Bioenerg. Res. (2015) 8:1344–1351
DOI 10.1007/s12155-015-9596-z

Quantification of Biomass Production Potentials from Trees Outside Forests—A Case Study from Central Germany

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Abstract Woody biomass of trees outside forests (TOF) is gaining increasing interest in many countries as it is a renewable energy source that has not been managed for bioenergy production. Our case study describes two independent approaches to assess regional area of TOF as a means for the biomass production potential of TOF within a study region in Germany, the Göttingen district (area: 1,118 km^2): (1) a statistical sampling with field inventory data, and (2) an area-wide GIS-mapping approach based on open-access aerial imagery. For our particular study, the differences between the mapping-based approach and the sample-based approach were minor (sampling: 24.37 ha and 16,670 t of dry wood per year with a relative standard error 11.6 % vs. area-wide mapping: 24.35 ha and 16,055 t; standard error not available). Due to a minor difference of only 3.7 % between the two approaches, we conclude that area-wide mapping serves as a sound basis for a quantification of bioenergy potentials from TOF. It also shown that only about 62 % of all TOF objects (74 % of the total annual biomass production) would be directly accessible via the existing road infrastructure (without heavy machinery). In terms of available end-use energy, the regional biomass potential translates to an annual amount of 233 TJ which, in turn, reflects only about 0.9 % of the annual end-use energy demand in the study area. This marginal contribution to the region's energy supply is due to the fact that TOF covers only around 24 km^2 (~2 %) in our study area.

Keywords Bioenergy · Web-mapping services · GIS · Open-access imagery · Sampling

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Introduction

With the ratified "20–20–20" climate protection goal, the European Union has set the agenda to reduce greenhouse gas emission, diminish energy consumption, and increase the utilization of renewable energy by 20 % until 2020 in relation to the 1990 levels [1]. In Germany, the ratified agenda is even more ambitious when setting the goals to 40 % reduction of greenhouse gas emission and increasing the share of renewable energy consumption to 25–30 % until 2020 [2]. With this growing demand for renewable energy sources, and due to substantially rising energy prices, the interest in woody biomass is increasing and not restricted to forest resources only [3–5].

According to the Food and Agricultural Organization (FAO), a forest is defined as land spanning over an area of more than 0.5 ha with trees that are (or can potentially grow) higher than 5 m and that create more than 10 % canopy cover [6]. Land that is predominantly under agricultural or urban use is excluded from this definition. All other woody vegetation from outside forest is usually referred to as “trees outside forest” (TOF; e.g., Ref. [7]). The term TOF is used in our study according to the definition of the FAO, meaning that it includes all woody plants (shrubs and trees) that do not fall under the forest definition [8]. Shrubs can make up for a considerable share of TOF in many regions where land use is dominated by agriculture. The quantitative relevance of TOF is regionally quite distinct as a result of both historic cultural landscape development and intensification of modern agricultural land use [7, 9]. Intensification, industrialization, and land consolidation in agriculture led to substantial decline of TOF area since the provided services and goods, such as wind protection, firewood, or fruits and berries, were of a relatively low value compared to an optimization of field size toward lower machinery and labor costs. However, with the increasing awareness of biodiversity losses in agricultural landscapes, TOF structures are nowadays recognized as important habitats for many species and are assessed to be of high nature value [10]. Being scattered in many German agricultural landscapes, protecting, developing, and managing TOF toward an optimization of its ecological functions is a complex and costly measure. The economic return of the biomass utilization from TOF may be one source of income to cover parts of the conservation management cost. As a consequence, strategies are being discussed on how to lower management expenses without compromising conservation goals and biomass supply. To address this issue, spatially explicit information on accessibility, biomass production potential, or variation of TOF types would be needed.

As part of coordinated research activities on sustainable land management within Germany, several research address biomass production potentials of TOF in the landscape. This has been difficult, so far, as one limitation for a large-scale consideration of woody material from hedges, copses, groves, single trees, alleys, or forest remnants on agricultural lands has been the lack of resource inventories that offer information on where a resource (here: wood) can be found in the landscape [11]. During the last years, scientists adapted sample-based inventory approaches to the assessment of TOF. These sampling designs produce estimations at landscape scale [12, 13] and proved to be efficient for sparse study objects [14]. However, if spatially explicit information is needed (maps), airborne or spaceborne remote-sensing data should be used along with mapping activities.

