Makkonen K., Kellomaki S., Valtonen E., Malkonen E. [2002]: Below and aboveground biomass, production and nitrogen use in Scots pine stands in eastern Finland. Journal Forest Ecological Management 165: 317–326

Hristovski S., Melovski L., Shushlevska M., Grupche L. [2008]: Belowground plant biomass and production in beech ecosystem *Calamintho grandiflorae-Fagetum* in National park "Mavrovo". III. Belowground plant biomass of major roots of trees and shrubs. Journal Ecology and Environmental Protection 11 [1/2]: 3–10

Iliev A., Dimitrov E., Bogdanov K. [1980]: Методично ръководство за практически занятия по горска таксация (Methodological guidance for practical exercises of forest taxation). Sofia, Zemizdat: 132

Kavrakova V., Dimova D., Dimitrov M., Tzonev R., Belev T. (ed.) [2009]: Ръководство за определяне на местообитанията от европейска значимост в България
(Guidance for identifying habitats of European importance in Bulgaria). Second edition: 131

Kurz W., Beukema S., Apps M. [1996]: Estimation of root biomass and dynamics for the carbon budget model of the Canadian forest sector. Canadian Journal of Forest Research 26 [11]: 1973–1979

Lalova J. [1994]: Investigations on the cycling of main macrobiogens in ass. *Quercus cerris -Quercus frainetto* and *Fagus sylvatica* in Vidin region. Journal Forest science 4: 8–16

Lalova J. [1994]: Primary production of representative forest associations in NW Bulgaria. Journal of Forest Science 3: 10–20

Le Goff N., Ottorini J.-M. [2001]: Root biomass and biomass increment in a beech (*Fagus sylvatica* L.) stand in North – East France. Journal of Forest Science 58: 1–13

Lyubenova M., Bondev I. [1987]: Belowground biomass of tree story of ass.*Quercus frainetto + Quercus cerris - Festuca heterophylla + Poa nemoralis* in Gabra village, Sofia region. Proc. IVth National Conference of Botany 3: 72–76

Lyubenova M. [1992]: Energetic reserves in belowground biomass of ass.*Quercus frainetto + Quercus cerris - Festuca heterophylla + Poa nemoralis* in Vakarel mountain. Ann. University of Sofia 82 [2]: 187–196

Lyubenova M. [2004]: Фитоекология (Plant Ecology). Sofia, Acad. Publisher "M. Drinov": 574 (in Bulgarian)

Lyubenova M. [2009]: Функционална биоценология (Functional Biocenology). Sofia, An-Di Publishing house: 368

Grupce Lj., Melovski Lj., Mulev M. [1995]: Plant biomass and primary production of *Quercetum frainetto-cerris macedonicum* ecosystem in Galicica national park. Proc. of the Jubilee Symposium "100 Years from birthday of the Acad. Boris Stefanov [1894–1979]" 2: 85–92

Melovski L., Mulev M., Derlieva L. [1994]: Aboveground plant mass in a *Quercetum frainetto-cerris-macedonicum* forest ecosystem in the Veles foothill area (central Macedonia). Journal Ecology and Environmental Protection 47: 107–125

Meshinev T., Nikolov V. [1986]: Bio productivity of association from the region of Elena Fore Balkans. Journal Ecology 19: 3–18

Mihov I. [1979]: Съдържание на минерални елементи за белия бор (Pinus sylvestris L.) на три типа почви (Content of mineral substances for Scots pine (*Pinus sylvestris* L.) on three types of soils). In: Proceedings of VLTI 21: 35–43

Molchanov A., Smirnov V. [1967]: Методы изучения роста древесины растений (Method for studying the growth of woody plants). Moscow, Science publisher: 72

Ninov N. [1995]: Primary production and functional of xerothermic oak ecosystems in Bulgaria. Journal of Forest Science 3: 3–15

Puhe J. [2002]: Growth and development of the root system of Norway spruce (*Picea abies*) in forest stands – a review. Journal Forest Ecological Management 5952: 1–21

Rodin L., Remezov N., Bazilevich N. [1968]: Методы изучения динамики биомассы и биологического круговорота в растительных сообществах (Methodological guidelines for the study of the dynamics and the biological cycle in plant communities): 145

Vogt, K., Erin M., Vogt D., Redlin M., Edmonds R. [1983]: Conifer fine root and mycorrhizal root biomass within the forest floors of Douglas-fir stands of different ages and site productivities. Canadian Journal Forest Research 13 [3]: 429–437

Winrhizo [2009]: Regent instruments Canada Inc [Computer Program]

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ALLOCATION OF ELEMENTS IN A CHRONOSEQUENCE OF SILVER BIRCH AFFORESTED ON FORMER AGRICULTURAL LANDS

Research on the effect of birch regeneration on changes occurring in the environment on former farmlands included a quantitative and qualitative analysis of the biomass growing on the research plots. Five experimental plots were selected in the Mazovia region: two in Dobieszyn and the Kampinos National Park and one in Kozienice. The analysis performed on each plot was concerned with the amount and chemical composition of biomass in four patches of vegetation, characterised by the different ages of the birch trees growing there. The vegetation patches were classified according to age group, i.e. I: 1–4 years old, II: 5–8 years old, III: 9–12 years old and IV: over 12 years old. Biomass samples were collected in the field and determined in kg DM/ha using the following components: roots, stem, bark, branches, assimilation apparatus, litterfall and the total biomass of the other (except birch) plants. For all the above-mentioned groups, the content of the elements N, C, S, Ca, K, Mg, Na, P, Mn, Cu, Fe, Zn, Pb, and Cd was determined. This allowed us to obtain both the values of the concentrations of particular substances and their allocation in both the organic matter and litterfall. The aim of the research was to discover whether the allocation of elements changes with the age of birch growing on former farmland.

Keywords: secondary succession, post-agricultural lands, silver birch, allocation of elements, chronosequence

Introduction

Silver birch (*Betula pendula* Roth.) is widely distributed in Eurasia, and it is one of the most abundant broad-leaved tree species in northern Europe [Hynynen et al.

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2010]. In Baltic and Nordic countries, the proportion of birch in the total volume of forest growing stock varies between 11% and 28% [Uri et al. 2012]. Silver birch is also an important tree species in Poland, where it occupies ca. 7.5% of the total area of forest [GUS 2011].

At the end of the 20th century in many countries of Central and Eastern Europe, a shift in land use was observed caused by economic changes. Large areas of post-agricultural lands have since been spontaneously and naturally afforested by fast-growing pioneer species, including silver birch [Karlsson et al. 1998]. Quantifying the amount and allocation of various elements is important for an understanding of the potential impact of newly-established forest ecosystems.

A review of literature on the element allocation of silver birch reveals that the replacement of field with forest brings about various changes in the species composition and biomass of the vegetation, as well as in soil properties. An estimation of the biomass and nutrient accumulation in relation to the foliar and root parameters is essential for understanding the structure and functioning of a new forest ecosystem formed on abandoned agricultural land. Such knowledge will provide an estimate of the resources and potential of young birch stands and their impact on the environment, e.g. on soil development, nutrient cycling and carbon sequestration [Uri et al. 2007]. These studies are the first ever in Poland to describe the allocation of elements on former farmland that has been afforested with birch of varying ages.

Previous studies focus mainly on the quantification of aboveground biomass of birch [Mälkönen 1977; Johansson 1999; Claesson et al. 2001]. In recent years, the scope of research has broadened to belowground biomass, and the allocation of carbon and nutrients in various components has been included in analyses [Uri et al. 2007b; Kuznetsova et al. 2011; Uri et al. 2012; Bijak et al. 2013; Varik et al. 2013]. In Poland, Bernadzki and Kowalski [1983] identified birch as a pioneer species adapting the ground for colonization by other trees on post-agricultural lands; Jakubowski and Sobczak [1999] analysed the possibilities of growing birch as intensive plantations established on post-agricultural lands; Glanc et al. [2000] investigated the content of Mn, Fe, Zn and Cu in birch juice and Kayzer et al. [2011] analysed the effect of trace elements on the state of birch foliage. Liepins [2007] also demonstrated the excellent performance of silver birch on former agricultural lands. This was also confirmed in a number of studies in Latvia.

The hypotheses of the presented study assumed that (I) the quantity of chemical elements (N, C, S, P, K, Na, Ca, Mg, Mn, Zn, Cu, Fe, Pb, Cd) changes with the age of birch, and (II) the quantity of the components varies between tree and ecosystem elements. To test these hypotheses, the objectives included: i) an assessment of the amount of biomass stored in the above and belowground parts of young birch trees, as well as the amount of litterfall on post-agricultural lands in central Poland; ii) an analysis of the effect of tree age on the allocation of elements.

Materials and methods

The study included 20 stands growing on former agricultural lands in five locations in the Mazovia region of Poland (table 1). The plots were established in pure silver birch stands of successional origin. All the investigated stands originated from natural regeneration started after farming was abandoned, and remained free from any agri- or silvicultural treatments.

Experimental plots were selected in five stands: Dobieszyn (2), Kampinos National Park (2) and Kozienice (1). The analysis performed on each plot was concerned with the chemical composition and amount of biomass in four patches of vegetation, characterised by the different ages of the birch trees growing there. The vegetation patches were classified according to age, i.e. I: 1–4 years old, II: 5–8 years old, III: 9–12 years old and IV: over 12 years old.

Table 1. Locations and characteristics of study plots

Plot	Location	Soil types	Humus content
Dobieszyn 1	51°35′N, 21°10′E	Podzols & luvisols	0–1%
Dobieszyn 2	51°33′N, 21°09′E	Podzols & luvisols	1–2%
Kozienice	51°24′N, 21°26′E	Podzols & luvisols	2–3%
Kampinos 1	52°21′N, 20°43′E	Luvisols & cambisols	2–3%
Kampinos 2	52°19′N, 20°40′E	Luvisols & cambisols	3–10%

All the study sites were located within a transition zone from a maritime to continental climate [Martyn 2000] with annual average temperatures equal to 6–8°C and average annual rainfall equal to 550–600 mm. The coldest month (January) has an average temperature slightly below -2°C and the warmest (July) has a temperature ranging from 16 to 18°C. The study area has infertile soils developed on glacio-fluvial sand, glacial till, clay and peat.

At each of the five locations, four stands of increasing ages were selected. Ten trees were randomly chosen at each location according to the diameter range. A total of 181 trees were used for further analyses. All parts of the model trees (stem, foliage, branches and roots) were weighed in the field using portable scales with an accuracy equal to 0.01 g.

On each plot, five places were randomly chosen to determine the amount of organic matter on the ground. A 0.6 × 0.6 m sampler was used to collect all the organic components down to the mineral soil. The organic matter was further divided into litterfall and plants other than birch (mainly grass) and weighed using portable scales with an accuracy equal to 0.01 g.

Samples from each of the components from every model tree, litterfall and other ground organic matter were taken in order to determine the relationship between their fresh and dry biomass. The samples were oven-dried at 105°C and weighed. The dry biomass of the components was calculated for each tree on the basis of the corresponding fresh to dry mass ratios [Snowdon et al. 2000, 2002; Uri et al. 2007, 2012]. The dried components were further ground and homogenised. Of the next three samples, 50 g each were taken and mineralised in HNO_3. Then the content of K, Na, Ca, Mg, P, Fe, Mn, Cu, Zn, Pb and Cd in all parts of the trees was determined using an ICP-OES device. The content of C, N and S was determined using a LECO TruMac CNS device without mineralisation. The obtained biomass of the tree components (roots, stem, bark, branches, assimilation apparatus, litterfall and total biomass of the other (except birch) plants) and the content of the elements was further expanded to the plot level and expressed in kg DM/ha. The differences between the age classes were assessed using the Kruskal-Wallis test at 0.05 significance level.