Today, modern Web-mapping services enable open access to high-resolution aerial imagery from large parts of our planet, such as Bing maps [15] or Google maps [16], to just mention two examples. Additionally, open-access GIS software, such as Quantum GIS [17], can be used for free to perform related Web-mapping tasks. A combination of both, open-access data and open-access software offers new possibilities in the assessment of environmental information that appeared to be not fully exploited yet for research on inventory of landscape elements. Apart from trees in forests, which have been studied in detail, e.g., based on Google Earth Imagery (e.g., Refs. [18, 19]), urban trees have been in the focus of several studies that utilized open-access imagery. Publicly available spaceborne and airborne imagery was used to determine urban tree cover [20] or changes in tree cover over time [21]. Merrin and Pollino [22] presented an approach that used Bing Imagery as base map in ArcGIS for tree species’ habitat modeling. However, assessing the economic or ecological importance of TOF at a local, regional, or national scale was often hindered by the general unavailability of information. An adequate assessment of TOF with regard to their location, form, and extent is still missing [23]. Such information indeed would be very valuable for first pilot projects dealing with the actual implementation of utilization chains for TOF.

The goal of our study was to quantify the annual biomass production of trees outside forests in a study region located in Central Germany and to suggest a suitable inventory methodology for that purpose. Furthermore, we investigated the accessibility of TOF biomass through the existing road network as an indicator for costs of harvesting and transport of the material.

Methods

Study Area

The study was conducted in the administrative district of Göttingen (Lower Saxony, Germany; see Fig. 1), that has a total area of 1,118 km^2. The study area is dominated by agricultural land use (48 %) and forest (33 %). The climate is determined by maritime as well as continental influences with a mean annual temperature of 8.3 °C and mean annual temperature amplitude of about 17.4 °C. The precipitation long-term average varies between 580 mm/year in the drier east of the area and 1,050 mm in the southwestern region [24] (period 1971–2000). The dominant soil types are Luvisols and Stagnosols which are often accompanied by Cambisols [25].

Field Sampling

In order to estimate the biomass production in the study area, we used an existing dataset on all TOF objects obtained from a sampling campaign that was conducted over the same study area [12] (see also Fig. 2). This dataset was originally collected to enable for analysis with multiple purposes within the BEST research project, e.g., to evaluate management status of TOF, their species assemblages or habitat properties of TOF. Here we used data on position [global positioning system (GPS) coordinates], shape (field-based delineation of the edge line), height (maximum height of each object), and

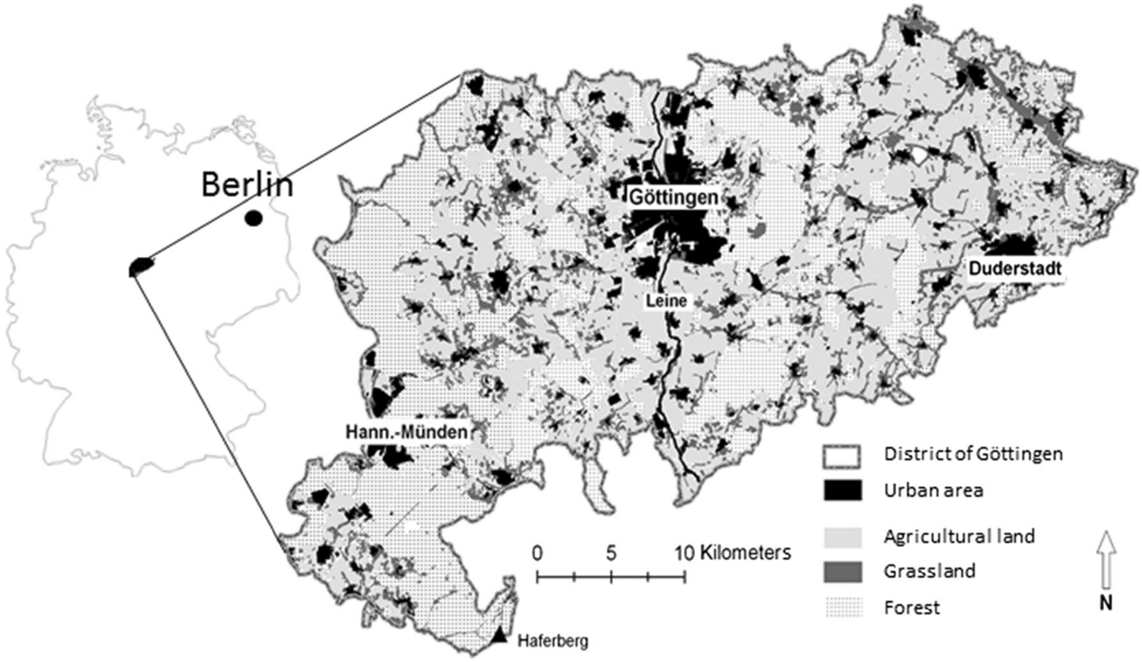

Fig. 1 The study area and its major land cover types. Data from ATKIS Basis DLM 2009