Results and discussion

The major quantitative characteristics of the age groups are presented in table 2.

Table 2. Characteristics of age groups

Age class	Average age	Average biomass [m³/ha]	Average biomass [kg/ha]			
			aboveground	roots	litterfall	other herbaceous plant
I	3	2	2 521.58[a]	510.83[a]	2 523.39[a]	3 478.01[a]
II	5	19	13 807.89[b]	1 086.39[b]	3 748.64[b]	2 725.70[b]
III	9	57	35 677.44[c]	1 485.48[c]	6 784.16[c]	1 942.08[c]
IV	12	126	78 082.05[d]	1 475.87[c]	9 643.49[d]	1 306.86[d]

a, b, c, d – homogenous groups determined at 0.05 significance level

The dry biomass of the aboveground tree components increased significantly with age ($p = 0.0000$) and was on average equal to 2.5 t/ha for age class I (average age 3 years), 13.8 t/ha for age class II (average age 5 years), 35.7 t/ha for age class III (average age 9 years) and 78 t/ha for age class IV (average age 12 years). In experiments performed by Uri et al. [2012] in Estonia, biomass equal to 25.7 t/ha was reported in a 6-year-old stand, 67.6 t/ha in a 13-year-old stand, and 39.9 t/ha in a 14-year-old one. Johansson [1999] reported the biomass of birch on post-agricultural areas in Sweden amounted to 5.7–55.7 t/ha at 7–11 years. The biomass of the 8-year-old birch assessed in the experiment by Uri [2007b] was equal to 31.2 t/ha, and in research from Uri et al. [2007] varied from 6 to 22.8 t/ha. The results obtained are similar, and the differences are mainly due to different soil conditions. It should be noted that the slightly lower values coming from Estonia and Sweden may have been caused by shorter vegetation periods.

Table 3. Nutrient accumulation in plant biomass components [kg/ha]

Age class	N	C	S	P	K	Ca	Mg
Foliage							
I	19.05^{a}	367.29^{a}	1.55^{a}	2.56^{a}	5.56^{a}	4.57^{a}	2.22^{a}
II	48.83^{b}	939.35^{b}	3.87^{b}	6.92^{b}	13.53^{b}	12.76^{b}	4.98^{b}
III	152.70^{c}	2886.33^{c}	11.72^{c}	18.74^{c}	54.30^{c}	27.47^{c}	9.80^{c}
IV	372.70^{d}	7626.91^{d}	27.60^{d}	38.65^{d}	121.57^{d}	97.61^{d}	34.96^{d}
Branches							
I	4.35^{a}	268.67^{a}	0.36^{a}	0.70^{a}	2.11^{a}	2.08^{a}	0.46^{a}
II	11.78^{b}	950.13^{b}	1.07^{b}	1.80^{b}	4.63^{b}	7.77^{b}	1.14^{b}
III	29.64^{c}	2561.88^{c}	2.72^{c}	4.15^{c}	12.70^{c}	14.87^{c}	2.20^{c}
IV	70.32^{d}	5665.98^{d}	6.49^{d}	9.42^{d}	28.64^{d}	39.54^{d}	5.33^{d}
Stem							
I	2.63^{a}	411.08^{a}	0.22^{a}	0.46^{a}	1.25^{a}	1.34^{a}	0.35^{a}
II	14.29^{b}	3786.27^{b}	1.26^{b}	2.39^{b}	7.48^{b}	7.45^{b}	1.33^{b}
III	35.77^{c}	11453.53^{c}	3.63^{c}	4.99^{c}	15.93^{c}	19.99^{c}	3.51^{c}
IV	65.84^{d}	26086.65^{d}	5.89^{d}	9.90^{d}	30.88^{d}	53.23^{d}	8.39^{d}
Bark							
I	2.02^{a}	125.90^{a}	0.14^{a}	0.17^{a}	0.58^{a}	1.35^{a}	0.18^{a}
II	7.89^{b}	979.89^{b}	0.58^{b}	0.80^{b}	2.08^{b}	7.23^{b}	0.66^{b}
III	17.84^{c}	2379.96^{c}	1.33^{c}	1.31^{c}	4.03^{c}	12.98^{c}	1.04^{c}
IV	34.55^{d}	4862.30^{d}	2.56^{d}	2.06^{d}	5.33^{d}	30.02^{d}	1.80^{d}
Aboveground part of trees							
I	28.05^{a}	1172.94^{a}	2.27^{a}	3.89^{a}	9.50^{a}	9.34^{a}	3.21^{a}
II	82.79^{b}	6655.64^{b}	6.78^{b}	11.91^{b}	27.72^{b}	35.21^{b}	8.11^{b}
III	235.95^{c}	19281.70^{c}	19.40^{c}	29.19^{c}	86.95^{c}	75.31^{c}	16.55^{c}
IV	543.41^{d}	44241.84^{d}	42.54^{d}	60.03^{d}	186.42^{d}	220.40^{d}	50.48^{d}
Roots							
I	5.57^{a}	478.83^{a}	0.71^{a}	1.23^{a}	3.12^{a}	3.77^{a}	0.75^{a}
II	15.92^{b}	1302.14^{b}	2.51^{b}	3.20^{b}	6.78^{b}	11.45^{b}	1.51^{b}
III	37.49^{c}	3085.71^{c}	5.02^{c}	6.70^{c}	15.74^{c}	16.19^{c}	2.80^{c}
IV	59.67^{d}	6429.23^{d}	9.84^{d}	13.44^{d}	33.09^{d}	40.55^{d}	6.39^{d}
Litter fall							
I	10.31^{a}	280.81^{a}	0.99^{a}	0.80^{a}	1.04^{a}	3.60^{a}	0.47^{a}
II	82.81^{b}	1754.80^{b}	7.53^{b}	6.04^{b}	6.09^{b}	34.64^{b}	6.66^{b}
III	143.01^{c}	3279.47^{c}	14.69^{c}	9.60^{c}	8.18^{b}	56.74^{c}	8.17^{b}
IV	197.35^{c}	4511.78^{d}	19.76^{c}	12.98^{c}	10.53^{b}	66.29^{c}	10.31^{b}

a, b, c, d – homogenous groups determined at 0.05 significance level

The share of foliage biomass within the whole tree biomass decreased with age (p = 0.0001), while the share of the trunk increased significantly (p = 0.0012). After an initial moderate increase, the share of bark and branches stabilized, starting from age class II. The share of roots initially decreased and then levelled off [Bijak et al. 2013].

An average nutrient accumulation in the biomass of the plants across the analysed chronosequence is presented in table 3.

The carbon accumulation in the aboveground parts of the researched trees increased from 1.2 t/ha in age class I (average 3-year-old) stand, to 6.7 t/h in age class II (average age 5 years) and 19.3 t/ha in age class III (average age 9 years), to 44.2 t/ha in class IV (average 12 year-old part) (table 3). In the Estonian research by Uri et al. [2012], the carbon accumulation in the aboveground parts of the 6-year-old birch, equalled 12.5 t/ha and in the 13-year-old birch – 32.4 t/ha. Uri et al. [2012] reported carbon equal to 40–45 t/ha only in the 18–28 year-old samples. This indicates a much larger carbon uptake in the conditions of the Mazovia region. The author of the Estonian research also indicated that a silver birch stand growing on a fertile site had a high capacity for C accumulation, both in the biomass and in the soil. At the same time, the author pointed out that in the younger age classes, much depended on tree density. In the case of loosely wooded patches, part of C was accumulated in herbaceous vegetation so that the accumulation in birch was lower. According to this study, the root systems of the 5 year-old birches accumulated 1.3 t C/ha, and in the 13 year-old – 6.4 t/ha. In the case of the Estonian research, the accumulation amounted to 3.8 t/ha at 6 years of age and 7.6 t/ha at 13 years of age, respectively, while it should be noted that in this particular study the amount of belowground biomass was estimated. Lower biomass, and thus lower carbon accumulation, could be explained by the higher site fertility, because the studied birch stands grew on fertile soils and, according to an intensive fine root strategy, there was no need for the tree to grow a large number of fine roots for more sufficient nutrient uptake [Varik et al. 2013].

Nitrogen content in the aboveground parts of the birch trees in the investigated chronosequence increased from 28 to 543 kg/ha. In the Estonian research on the 8 year-old birch, the accumulation of biogenic elements was equal to 192.6 kg N/ha, 24.9 kg P/ha and 56.6 kg K/ha [Uri et al. 2007]. These values were much lower than those obtained in the present study on the 9-year old birch, which amounted to 235.95 kg N/ha, 29.19 kg P/ha and 86.95 kg K/ha (table 3). The N:P:K ratio, which in the first case was 70:9:21 and in the second was 67:8:25, was very similar with a slight shift of the nitrogen content towards potassium, which may have been the result either of the soil conditions or the seasonal vegetation, in which the samples were taken. In yet another Estonian research study [Uri et al. 2007], it was found that the average content of biogenic elements in the aboveground parts of 8 year-old birch trees was equal to 110.44 kg N/ha, 15.30 kg P/ha and 46.74 kg K/ha, which confirmed that under less fertile site conditions and a shorter vegetation season, the accumulation of elements in plants was definitely lower. In the roots, it was assessed that the content of nitrogen was equal to 5.57 kg/ha in the first age class, 15.92 kg/ha in the second age class, 37.49 kg/ha in the third class and 59.67 kg/ha in the fourth one. Estonian researchers reported that the content of nitrogen was equal to 39.3 kg/ha in the 6 year- old stand and 53.2 kg/ha in the 14 year-old one [Varik et al. 2013]. The reported results from Estonia and central Poland are comparable and there is no evidence of differences in climate and soil on the nitrogen content, which were visible in the case of carbon. The distribution of various biogenic elements (especially NPK) in the separate parts of the plants is shown in table 3. In the investigations by Uri et al. [2007], the content of NPK was noticeably lower in the branches, stems and bark, but definitely higher in the leaves. This varying allocation of the investigated elements was caused by the collecting of the samples in different phases of the vegetation season.

The content of the remaining biogenic elements, such as S, Ca, Mg, also increased with age. These elements reached the highest content in the leaves, and their share, in comparison to the rest of the plant in many cases exceeded 50%. It is worth mentioning the relatively low content of magnesium (Mg) in the woody parts of the plants and in the bark, as opposed to calcium (Ca) with its high amount in the stem, reaching nearly 25% of the total Ca content stored in the aboveground parts of the trees.

When analysing the allocation of microelements in the separate parts of the plants (Table 4) it is visible that the content of the majority of the analysed microelements in the biomass increased with age, with the exception of the roots where the amount of sodium (Na) and iron (Fe) clearly stabilized in the older age classes. Similar trends can be observed in the case of heavy metals in the litterfall. The content of cadmium (Cd) was lower than that of lead (Pb) in almost the whole plant, with the exception of the bark, where the results were the opposite. A high content of sodium, lead and iron in particular was observed in the roots. In the second age class, over 80% of the iron was located in the roots. The sodium content in the roots significantly decreased with age and increased in the stems. Similar patterns of element transfer from the roots to the shoots could be seen for copper and, to a lesser extent, for lead. There was a relatively low level of Pb accumulation in the foliage of the trees. This is why there was no significant influence of the presence of trace elements in the environment on the size of the assimilation apparatus [Kayzer et al. 2007].

The highest content of copper and zinc could be found in the bark of the trees.

For the litterfall, a significant drop in most elements could be observed in the initial phase, followed by a relatively stable moderate increase. However, the amount of litterfall increased more or less linearly. In addition, for the litterfall, the content of the majority of the analysed elements increased in the young ages and then decreased. Reverse tendencies could be observed for the foliage.

Table 4. The allocation of microelements in plant biomass components [kg/ha]

Age class	Na	Cu	Zn	Mn	Fe	Pb	Cd
Foliage							
I	0.028[a]	0.005[a]	0.237[a]	0.929[a]	0.124[a]	0.0009[a]	0.0005[a]
II	0.071[b]	0.013[b]	0.525[b]	3.053[b]	0.299[b]	0.0025[b]	0.0015[b]
III	0.173[c]	0.031[c]	1.053[c]	8.353[c]	0.682[c]	0.0065[c]	0.0020[b]
IV	0.410[d]	0.040[c]	2.554[d]	20.689[d]	2.046[d]	0.0126[d]	0.0077[c]
Branches							
I	0.017[a]	0.003[a]	0.176[a]	0.206[a]	0.038[a]	0.0008[a]	0.0006[a]
II	0.054[b]	0.008[b]	0.601[b]	0.787[b]	0.067[b]	0.0026[b]	0.0020[b]
III	0.150[c]	0.022[c]	1.069[c]	3.141[c]	0.182[c]	0.0073[c]	0.0037[c]
IV	0.364[d]	0.046[d]	2.184[d]	6.015[d]	0.441[d]	0.0137[d]	0.0079[d]
Stem							
I	0.023[a]	0.002[a]	0.100[a]	0.149[a]	0.045[a]	0.0014[a]	0.0004[a]
II	0.111[b]	0.021[b]	0.497[b]	0.853[b]	0.186[b]	0.0084[b]	0.0025[b]
III	0.220[c]	0.053[c]	1.268[c]	3.496[c]	0.806[c]	0.0331[c]	0.0051[c]
IV	0.588[d]	0.137[d]	2.259[d]	7.700[d]	2.206[d]	0.0556[d]	0.0108[d]
Bark							
I	0.019[a]	0.002[a]	0.094[a]	0.075[a]	0.026[a]	0.0002[a]	0.0003[a]
II	0.071[b]	0.015[b]	0.374[b]	0.586[b]	0.143[b]	0.0010[b]	0.0013[b]
III	0.125[c]	0.035[c]	0.606[c]	1.775[c]	0.363[c]	0.0030[c]	0.0022[c]
IV	0.175[d]	0.073[d]	1.211[d]	2.873[d]	0.664[d]	0.0049[d]	0.0040[d]
Aboveground part of trees							
I	0.087[a]	0.012[a]	0.607[a]	1.359[a]	0.233[a]	0.0033[a]	0.0018[a]
II	0.307[b]	0.057[b]	1.997[b]	5.279[b]	0.695[b]	0.0145[b]	0.0073[b]
III	0.668[c]	0.141[c]	3.996[c]	16.765[c]	2.033[c]	0.0499[c]	0.0130[c]
IV	1.537[d]	0.296[d]	8.208[d]	37.277[d]	5.357[d]	0.0868[d]	0.0304[d]
Roots							
I	0.104[a]	0.007[a]	0.171[a]	0.228[a]	1.375[a]	0.0087[a]	0.0008[a]
II	0.286[b]	0.018[b]	0.521[b]	0.549[b]	17.478[b]	0.0628[b]	0.0035[b]
III	0.480[c]	0.041[c]	0.865[c]	2.843[c]	10.138[c]	0.1047[c]	0.0054[c]
IV	0.497[c]	0.084[d]	1.500[d]	4.478[d]	18.559[b]	0.2139[d]	0.0095[d]
Litter fall							
I	0.013[a]	0.005[a]	0.096[a]	0.670[a]	0.236[a]	0.0024[a]	0.0003[a]
II	0.214[b]	0.042[b]	1.249[b]	6.245[b]	2.538[b]	0.0213[b]	0.0041[b]
III	0.314[c]	0.072[c]	2.432[c]	13.738[c]	5.002[c]	0.0463[c]	0.0101[c]
IV	0.412[c]	0.099[c]	2.245[c]	17.438[c]	6.714[c]	0.0599[c]	0.0090[c]

a, b, c, d – homogenous groups determined at 0.05 significance level

Summary and conclusions

A significant accumulation of elements, including particularly biogenic ones, such as carbon (about 50% of the dry aboveground biomass), nitrogen, phosphorus, potassium, calcium and magnesium occurred in the spontaneous birch afforestation on post-agricultural lands. Biomass increments, and consequently the accumulation of elements recorded in this study, were significantly higher than the increment described for Sweden and Estonia. This was probably due to the longer growing season and better habitat conditions that characterize sites located in the Mazovia region. The fertility of the habitat is probably also the reason for a somewhat weaker root development. This is because there is less need for such a significant penetration of the soil environment where there is a higher availability of nutrients.

The allocation of biogenic elements in particular parts of trees was surely affected by the phase of the vegetation season in which the samples were collected. To confirm this hypothesis it would be desirable to investigate whether the given elements existed in the mobile or bound fraction. This could be done by an analysis of the chemical composition of the juices from the analysed birches. It can be indisputable, however, as the highest content of biogenic elements was located in the foliage, with the exception of carbon, which was mainly allocated to the growing stems.

The content of microelements in various parts of the trees varied, and their location depended on their physiological role. The highest content of these elements existed mainly in the leaves, but some of them (sodium, lead and iron) were to a large extent allocated to the roots while copper was located in the stems and bark.

Based on the presented results, after supplementing them with a soil analysis and taking into account litterfall and herbaceous vegetation, it should be possible to make an introductory balance of the matter flow that takes place in the process of the initiated transformation of the former agricultural area into forest land. Such an analysis of the spontaneous birch afforestation could help answer the question if such a process is beneficial to the environment in terms of ecosystem protection, biodiversity, habitat conservation, as well as the economy and sustainable environmental management.

References

Bernadzki E., Kowalski M. [1983]: Brzoza na gruntach porolnych (Birch on post-agricultural land). Sylwan 12 [127]: 33–42

Bijak Sz., Zasada M., Bronisz A., Bronisz K., Czajkowski M., Ludwisiak Ł., Tomusiak R., Wojtan R. [2013]: Estimating coarse roots biomass in young silver birch stands on post-agricultural lands in central Poland. Silva Fennica 47 [2]: 14

Claesson S., Sahlén K., Lundmark T. [2001]: Functions for biomass estimation of young *Pinus sylvestris*, *Picea abies* and *Betula* spp. from stands in northern Sweden with high stand densities. Scandinavian Journal of Forest Research 16: 138–146

Glanc W., Pazdrowski W., Cybulko T. [2000]: Zawartość Mn, Fe, Zn i Cu w soku brzozowym (*Betula verrucosa* Ehrh.) (Contents of Mn, Fe, Zn and Cu in birch juice). Zeszyty Problemowe Postępów Nauk Rolniczych [471]: 693–698

GUS [2011]: Leśnictwo 2011 (Forestry 2011). Zakład Wydawnictw Statystycznych, Warszawa

Hynynen J., Niemistö P., Viherä-Aarnio A., Brunner A., Hein S., Velling P. [2010]: Silviculture of birch (*Betula pendula* Roth. and *Betula pubescens* Ehrh.) in northern Europe. Forestry 83 [1]: 103–119

Jakubowski G., Sobczak R. [1999]: Możliwości intensywnej uprawy sosny i brzozy na gruntach porolnych (The possibilities of intensive growing of pine and birch on post-agricultural lands). Prace Instytutu Badawczego Leśnictwa Seria A [882]: 61–93

Johansson T. [1999]: Biomass equations for determining fractions of pendula and pubecsens birches growing on abandoned farmland and some practical implications. Biomass Bioenergy 16: 223–238

Karlsson A., Albrektson A., Forsgren A., Svensson L. [1998]: An analysis of successful natural regeneration of downy and silver birch on abandoned farmland in Sweden. Silva Fennica 32 [3]: 229–240

Kayzer D., Czerniak A., Poszyler-Adamska A. [2011]: Wpływ pierwiastków śladowych na parametry morfometryczne aparatu asymilacyjnego brzozy brodawkowatej (Effect of trace elements on the morphometric parameters of assimilation apparatus in white birch). Infrastructure and ecology of rural areas 2: 261–273

Kuznetsova T., Lukjanova A., Mandre M., Lõhmus K. [2011]: Aboveground biomass and nutrient accumulation dynamics in young black alder, silver birch and Scots pine plantations on reclaimed oil shale mining areas in Estonia. Forest Ecology and Management 262 [2]: 56–64. DOI:10.1016/j.foreco.2010.09.030

Liepins K. [2007]: First-year height growth of silver birch in farmland depending on container stock morphological traits. Baltic Forestry 13 [1]: 54–60

Martyn D. [2000]: Klimaty kuli ziemskiej (Climates of the Earth). PWN, Warszawa

Mälkönen E. [1977]: Annual primary production and nutrient cycle in birch stand. Communicationes Instituti Forestalis Fenniae 91 [5]: 35

Snowdon P., Eamus D., Gibbons P., Khanna P., Keith H., Raison. J., Kirschbaum M. [2000]: Synthesis of allometrics. Review of root biomass and design of future woody biomass sampling strategies, NCAS Technical Report 17: 113

Snowdon P., Raison. J., Keith H., Ritson P., Grierson P., Adams M., Montagu K., Hiu-Quan B., Burrows W., Eamus D. [2002]: Protocol for sampling tree and stand biomass. NCAS Technical Report 31: 66

Uri V., Lõhmus K., Ostonen I., Tullus H., Lastik R., Vildo M. [2007]: Biomass production, foliar and root characteristics and nutrient accumulation in young silver birch (*Betula pendula* Roth.) stand growing on abandoned agricultural land. European Journal of Forest Research 126 [4]: 495–506. DOI:10.1007/s10342-007-0171-9

Uri V., Varik M., Aosaar J., Kanal A., Kukumägi M., Lõhmus K. [2012]: Biomass production and carbon sequestration in a fertile silver birch (*Betula pendula* Roth.) forest chronosequence. Forest Ecology and Management 267: 117–126. DOI:10.1016/j.foreco.2011.11.033

Varik M., Aosaar J., Ostonen I., Lõhmus K., Uri V. [2013]: Carbon and nitrogen accumulation in belowground tree biomass in a chronosequence of silver birch stands. Forest Ecology and Management 302: 62–70. DOI:10.1016/j.foreco.2013.03.033

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ESTIMATING FOREST BIOMASS BY REMOTE SENSING RADAR DATA IN BRAZIL

Remote sensing-radar was used to analyze forest mapping and biomass estimates on Brazilian territory. Two examples of SAR attributes for the modeling of the aboveground biomass of forest stands are presented: (1) full-polarimetric attributes of PALSAR/ALOS (Phased Array type L-band Synthetic Aperture Radar/ Advanced Land Observing Satellite) for modeling in the Amazonian tropical forest, considering the influence of the geomorphometric aspects on this radar response, and (2) polarimetric and interferometric airborne data (X_{HH} and full-polarimetric of P-band) for modeling Eucalyptus sp. stands. In both cases, an analysis of forest structure variability through polarimetric signatures was conducted. A multivariate regression technique was used to integrate the variables from polarimetric and/or interferometric radar attributes and field inventory. Considering the terrain aspects where the tropical forest was located, the most significant variables for the biomass modeling were the Volumetric Scattering of Freeman-Durden target decomposition, Anisotropy, Relief Elevation, Slope, and the first and third helicity components of the Touzi model. For the Eucalyptus biomass model, the Interferometry Height and Canopy Scattering Index variables were significant. The statistical analysis based on field survey measures to validate each model, indicated a margin of error below 20% for the biomass estimations, showing the importance of SAR attributes for models of natural and planted forest stock density.

Keywords: biomass modeling, forest inventory, radar data, tropical forest, Eucalyptus stand, remote sensing.

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Introduction

The current status of mapping and monitoring forest resources, at local, regional and global levels, has increased in importance as a tool for economic strategy. This is due to strong competition which predicts a rising market demand for wood products and especially for wood-based bioenergy. According to Koch [2010], there is also a growing need for information to improve the sustainability of our forests with regard to carbon flux magnitude, which is a significant area of scientific interest in terms of climate change.

Forest inventories assisted by remote sensing reap not only the benefit of incurring lower costs and obtaining results in less time than traditional methods, but also enable inventories to be conducted in large forest areas [Hou et al. 2011]. Some possibilities of and limitations to remote sensing data and methods (table 1), which can support mapping and forest inventory are listed by Gibbs et al. [2007]. The limitations to using remote sensing data for biomass mapping are related to data and appropriate method availability. The methods used today refer mainly to multispectral optical data sets and their digital classification methods, but often cannot fulfill the information requirements with regard to timeline and quality [Koch 2010]. This author mentioned that multi-sensor approaches based on polarimetric radar interferometry, fullwave laser, or hyperspectral data, have not yet been sufficiently developed to fill these gaps in information.

Within the range of sensor-products, this article focuses on how specifically remote sensing technology – RADAR – has been used in Brazil as a tool for the analysis of forest structure and its aboveground biomass. The physical principles of radar-interaction with the components of forest structure are complex, and determine the scattering mechanisms of the incident radiation that hits the forest components and returns to the RADAR sensor, the responses of which also depend on the imagery wavelength, polarization, and incidence angle of imagery [Koch 2010].

The methodological approach derived from the multi-polarimetric and/or interferometric Synthetic Aperture Radar – SAR data, enables detailed information on three-dimensional forest structure [Kasischke et al. 1997; Treuhaft et al. 2009] to be obtained. Indices based on ratios and normalized differences of multi-polarimetric data were developed and tested on tropical forests in Central America [Pope et al.1994]. These indices can be related to certain characteristics of vegetation cover, such as the biomass index [$BMI = (\sigma^o_{HH} + \sigma^o_{VV}) / 2$], the canopy structure index [$CSI = \sigma^o_{VV} / (\sigma^o_{VV} + \sigma^o_{HH})$], and the volume scattering index [$VSI = \sigma^o_{HV} / (\sigma^o_{HV} + BMI)$], where σ^o (sigma nought) refers to the scattering coefficient which describes the amount of backscattered power compared to that of the incident target; while HH, VV, HV polarizations are related to the state of polarization of the wave, that represent the electric field from the transmitting and receiving antenna (HH – for horizontal transmission and horizontal reception;

VV – for vertical transmission and vertical reception; and HV – for horizontal transmission and vertical reception).

Table 1. Benefits and limitations of remote sensing data to forest structure and biomass studies

Products	Description	Benefits	Limitations	Uncertainty
Optical remote sensors	– Use visible and infrared wavelengths to measure spectral indices and correlate to ground-based forest biomass measurements. Eg: Landsat, AVNIR/ALOS, HRV/SPOT, MODIS	– Satellite data routinely collected and available on regional and/or global scale – Regionally and/or globally consistent	– Limited ability to develop good models for tropical forests – Spectral indices saturate at relatively low C stocks – Can be technically demanding	High
Very high resolution optical remote sensors	– Use very high resolution images to measure tree height and crown area and allometry to estimate biomass stocks – Eg: 3D digital aerial imagery, IKONOS, QuickBIRD	– Reduce time and cost of collecting forest inventory data – Reasonable accuracy – Excellent ground verification for deforestation baseline	– Only cover small areas (10 000s ha) – Can be expensive and technically-demanding – No allometric relations based on crown area are available	Low to medium
Radar remote sensors	– Use microwave signal to measure forest vertical structure – Eg: ALOS/PALSAR-2, RADARSAT-2, COSMOSkyMed, TanDEM/TerraSAR-X	– Satellite data are generally free – Can be accurate for open or sparse primary forest and secondary succession	– Less accurate in complex canopies of mature tropical forests because signal saturates – Mountainous terrain also increases number of errors – Can be expensive and technically-demanding	Medium
Laser remote sensors	– LiDAR uses laser light to estimate forest height/vertical structure – Eg: Structure and biomass 3-D satellite system combines Vegetation canopy LiDAR (VCL) with horizontal imager	– Accurately estimates full spatial variability of forest carbon stocks – Potential for satellite-based system to estimate global forest carbon stocks	– Airborne-mounted sensors only option – Requires extensive field data for calibration – Can be expensive and technically-demanding	Low to medium

Source: Modified from Gibbs et al. [2007]

Neeff et al. [2005a] and Kugler et al. [2006] discuss the contribution of the interferometric mode to estimate biophysical parameters in forest areas. Some studies on radar applications conducted in Brazil to support the tasks of mapping, inventory and forest monitoring [Santos et al. 2003; Neeff et al. 2005b; Gama et al. 2010a; Treuhaft et al. 2010; Gonçalves et al. 2011; Saatchi et al. 2011; Li et al. 2012] explain the contributions of SAR attributes related to the structural complexity of primary and secondary tropical forests and also of reforested areas, when modeling of aboveground biomass and/or volume is needed. In this scenario, the present work aims to show the results derived from two scientific projects in Brazilian forest areas, as described below:

- to generate an estimating model of aboveground biomass of tropical forest, based on a combination of full-polarimetric attributes of the active microwave sensor PALSAR/ALOS (Phased Array type L-band Synthetic Aperture Radar/ Advanced Land Observing Satellite), considering the influence of the geomorphometric aspects of terrain on the radar response;
- to generate an estimating model of aboveground biomass of *Eucalyptus* sp. stands, using a multivariate analysis for the associating coherent and incoherent polarimetric attributes in P-band, as well as the interferometric height derived from airborne SAR imagery with X- and P-bands.

Multi-attributes from PALSAR data for the modeling of aboveground biomass in Amazonian primary forest considering terrain aspects

The first study, was conducted in Tapajós National Forest – FNT (North East of Pará State, Brazil), at geographic coordinates S 2º42’24” – S 4º07’18” and W 54º52’37” – W 54º57’38”, a region dominated by Dense and Open Ombrophylous Forests and sections with legal and controlled timber exploitation activities. The local topography varies from flat (in the northern part of the area) to strongly undulating (in the southern zone). The predominant soil types in the area are Dystrophic Yellow Latosol and Red-Yellow Podzolic.

In this study, full polarimetric data from PALSAR/ALOS images (PLR format), in ascending mode, with a spatial resolution of 3.58 m in azimuth and 9.36 m in range, with an incidence angle of 24º were used. The geomorphometric attributes of the terrain (elevation and slope) for the area under investigation were derived from the Brazilian Geomorphometric Database – called Topodata – [Valeriano, Albuquerque 2010]. According to Valeriano, Rossetti [2012], the SRTM data, available from JPL/NASA [2001], was refined from 3 to 1 arc-second angle using a geostatistical technique, and the geomorphometric variables could be obtained using different neighborhood operations [Valeriano, Albuquerque 2010].

The geometric and radiometric calibrations of full-polarimetric PALSAR images were performed according to the methodology of Shimada et al. [2009]. These corrections were necessary to obtain the real values referring to the analysed images at $L_{HH,HV,VV,VH}$ -band. A scattering matrix (Sinclair matrix [S]) was generated, and then converted to a covariance matrix [C] and to a coherence matrix [T], applying a spatial averaging of 7 × 1 pixels. The spatial averaging permitted a conversion of the pixel spacing from approximately 3.58 m in azimuth by 9.36 m in slant range to 23 m in azimuth by 25 m in ground range. After this processing, the speckle noise was reduced using the polarimetric Refined Lee filter (5 × 5 window). The following incoherent attributes, which are based on information from the real part of each pixel, were considered: the backscatter coefficient ($\sigma°$), described by Woodhouse [2006]; the ratio of parallel polarization (Rp) and cross polarization (Rc), mentioned by Henderson, Lewis [1998]; and several indices formulated by Pope et al. [1994] in forest environments, known as the biomass index (BMI), the canopy structure index (CSI) and the volume scattering index (VSI).

These filtered polarimetric images, exploring the SAR phase-information, were also used to generate the coherent attributes: polarimetric coherence of HH-VV (γ) and phase difference of HH-VV ($\Delta\varphi$), described by Henderson, Lewis [1998]; the parameters resulting from the target decomposition by coherence matrix [T] according to Cloude, Pottier [1996] and Lee, Pottier [2009] known as entropy (H), anisotropy (A) and the mean alpha angle ($\bar{\alpha}$); the volume scattering components (Pv), double bounce (Pd) and surface (Ps), resulting from the decomposition matrix [C] [Freeman, Durden 1998]; and also, the magnitude (αs) and Touzi phase ($\Phi\alpha s$). Besides that, the orientation angle (ψ) and heliticity (τ_m), derived from two stages of the same former decomposition model were considered: (1) the Graves matrix [G]; (2) the Kennaugh-Huynen matrix, described in Touzi [2007] and Touzi et al. [2009], where a different procedure was used, with multilook 3x1 (azimuth x range).

The amplitude and phase information was generated in the reference system of the radar image (slant range) and the ground survey samples established for the forest inventory [Bispo et al. 2012] were projected for this system based on the process of inverse geocodification [Meier et al. 1993]. All the abovementioned polarimetric SAR attributes were extracted from ROIs – given Regions of Interest – which include a sufficient number of theme representative pixels, thus reducing statistical uncertainties and the influence of speckle noise. The field inventory was carried out based on DBH and height measurements of 4,448 trees (related to the 49 botanic families and 232 species) for 40 established independent plots (with a dimension of 2.500 m^2 each). Specific allometric equations of primary forest were used to calculate the aboveground biomass values of each sample according to the procedure in the study by Bispo [2012].

Considering the 40 plots duly georeferenced during the field survey, 30 of them were selected for generating the biomass model (10 plots situated on flat terrain, 10 on undulating and 10 on strongly undulating terrain), and the plots remaining were used to validate the best generated model (distributed also in the same geomorphometric types mentioned above).

To select the radar attributes (coherent and incoherent variables) for the regression model, the following were used as part of the methodological approach, during the interaction analysis of SAR and the field survey data (table 2): Mallow's Cp criterion (to assess the fit of a regression model which has been estimated using ordinary least squares), the R^2 (coefficient of determination) and R^2_{adj} (adjusted coefficient of determination) criteria (best subset), as well as some statistical procedures such as the presence of interaction effects (by bivariate interaction terms), the diagnosis of multi-collinearity (by calculus of Variance Inflation Factor – VIF) according to Stine [1995] and Neter et al. [1996], and the outliers (Cook´s distance) and residuals analysis [Neter et al. 1996].

Table 2. Statistical parameters derived from biomass model based on polarimetric and geomorphometric variables

Variable	β	SE	t	p	VIF
Constant	31.11	39.48	0.79	0.439	–
Pv	142.01	83.96	1.69	0.104	1.5
An	-598.3	161.7	-3.70	0.001	1.5
h	1.4635	0.1728	8.47	0.000	1.3
G	3.350	1.206	2.78	0.011	1.2
τ_m3	0.4288	0.2545	1.68	0.106	1.1
τ_m1	-9.478	3.723	-2.55	0.018	1.1

* R^2 = 79.4%; R^2 (adjusted) = 74.0%; R^2 (predict) = 55.29%; p = 0.000

The spatial arrangement of aboveground biomass density of tropical forest is very complex, where the topography is one of the principal aspects that affects this heterogeneity [Luckman 1998]. Thus, biomass density has a strong influence on radar response related to the scattering mechanisms. For this reason, it was also important to generate a model using geomorphometric variables (fig. 1). Therefore, based on the statistical criteria, the following final model ($R^2 = 0.74$ and $p = 0.0000$) was selected [Bispo 2012]:

$$AGB = 31.11 + 142.01\ Pv - 598.3\ An + 1.465\ h + 3.35\ G + 0.4288\ \tau\_m^3 - \\ - 9.478\ \tau\_m_1 \tag{1}$$

where: AGB – the aerial aboveground biomass
Pv – the Freeman-Durden volumetric scattering
An – anisotropy
h – elevation
G – slope
τ_m_1 and τ_m_3 – helicity of the dominant (first) and lowest (third) scattering component generated by Touzi decomposition.

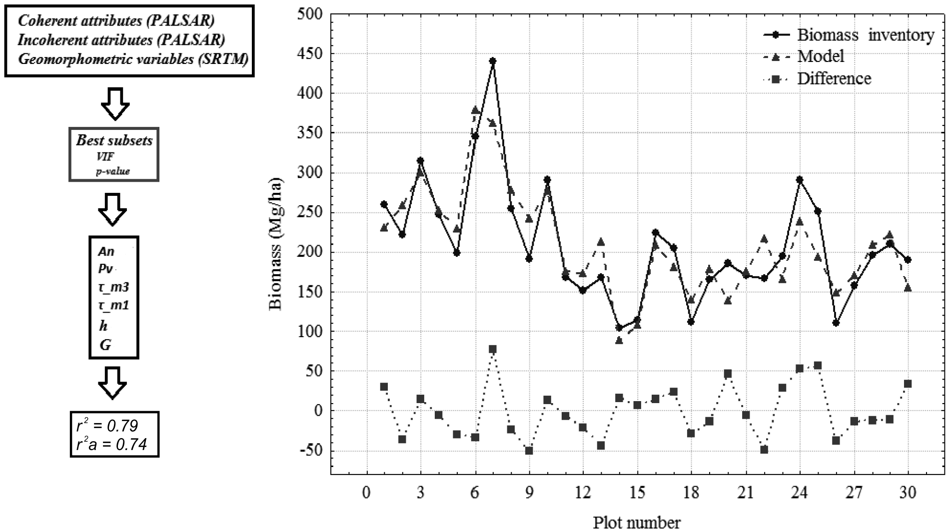


Fig. 1. Diagram showing the SAR attributes and geomorphometric variables used and the comparative behaviour of primary forest biomass from field survey and model in the Tapajós region

In this model, the anisotropy (*An*) showed a strong negative correlation with the biomass, indicating the presence of secondary scattering mechanisms, due especially to four strata composing the vertical structure of the Ombrophylous Forest in the Tapajós region. The τ_m_3 and *Pv* variables were positively correlated with the biomass, due to the number of trees spatially distributed at several forest strata. This forest arrangement is considered a cloud of randomly oriented dipoles, showing a good adherence to the theoretical polarimetric signature model proposed by Zebker, Norikane [1987]. In additional to the high biomass content, this arrangement with its high quantity of randomly-distributed elements, also controlled the SAR backscatter within the image resolution cell.

During the field inventory, the total observed biomass was 210.02 t/ha. with a standard deviation of ±74.31 t/ha. The configuration of biomass values from the model was compared with the biomass estimated in the field survey, using 10 independent plots (AGB mean value of 210.68 ± 40.54 $Mg \cdot ha^{-1}$). The RMSE values were approximately 42.96 $Mg \cdot ha^{-1}$, whose validation, estimated by the model, showed an error of 20% compared to the mean observed aboveground biomass on the Tapajós site.

Polarimetric and interferometric airborne SAR data for the aboveground biomass estimation of *Eucalyptus* sp.

In Brazil, a significant amount of carbon dioxide (1.3 billion tons) and other greenhouse gases (GHGs) are sequestered from the atmosphere by *Eucalyptus* and pine forest plantations, contributing to the mitigation of climate change effects [Folha da Bracelpa 2013].

Nowadays, there are approximately 6.7 million hectares occupied by homogeneous planted forests in Brazil, with a pulp production of 14 tons per year, thus generating 9.8 tons of paper per year.. This activity resulted in a trade balance of US$ 4.7 billion in 2012 [Brasil Econômico 2013]. In addition, there is a strong charcoal production. The horizontal expansion and value increase of the forest--based sector have encouraged the improvement of mechanisms for inventory and the monitoring of forest farms with advanced remote sensing tools, especially with high resolution optical images, LiDAR [Zonete et al. 2010; Oliveira et al. 2012; Macedo et al. 2013]and also radar data [Gama et al. 2010a]. Such issues are of interest to reforestation companies seeking to minimize their costs, as well as to improve control and management efficiency. Moreover, remote sensing techniques improve the accuracy of forest measurements when compared with traditional field inventory, allowing a synoptic view of the forest.

Within this context, a second study was carried out in the Paraíba River Valley (W 45° 23’ to 45° 25’and S 22° 54’ to 22° 55’), São Paulo State, using airborne OrbiSAR system to provide the radar data from a reforested area with *Eucalyptus* sp. (6 year old stands ~, spaced 3 m × 2 m and tree height varying between 14 to 23 m).

The airborne data acquisitions were carried out in X_{HH}-band (1 m resolution) and in fully polarimetric P-band (range and azimuth resolution of 2 m), both with a 45° boresight angle. The mapping flights were crossed to minimize the shadowing effect, and so the image regions which lacked information due to shadows were filled in by mosaic techniques. X-band interferometry was carried out in one pass with 2.77 m of baseline, while for the P-band interferometry two passes were necessary with 50 m of baseline. X-band coherence, DEM (Digital Elevation Model) and complex images were generated in HH polarization. P band data, as interferometric coherence, DEM and complex images were obtained in four polarizations.

These microwave data (X- and P-bands) were radiometrically calibrated using corner reflectors. The antenna pattern correction was performed using a homogeneous target area. The polarimetric calibration was also performed to minimize the distortions imposed by the SAR system in the scattering matrix (cross-talk and channel imbalance), using the method proposed by Quegan [1994].

The *Eucalyptus* aboveground biomass model was estimated by linear regression modeling between the field inventory data and the interferometric and polarimetric airborne SAR data. The field inventory data was collected based on the measurement of DBH and height values of 80 trees for each one of the established 23 plots of 400 m^2. The absence of trees in the forest stand was also studied, because it caused a reduction of biomass values in each plot. During the field survey, the biomass of the stands was obtained by a destructive method. One representative tree from each plot was selected, the DBH value of which was similar to the average found for all individuals of each sample. Then, these selected trees were cut-down and weighed to represent the whole stand. Simultaneously, some topographic profiles were carried out using an infrared Total Station (Topcon, GTS-701 model with 3 arc-second angle accuracy) for the analysis of P_{HH}, P_{HV}, P_{VV} interferometric DEM quality (Digital Elevation Model), which showed the lowest standard deviation of 2 m [Gama et al. 2010b]. On the other hand, the comparison of the sum of inventoried tree heights with these topographic ground measurements, and with X band DEM heights, indicated a standard deviation of approx. 3.4 m.

To select the SAR coherent and incoherent variables (fig. 2a) for the regression model, Stepwise, Cp, R^2 and R^2_a criteria were used, as well as Cook's distance to find the outlier cases. Levene's method was used to verify the homoscedastic behavior of regression residues. Based on this approach, the variables $Hint^2$ (Hint – difference between interferometric values in X- and P-bands) and CSI (measure of the relative importance of vertical versus horizontal structure in the forest cover) presented a linear behavior, the final model of which is:

$$AGB = -114.505 + 0.137\, H_{int}^{2} + 316.058\, CSI \qquad (2)$$

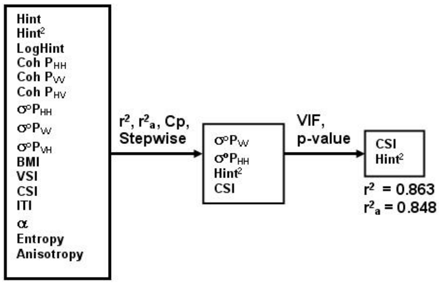
where: AGB – the aerial aboveground biomass
H_{int} – interferometric height obtained from the difference between interferometric digital elevation models in X-and P-bands
CSI – canopy structure index from Pope's ratio, which represents the microwave interaction with the vegetation canopy.

Table 3 presents the statistical values derived from this aboveground biomass model. The AGB model obtained a determination coefficient of 0.863, with one outlier case related to plot 1. The CSI variable brought some radiometry contribution of $\sigma°P_{VV}$ and $\sigma°P_{HH}$, therefore the radiometry contributed to the model due to fact the interaction of the radar beam with the vertical and horizontal stand elements (branches, leaves, and stem) represented by the CSI index. The squared Hint ($Hint^2$) variable strongly contributed to the biomass model too, since *Eucalyptus* biomass has a second order relationship with its height.

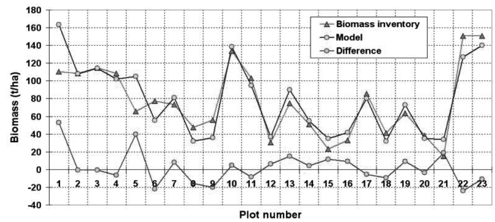
Table 3. Statistical data from the regression biomass model of *Eucalyptus* stands

Variables	β	p-value	MSE	PRESS	R^2	$R^2_{adjusted}$
Intercept	-114.505	4.89%	245.26	6187.43	86.29%	84.84%
$Hint^2$	0.137	0.013%				
CSI	316.058	2.18%				

The aboveground biomass model is very similar to the inventory data (23 plots) in the Eucalyptus stand (fig. 2b). The biomass variations of all the plots obtained during the ground survey were related to the different local site index where the forest stands were located and also to the particular genetic differences (seminal and clones) of these plantations.



(a)



(b)

Source: adapted from Gama et al. [2010a]

Fig. 2. Diagram of SAR attributes tested to generate the model (a); and comparative behaviour of aboveground biomass modeling of *Eucalyptus* sp. stands (b)

The criteria PRESS (Predicted Residual Sum of Squares) and SSE (Sum of Squared Errors) were used to validate the model (table 3). This allowed the use of MSE (Mean Squared Errors) to predict the errors [Neter et al. 1996; Rencher, Schaalje 2008]. The MSE for the biomass regression model presented a value of 245.26, which meant that this biomass model had a prediction error of 10.38% when compared with the minimum stand biomass.

Conclusions

Currently, polarimetry and interferometry research concepts largely focus on tropical regions, not only to map deforestation and degradation caused by timber exploitation or by forest fire actions, but also to be used as input for biomass calculations. These SAR techniques can be directed to improve biomass estimations, which have recently been methodologically developed in Brazil, by Gonçalves et al. [2011], Saatchi et al. [2011]; Sambatti et al. [2012], Santos et al. [2013] among others.

Based on the two results presented in this paper the following conclusions have been reached:

– Relief elevation and slope orientation attributes are innovative variables in the calculation of aboveground biomass of tropical primary forest, which, associated with the SAR attributes from the volumetric scattering of Freeman-Durden target decomposition, anisotropy, and the first and third helicity components of the Touzi model, improve the consistency of this estimation prediction using L-band data.
– The aboveground biomass modeling of *Eucalyptus* stands, when incorporating interferometric height and incoherent attributes (Canopy Structure Index

from the Pope equation), provide a higher degree of accuracy in the estimation process. The interferometric SAR attributes have a strong relationship with the *Eucalyptus* biomass content, because reforested area is clear in the understory strata, and the species under study has a small canopy despite its great height.

– In both the cases mentioned above, according to a set of independent data from the field inventory used for model validation, the results showed an error margin below 20% for estimates of aboveground biomass. This demonstrates the potential of SAR technology tools for the biomass modeling of natural and planted forest stock density, within an acceptable accuracy, and for optimized surveys of large areas, compared to traditional inventory. The methodology presented here can be applied to support management and monitoring tasks for the production and control of the Brazilian forest landscape.

References

Brasil Econômico [2013]: http://brasileconomico.ig.com.br/noticias/producao-de-celulose-e--papel-fica-estavel-em-2012_127996.html [accessed: 8.12.2013]

Bispo P.C. [2012]: Efeitos da geomorfometria na caracterização florístico-estrutural da Floresta Tropical na região de Tapajós com dados SRTM e PALSAR (Effects of geomorphometry in floristic-structural characterization of Tropical Forest at Tapajós region with use of SRTM and PALSAR data). National Institute for Space Research (INPE) [accessed 13.05.2014] Available from: http://urlib.net/8JMKD3MGP7W/3C34QC8 [Ph.D thesis]

Bispo P.C., Valeriano M.M., Santos J.R. [2012]: Effects of the geomorphometric characteristics of the local terrain on floristic composition in the central Brazilian Amazon. Austral Ecology 34 [4]: 491–499

Cloude S.R., Pottier E. [1996]: A review of target decomposition theorems in radar polarimetry. IEEE Transactions on Geoscience and Remote Sensing 34 [2]: 498–518

Carvalhaes E. [2013]: Mudanças climáticas - ações globais precisam ser efetivas. 8, [fev. março], Folha da Bracelpa, Publicação da Associação Brasileira de Celulose e Papel (Climate changes - global actions need to be effectives. 8, [fev.março] Folha da Bracelpa Publication of the Brazilian Association of Pulp and Paper) [accessed 13.05.2014]. Available from: http://www.bibliotecaflorestal.ufv.br/bitstream/handle/123456789/3902/FolhaBracelpa-008.pdf?sequence=2, São Paulo

Folha da Bracelpa [2013]: Mudanças climáticas – ações globais precisam ser efetivas. 8, [fev. março] Publicação da Associação Brasileira de Celulose e Papel (Climate changes – global actions need to be effectives. 8, [fev.março] Publication of the Brazilian Association of Pulp and Paper). [accessed 13.05.2014] Available from: http://www.bibliotecaflorestal.ufv.br/bitstream/handle/123456789/3902/FolhaBracelpa-008.pdf?sequence=2, São Paulo

Freeman A., Durden S.L. [1998]: A three-component scattering model for polarimetric SAR data. IEEE Transactions on Geoscience and Remote Sensing 36 [3]: 963–973

Gama F.F., Santos J.R., Mura J.C. [2010a]: Eucalyptus biomass and volume estimation using interferometric and polarimetric SAR data. Remote Sensing 2 [4]: 939–956

Gama F.F., Mura J.C., Albuquerque P.C.G., Santos J.R. [2010b]: Avaliação do potencial da interferometria SAR para o mapeamento altimétrico de áreas reflorestadas por *Eucalyptus* sp. (Evaluation of the potential of SAR interferometry for altimetry mapping of reforested areas by *Eucalyptus* sp.). Boletim de Ciências Geodésicas 16 [4]: 519–537

Gibbs H.K., Brown S., Nieles J.O., Foley J.A. [2007]: Monitoring and estimating tropical forest carbon stocks: making REDD a reality. Environmental Research Letters 2: 045023

Gonçalves F.G., Santos J.R., Treuhaft R.N. [2011]: Stem volume of tropical forests from polarimetric radar. International Journal of Remote Sensing 32 [2]: 503–522

Hendersen F. M., Lewis A.J. [1998]: Radar fundamentals: The geoscience perspective. In: Ryerson, R.A. (ed.), Manual of Remote Sensing: Principles and Applications of Imaging Radar. John Wiley & Sons, Inc. New York

JPL/NASA: http://www2.jpl.nasa.gov/srtm/ [accessed: 15.06.2001]

Hou Z., Xu Q., Tokola T. [2011]: Use of ALS, airborne CIR and ALOS AVNIR-2 data for estimating tropical forest attributes in Lao PDR. ISPRS Journal of Photogrammetry and Remote Sensing 66 [6]: 776–786

Kasischke E.S., Melack J.M., Dobson M.C. [1997]: The use of imaging radar for ecological applications: a review. Remote Sensing of Environment 59 [2]: 141–156

Koch B. [2010]: Status and future of laser scanning, synthetic aperture radar and hyperspectral remote sensing data for forest biomass assessment. ISPRS Journal of Photogrammetry and Remote Sensing 65 [6]: 581–590

Kugler F., Papathanassiou K.P., Hajnsek I. [2006]: Forest height estimation over tropical forest by means of polarimetric SAR interferometry. Proceedings of: VII Seminário de Atualização em Sensoriamento Remoto e Sistemas de Informações Geográficas Aplicados à Engenharia Florestal, October 2006. Curitiba: 504–512

Lee J.S., Pottier E. [2009]: Polarimetric radar imaging: from basics to applications. Taylor & Francis, Boca Raton

Li G., Lu D., Moran E., Dutra L.V., Batistella M. [2012]: A comparative analysis of ALOS PALSAR L-band and RADARSAT-2 C-band data for land-cover classification in a tropical moist region. ISPRS Journal of Photogrammetry and Remote Sensing 70: 26–38

Luckman A.J. [1998]: Correction of SAR imagery for variation in pixel scattering area caused by topography. IEEE Transactions on Geoscience and Remote Sensing 36 [1]: 344–350

Macedo R.C., Santos J.R., Soares J.V. [2013]: TreeX (TREE EXTRACTOR) – a tool for forest canopy analysis and tree counting with LiDAR data. Revista Brasileira de Cartografia 65 [4]: 627–634

Meier E., Frei U., Nuesch D. [1993]: Precise terrain corrected geocoded images. In: Wichmann Verlag, SAR geocoding: data and system, Kalsruhe

Neeff T., Biging G.S., Dutra L.V., Freitas C.C., Santos J.R. [2005a]: Modeling spatial tree pattern in the Tapajós forest using interferometric height. Revista Brasileira de Cartografia 57 [1]: 1–6

Neeff T., Dutra L.V., Santos J.R., Freitas C.C., Araujo L.S. [2005b]: Power spectrum analysis of SAR data for spatial forest characterization in Amazonia. International Journal of Remote Sensing 26 [13]: 2851–2865

Neter J., Kutner N.H., Nachtssheim C.J., Wasserman W. [1996]: Applied Linear Statistical Models. 4 ed. McGraw Hill, Boston

Oliveira L.T., Carvalho L.M.T., Ferreira M.Z., Oliveira T.C.A., Acerbi Junior F.W. [2012]: Application of LIDAR to forest inventory for tree count in stands of *Eucalyptus* sp**.** Cerne 18 [2]: 175–184

Pope K.O., Rey-Benayas J.M., Paris J.F. [1994]: Radar remote sensing of forest and wetland ecosystems in Central American Tropics. Remote Sensing of Environment 2 [48]: 205–219

Quegan S. [1994]: A unified algorithm for phase and cross-talk calibration of polarimetric data – theory and observations. IEEE Transactions on Geoscience and Remote Sensing 32 [1]: 89–99

Rencher A.C., Schaalje G.B. [2008]: Linear models in statistics. Wiley-Interscience. John Wiley & Sons, Inc., New Jersey

Saatchi S., Marlier M., Chazdon R.L., Clark D.B., Russel A.E.S. [2011]: Impact of spatial variability of tropical forest structure on radar estimation of aboveground biomass. Remote Sensing of Environment 115 [11]: 2836–2849

Sambatti J.B.M., Leduc R., Lübeck D., Moreira J.R.; Santos J.R. [2012]: Assessing forest biomass and exploration in the Brazilian Amazon with airborne InSAR: an alternative to REDD. The Open Remote Sensing Journal 5: 21–36

Santos J.R., Freitas C.C., Araujo L.S., Dutra L.V., Mura J.C., Gama F.F., Soler L.S., Sant´Anna S.J.S. [2003]: Airborne P-band SAR applied to aboveground biomass studies in the Brazilian tropical rainforest. Remote Sensing of Environment 87 [4]: 482–493

Santos J.R., Martins F.S.R.V., Galvão L.S., Xaud H.A.M. [2013]: Contribution of polarimetric SAR attributes for modeling of the tropical forest biomass affected by fire. Proceedings of: 33º EARSeL Symposium, 3–6 June 2013. Towards Horizon 2020 – Earth Observations and Social Perspectives, Matera: 219–226

Shimada M., Isogushi O., Tadono T., Isono K. [2009]: PALSAR radiometric and geometric calibration. IEEE Transactions on Geoscience and Remote Sensing 47 [12]: 3915–3932

Stine R. A. [1995]: Graphical Interpretation of **Variance Inflation Factors**. The American Statistician 49 [1]: 53–56

Touzi R. [2007]: Target scattering decomposition in terms of roll-invariant target parameters. IEEE Transactions on Geoscience and Remote Sensing 45[1]: 73–84

Touzi R., Deschamps A., Rother G. [2009]: Phase of target scattering for wetland characterization using polarimetric C-band SAR. IEEE Transactions on Geoscience and Remote Sensing 47 [9]: 3241–3261

Treuhaft R.N., Chapman B.D., Santos J.R., Gonçalves F.G., Dutra L.V., Graça P.M.L.A., Drake J.B. [2009]: Vegetation profile in tropical forests from multibaseline interferometric synthetic aperture radar, field, and lidar measurements. Journal of Geophysical Research 114: D23110

Treuhaft R.N., Gonçalves F.G., Drake J., Chapman B., Santos J.R., Dutra L.V., Graça P.M.L.A., Purcell G.H. [2010]: Biomass estimation in a tropical wet forest using Fourier transforms of profiles from Lidar or Interferometric SAR. Geophysical Research Letters 37: L23403

Valeriano M.M., Albuquerque P.C.G. [2010]: Topodata: Processamento dos Dados SRTM (Topodata: Data Processing SRTM). National Institute for Space Reseacearch (INPE). [accessed 22.05.2014]. Available from: http://mtc-m19.sid.inpe.br/col/sid.inpe.br/mtc-m19%4080/2010/05.10.18.42/doc/publicacao.pdf?ibiurl.language=pt-BR

Valeriano M. M., Rossetti D.F. [2012]: Topodata: Brazilian full coverage refinement of SRTM data. Applied Geography 32 [2]: 300–309

Woodhouse I.H. [2006]: Introduction to microwave remote sensing, Boca Raton: Taylor & Francis Group CRC Press, Boca Raton

Zebker H. A., Norikane L. [1987]: Radar polarimeter measures orientation of calibration corner reflectors. Proceedings of the IEEE 75 [12]: 1686–1688

Zonete M.F., Rodriguez L.C.E., Packalén P. [2010]: An estimate of biometric parameters in eucalyptus clone plantations in Southern Bahia: an application of airborne laser scanning (ALS) technology. Scientia Forestalis 38 [86]: 225–235

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VALUE OF MERCHANTABLE TIMBER IN SCOTS PINE STANDS OF DIFFERENT DENSITIES

Differences in the intensity of silvicultural treatments, as well as natural tree mortality, insect damage and fungal disease can eventually lead to variable stand density even on sites of the same quality. In addition, the bigger the initial stand density, the smaller the crown and trunk volume of single trees. The objective of the research was a detailed analysis of the impact of stand density on the total stand volume and value of merchantable timber. The area studied was in Drawno Forest District, north-west Poland, on sites with sandy soil conditions typical for Scots pine (Pinus sylvestris L.*). The total volume of merchantable roundwood was measured on 20 sample plots (each covering an area of 0.5 ha) of which 19 were in 82-year-old stands and one in an 87-year-old stand. The stands were divided into three stand density groups (SDG), where the average number of trees growing per group was as follows: 547 (SDG I), 651 (SDG II) and 765 (SDG III). The volume of a single tree was calculated using diameter (DBH) and height measurement. A quality classification of all 6432 tree stems was carried out in accordance with the Polish Stan-*

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dard. Statistical analysis did not indicate that density influenced the total timber volume of the stands studied, which was recorded as an average of 323 m³·ha⁻¹. However, statistically significant differences in the value of merchantable timber were observed: the highest value of 100 m³ of merchantable timber was recorded in SDG I (€ 5118.87), 6 and 12% higher than in SDGs II and III (€ 4842.09 and € 4565.80, respectively). The results obtained suggest that in the final phase (the last two age classes), pine stands growing in Polish conditions should be maintained at a lower stand density.

Keywords: Scots pine (*Pinus sylvestris* L.), timber value, stand density, wood quantity and quality

Introduction

Timber production in stands is connected to silvicultural practices aimed at achieving optimal tree stand volume and quality when the trees are ready for final felling. Differences in the intensity of the silvicultural treatments and natural phenomena such as wind, fungi or insects, which lead to tree thinning, result in tree stands of varying densities at final age. This occurs despite identical initial spacing. The severe thinning of young stands, whether planned or not, leads to changes in light conditions and nutrient availability. The natural reaction of trees to better conditions and less competition is faster tree biomass growth [Borowski 1974], an increase in breast height diameter and tree height (in *Pinus larico* Poiret) [Picchio et al. 2011] and bigger radial growth (in *Pinus halepensis* L.) [Olivar et al. 2014]. However this can lead to faults in the structure of the timber [Bembenek et al. 2013; Stempski et al. 2011]. This is further confirmed by studies at an anatomical level: thinning can result in shorter tracheids in the wood of the remaining trees [Spława-Neyman et al. 1995]. According to Brazier [1977] and also Zobel and Jett [1995, after Macdonald, Hubert 2002], any factor that changes the growth pattern or form of a tree may result in a change in wood quality and properties. Tree growth patterns can be affected by silvicultural practice, site factors and the genetic quality of planting stock [Macdonald, Hubert 2002]. Better conditions for tree growth can also be created by establishing skid trails which positively affect annual ring widths and diameter increment [Yilmaz et al. 2010].

The aforementioned results of research indicating the influence of increased light on the development of individual trees, provided the basis for the hypothesis that in sites with a lower number of trees per hectare, single trees attain a larger diameter at breast height (DBH), and, as a consequence, greater volume. Timber value is related not only to quality but also thickness: the thicker the wood, the higher the value of 1 m³ ($d_{1/2} \leq$ 24 cm is rated as class I which has the lowest value, class II is $d_{1/2}$ = 25 − 34 cm, whereas $d_{1/2}$ > 35 cm is class III – the most expensive). Bearing this in mind, a further hypothesis was accepted: a tree stand of lower density will provide thicker and more expensive timber. It was also assumed that in the same habitat conditions, the production potential is also the same, that is, the production of biomass (total timber volume) would be similar. It was therefore accepted that silvicultural treatments would result in: 1) a higher number of trees per surface unit but a lower volume, or 2) a lower number of trees with a higher volume. The total volume of merchantable timber obtained from the two different methods would be the same.

The aim of this research was a detailed analysis of the influence of tree density on the value of timber obtained from tree stands of different density.

Materials and methods

The research was carried out in pine tree stands in the lowlands of north-western Poland, in Drawno Forest District (E 15°50'–16°0', N 53°10'–53°13'). The habitat and the sandy soil conditions were typical for Scots pine (*Pinus sylvestris* L.). The average annual rainfall in the area analysed is 589 mm, the average temperature is 7°C, and the growing season lasts 200–220 days. The volume of merchantable timber was measured on 20 sample plots (each covering an area of 0.5 ha) of which 19 were in 82-year-old stands and one in an 87-year-old stand. The 20 plots were divided into 3 groups according to tree stand density: SDG I (6 stands), SDG II (10 stands) and SDG III (4 stands, table 1). The difference in the number of trees between SDGs was 104 and 116 (SDG II – SDG I = 104, SDG III – SDG II = 116, table 1).

Table 1. Stand characteristics by density group

Stand density group	Mean age (±SD) [years]	Mean density (±SD) [tree·ha^{-1}]	Mean DBH (±SD) [cm]	Mean height (±SD) [m]	Mean basal area (±SD) [m^2·ha^{-1}]	Mean volume of merchantable timber (±SD) [m^3·ha^{-1}]
I	82.8±2.0	547.0±46.8	27.04±4.8	22.61±2.01	32.2±2.9	333.8±37.5
II	82.0±0.0	651.2±27.9	24.76±4.76	21.52±2.11	32.2±2.9	321.6±47.9
III	82.0±0.0	767.5±48.9	22.43±4.6	21.01±3.19	31.3±3.2	308.8±32.4

The DBH of all the trees on the sample plots was measured (in two directions N-S and E-W) using callipers (accurate to 1 mm), and the height of 20% of the trees was recorded with a Haglof Vertex Laser (accurate to 0.1 m). The measurements were used to create a hypsometric curve (modelled using the Näslund function) on the basis of which the height of all the trees was calculated (table 1). The volume of a single tree was calculated using empirical models for pine [Bruchwald 1996] on the basis of the measured DBH and tree height. The timber quality was determined by quality and dimension according to the Technical Conditions for Softwoods [Technical... 2013] (Appendix A). The thickness class of the large-size timber was determined on the basis that each tree yielded a 10 m log, and according to the mid-diameter of the log, the timber fell into one of three classes:

- 1st thickness class (≤24 cm mid-diameter under bark),
- 2nd thickness class (>24 cm ≤35 cm mid-diameter),
- 3rd thickness class (>35 cm mid-diameter).

Timber below 19 cm mid-diameter under the bark was classified as pulpwood. Due to the low number of trees in the high quality classes, all the timber (for simplicity) was graded as C quality class (large-size wood – wood with a minimum top diameter of 14 cm under the bark, defined as sawmill wood). The value of the timber was calculated on the basis of the average net price of timber sold in the Drawno Forest District in 2013, as follows:

- sawmill wood 1st class thickness = €[5] 48.84 · m^3
- sawmill wood 2nd class thickness = € 56.94 · m^3
- sawmill wood 3rd class thickness = € 65.04 · m^3
- pulpwood = €[6] 38.12 · m^3

The Polish Principles of Silviculture [CILP 2012] in the analysed habitat recommend identifying 350–500 healthy trees per hectare at the early thinning stage. These are the trees which should remain until felling age and form the tree stand structure. An optimal value was thus accepted and the 20 tree stands in the study were categorised according to tree density:

- density group I (DGI) (≤600 n ha^{-1})
- density group II (DGII) (>600 ≤700 n ha^{-1})
- density group III (DGIII) (>700 n ha^{-1}).

Three SDGs were therefore determined, which included 6, 10 and 4 tree stands, respectively.

Statistical analysis was performed using R statistical software and agricolae packages [R Development Core Team 2012]. Normal distribution was analysed using the Pearson chi-square normality test. A one-way analysis of variance was performed on the tree stand volume and its value. A post hoc Tukey HSD test was carried out in cases where significant differences emerged. In total, 6432 trees across all the SDGs were analysed.

Results and discussion

Despite a large difference in tree density, similar volumes within the analysed stands were observed. Statistical analysis did not indicate the influence of density on the volume of the analysed stands (ANOVA, $p = 0.661$), the mean volume of which was 323 $m^3 \cdot ha^{-1}$ (ranging from 283 to 394 $m^3 \cdot ha^{-1}$). This result confirmed the hypothesis that habitat conditions ultimately lead to optimal production ie. the same total volume of merchantable timber, though consisting of a different number of trees.

[5] € = 4.1974 PLN in accordance with the average exchange rate archive of the National Bank of Poland – table A, 2013.

[6] Prices obtained in Drawno Forest District.

The analysed SDGs can therefore be regarded as uniform in terms of volume. Per 100 m^3 of merchantable timber, the Pearson chi-square normality test revealed that the tested data group featured normal distribution (p = 0.4337). Furthermore, all the SDGs revealed homogeneity of variance.

The mean value of 100 m^3 of merchantable timber across the studied stands was € 4870 (min. 4418, max. 5240, standard deviation 248, n = 20). There was a clear difference in the mean value of 100 m^3 of merchantable timber between the stands: 6% higher in SDG I when compared to SDG II, and 12% in comparison with SDG III (table 2).

Table 2. Value of 100 m^3 timber

Stand density group	Value of 100 m^3 timber [€]	Standard deviation	Number of stands in group [n]
I	5118.87	112.76	6
II	4842.09	188.83	10
III	4565.80	179.94	4

One-way variance analysis revealed significant differences in the mean total tree value between SDGs (p = 0.000343). The post hoc Tukey HSD test revealed that all the average values of the tree stands differed significantly between the groups (α = 0.05). Tree value and the frequency of occurrence in the defined stands indicated significant differences between the groups, in particular between SDG I and SDG III (fig.1).

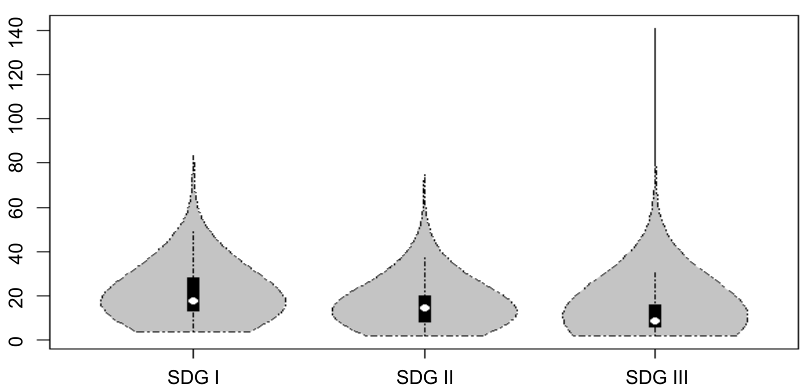

Fig. 1. Vioplot of single tree values (in €) in the SDGs showing the frequency of data groups; it presents a symmetrical reflection of kernel density estimation. The centre of each violin contains a boxplot. From the top: the number of trees increases as the value of a single tree falls to a certain point, then the number of trees decreases alongside the fall in the value of single trees

SDG I contained the smallest number of low-value trees, though a single tree here was still significantly more expensive (min. = € 3.36) than in SDG II or III

(€ 1.66 and € 1.57, respectively). The high median (€ 17.71) in SDG I indicated that there was a low incidence of the cheapest trees (white dot in fig. 1). Furthermore, the widest point in SDG I, the highest of all the three groups, indicated that the most frequently occurring trees were more expensive than in SDG II and III. In SDG I and II, the increase in the number of trees together with the increase in value was more dynamic than in SDG III (lower section of the plots). It is worth noting that the maximum value of € 141.26 was in SDG III. This should be regarded as an outlier – it is likely the tree developed under specific micro-habitat conditions with significant access to light. At the same time, this indicated the potential which may be exploited in the management of tree stands of lower density. Once this outlier had been removed, the plot clearly showed all the adverse parameters of SDG III, including the lowest maximum value (€ 65.04, fig. 2).

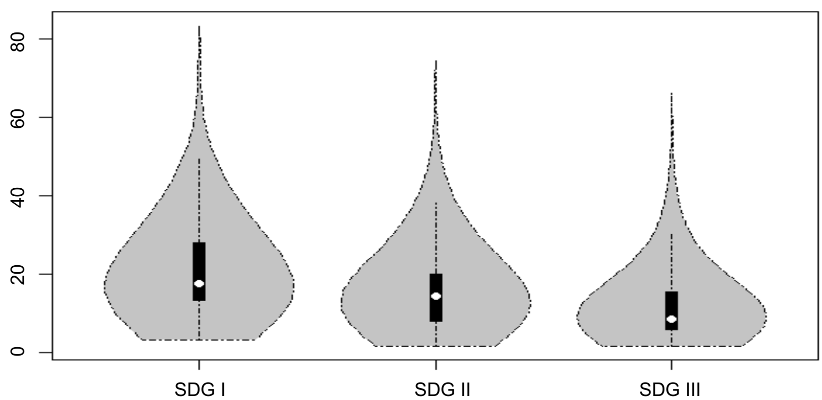

Fig. 2. Vioplot, frequency of data groups (in €) after the removal of the outlier (€ 141.26) from SDG III

Therefore – from the perspective of the round timber producer – in order to achieve a maximum profit from harvesting, the tree stand should be of a lower density (less than 600 trees per hectare) in the final growth phase (IV/V age class). Such management would also lead to greater income from more intensive pre-commercial thinning. It is important to bear in mind the local conditions affecting the growth and development of tree stands: habitat fertility, climate and phenotype. Research carried out in Finland [Ikonen et al. 2003] showed that in a 100-year-old, unthinned and very dense pine tree stand (995 trees per hectare), a stand yield of a higher value (€ 19 196 ha^{-1}) was achieved in comparison with a heavily-thinned stand (390 trees per hectare, € 13 369 ha^{-1}). These studies were carried out during the same period of time. However, other studies performed on Finnish pine and spruce stands indicated a reverse dependency – increases in: 1) the initial stand density and 2) the thinning intensity could be beneficial for energy wood production, timber and carbon stock enhancement, as well as to reduce CO_2 emissions for energy wood production [Alam et al. 2012].

It should also be noted that timber value in this study was determined on the basis of 10 m lengths. As the study by Porter [2012] indicated, timber cut-to--length can lead to an increase in the share of more expensive thickness classes (2nd and 3rd thickness classes) and, as a result, an increase of 6–15% in timber value. This also points to the additional potential which may be exploited in the case of growing trees with a larger DBH (managing tree stands of lower density).

More intensive thinning may cause a higher risk of injuries on the remaining trees. This could lead to the appearance of scars – defects which are taken into consideration during grading, not only in pine (scars seriously degrade beech sawmill wood, particularly the most valuable butt logs [Karaszewski et al. 2013a, 2013b]). Apart from defects, logging injuries have been identified as one reason for tree growth reduction [Vasiliauskas 2001]. However, some studies analysing the effects of injuries 10 years after treatment, found no negative consequences on pine growth (*Pinus laricio* Poiret) [Picchio et al. 2011]. As the aforementioned authors suggested, a deeper knowledge on the long-term effect of logging damage is needed.

Finally, a further point also worth highlighting is that SDG I featured a higher than average tree height in comparison to the tree heights in SDG II and III: by 5 and 8%, respectively (table 1). This is particularly interesting as trees growing in a higher density compete for light and growth, and therefore tend to focus on achieving height. However, it seems that in older tree stands (5th age class), crown volume is of greater influence. Trees with a bigger crown have greater volume and therefore the production of assimilates will also be higher. This positively affects growth in terms of both thickness and height.

Conclusions

The research results and proposed division of tree stands into 3 groups of different densities indicated that silvicultural practices in pine tree stands on soils typical for Scots pine (*Pinus sylvestris* L.) should lead to approximately 550 trees per hectare in stands entering the 5th age class. Such a number of trees means the stability of the tree stand can be maintained and it also results in an increase in timber value. A larger number of trees per hectare does not increase the total volume of timber in a stand, but rather leads to a decrease in the value of merchantable timber.

In the analysed pine stands, there was no impact of the tree density (from 476 to 836 per ha^{-1}) on the volume of merchantable timber and this was statistically proven. Timber from stands of low density had a higher value (€ 5118.87 per 100 m^3), 6 and 12% higher in comparison to the timber from SDG II and SDG III (€ 4842.09 and € 4565.80 per 100 m^3, respectively).

The higher timber values in the lower density tree stands were not due to increased total timber volume per hectare but rather from the greater thickness of the individual trees for which there was more demand due to the versatility of such timber.

References

Alam A., Kilpeläinen A., Kellomäki S. [2012]: Impacts of initial stand density and thinning regimes on energy wood production and management-related CO_2 emissions in boreal ecosystems. European Journal of Forest Research 131: 655–667

Bembenek M., Giefing D.F., Karaszewski Z., Łacka A., Mederski P.S. [2013]: Strip road impact on selected wood defects of Norway spruce (*Picea abies* (L.) H. Karst). Drewno 56 [190]

Borowski M. [1974]: Przyrost drzew i drzewostanów (Growth of trees and stands). PWRiL, Warszawa

Brazier J.D. [1977]: The effect of forest practices on the quality of the harvested crop. Forestry 50: 50–66

Bruchwald A. [1996]: New empirical formulae for determination of volume of Scots pine stands. Folia Forestalia Polonica, Series A 38: 5–10

CLIP [2012]: Principles of Silviculture. Centrum Informacyjne Lasów Państwowych, Warszawa

Ikonen V.P., Kellomäki S., Peltola H. [2003]: Linking tree stem properties of Scots pine (*Pinus sylvestris* L.) to sawn timber properties through simulated sawing. Forest Ecology and Management 174 [1]: 251–263

Karaszewski Z., Bembenek M., Mederski P.S., Szczepańska-Alvarez A., Byczkowski R., Kozłowska A., Michnowicz K., Przytuła W., Giefing D.F. [2013a]: Identifying beech round wood quality distributions and the influence of defects on grading. Drewno 56 [189]: 39–54. DOI: 10.12841/wood.1644-3985.041.03

Karaszewski Z., Bembenek M., Mederski P.S., Szczepańska-Álvarez A., Giefing D.F., Węgiel A. [2013b]: Linear relations between defect frequency and volume of beech logs. Annals of Warsaw University of Life Sciences – SGGW Forestry and Wood Technology 83: 32–36

Macdonald E., Hubert J. [2002]: A review of the effects of silviculture on timber quality of Sitka spruce. Forestry 75 [2]: 107–138

Picchio R., Neri F., Maesano M., Savelli S., Sirna A., Blasi S., Baldini S., Marchi E. [2011]: Growth effects of thinning damage in a Corsican pine (*Pinus laricio* Poiret) stand in central Italy. Forest Ecology and Management 262: 237–243

Porter B. [2012]: Effectiveness of Scots pine longwood timber cut-to-length (CTL) logging. Acta Scientarum Polonorum Silvarum Colendarum Ratio et Industria Lignaria 11 [3]: 37–43

R Development Core Team [2012]: R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. Available from: http://www.R-project.org/

Olivar J., Bogino S., Rathgeber C., Bonnesoeur V., Bravo F. [2014]: Thinning has a positive effect on growth dynamics and growth-climate relationships in Aleppo pine (*Pinus halepensis*) trees of different crown classes. Annals of Forest Science 71 [3]: 395–404

Stempski W., Grodecki J., Wudarczyk M. [2011]: Wpływ udostępniania drzewostanów siecią szlaków na występowanie i wielkość wad kształtu drzew (Influence of skid trails on frequency and size of tree shape defects). Forestry Letters 102: 93–101

Spława-Neyman S., Pazdrowski W., Owczarzak Z. [1995]: Wybrane biometryczne parametry budowy drewna sosny zwyczajnej (*Pinus sylvestris* L.) w aspekcie więźby sadzenia (Selected biometric parameters of wood structure of Scots pine (*Pinus sylvestris* L.) from the point of view of planting spacing). Folia Forestalia Polonica, Series B 26: 73–84

Vasiliauskas R. [2001]: Damage to trees due to forestry operation and its pathological significance in temperate forests: a literature review. Forestry 74 [4]: 319–336

Yilmaz E., Makineci E., Demir M. [2010]: Skid road effects on annual ring widths and diameter increment of fir (*Abies bornmulleriana* Mattf.) trees. Transportation Research Part D 15: 350–355

Zobel B.J., Jett J.B. [1995]: Genetics of Wood Production. Springer-Verlag, Berlin

List of standards

Directive no. 72 approved by General Director of the State Forests [2013]: Technical conditions for softwoods

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Appendix A. Guidelines for sawmill softwood grading in Polish conditions

<table>
<tr><td colspan="2" rowspan="2">Characteristics</td><td colspan="4">Classes</td></tr>
<tr><td>WA0</td><td>WBO</td><td>WC0</td><td>WD</td></tr>
<tr><td colspan="2">Minimum top diameter (dt)</td><td>22 cm</td><td colspan="3">14 cm</td></tr>
<tr><td colspan="2">Length</td><td colspan="4">from 2.7 m to 14.0 m – interval every 10 cm</td></tr>
<tr><td colspan="2">Minimal length of butt log without defects or with permitted defects</td><td colspan="2">4 m</td><td colspan="2">without limit</td></tr>
<tr><td rowspan="3">Knots</td><td>uncovered</td><td colspan="2">permitted to 2 cm,
not permitted in pine and larch</td><td colspan="2">permitted</td></tr>
<tr><td rowspan="2">covered knots</td><td colspan="2">to 1 cm high not taken into account, higher</td><td colspan="2" rowspan="2">permitted</td></tr>
<tr><td>not permitted</td><td>permitted on 1/2 of circumference</td></tr>
<tr><td rowspan="3">Shakes</td><td>end shake</td><td>permitted to 1/5 of face diameter</td><td>permitted to 1/3 of face diameter</td><td colspan="2">permitted</td></tr>
<tr><td>check</td><td>permitted of width to 3 mm</td><td colspan="3">permitted</td></tr>
<tr><td>deep crack and traversing crack</td><td colspan="3">not permitted</td><td></td></tr>
<tr><td colspan="2" rowspan="2">Sweep</td><td colspan="4">permitted when grading logs of 2.7 m in length with sweep of</td></tr>
<tr><td>2 cm/m</td><td colspan="2">3 cm/m</td><td>5 cm/m</td></tr>
<tr><td colspan="2">Spiral grain</td><td>permitted to ≤5 cm</td><td colspan="3">permitted</td></tr>
<tr><td colspan="2">Scars</td><td colspan="2">permitted, not in spruce</td><td colspan="2">permitted</td></tr>
<tr><td rowspan="2">Stain</td><td>blue stain</td><td colspan="2">not permitted</td><td>permitted to 1/2 of sapwood area</td><td>permitted</td></tr>
<tr><td>brown streak</td><td colspan="3">not permitted</td><td>permitted</td></tr>
<tr><td rowspan="3">Rot</td><td>inner</td><td colspan="2">not permitted</td><td>permitted on one face to ≤1/5 of diameter</td><td>permitted on one face to ≤1/3 of diameter</td></tr>
<tr><td>soft rot</td><td colspan="3">not permitted</td><td>permitted</td></tr>
<tr><td>outer</td><td colspan="2">not permitted</td><td>permitted on 1/4 of circumference to 1/10 of diameter</td><td>permitted</td></tr>
<tr><td colspan="2">Insect attack</td><td colspan="3">not permitted</td><td>permitted</td></tr>
<tr><td colspan="2">Foreign bodies</td><td colspan="3">not permitted</td><td>permitted</td></tr>
</table>