vegetation type to classify each TOF with regard to its related biomass production potentials (according to Table 1). This information served as ground truth for the area-wide mapping (see Section "Area-Wide Mapping").

To create this comprehensive dataset, commercial digital aerial imagery of the entire study area was obtained from the Land Survey Administration of the German Federal State of Lower Saxony (LGLN). The images were taken in 2010 with 0.2 m ground resolution. A sample of 279 square plots (400× 400 m) on a grid of 2×2 km was used to estimate the area of woody vegetation outside forests. A mask excluding all urban areas and forest areas as defined by the German official topographic map information system (ATKIS) was used to cut out open land. Classification of all TOF objects was done according to land cover types defined by the mapping key of the German Federal Agency of Nature Conservation [26]. In order to obtain ground data of classes of TOF, an intensive field campaign was performed to map the entire 4,464 ha of land within the sample squares. This corresponds to a sampling intensity of 4 % for cover estimation. Then all objects identified in the field survey (2011) were mapped using the aerial photographs as base map. As we aimed at quantifying biomass production, different types of TOF were transferred into biomass production classes according to the BfN key (see

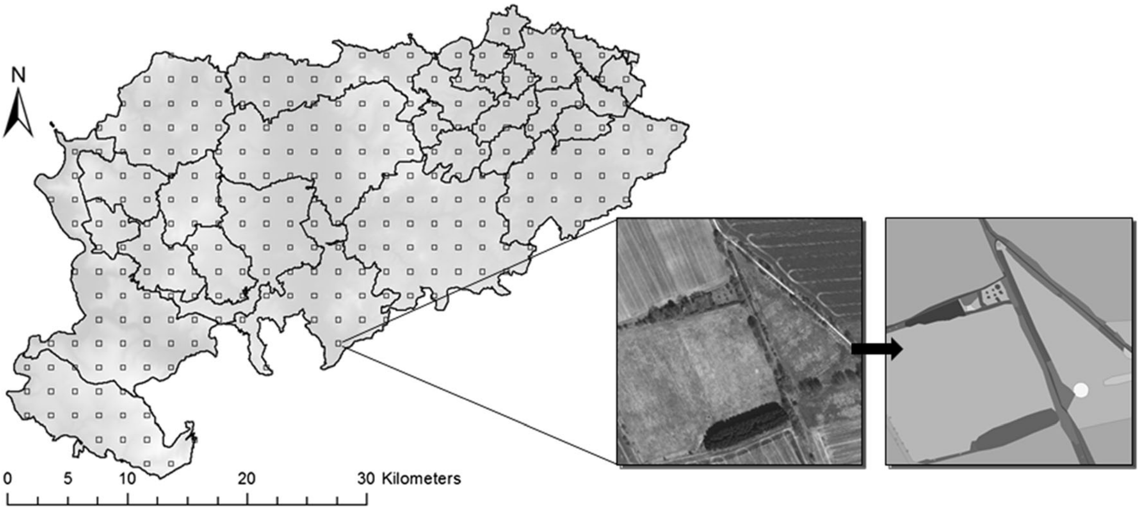

Fig. 2 *Left*: Systematic sample grid over the study area with 279 square sample plots. *Right*: Example of an aerial photograph of a fully mapped 400×400 m square sample plot, digitized and classified according to land cover types (see Ref. [12] for more information), where the details of mapping come from the field survey

Table 1 Types of trees outside forests (TOF) identified in the field survey and corresponding classifications according to biomass production classes from literature

Description	BfN key (for general reference)	Characterization/dominant vegetation	Biomass production class
Hedge A	6110	Bushes dominant	L
Hedge B	6140	Bushes and trees	L
Hedge C	6150	Trees dominant	L
Vegetation along roads	4790[a]	Linear vegetation along roads, railways, etc.	L
Grove	6210–6219	Trees dominant (bushes present)	A
Copse	6220	Group of bushes	A
Bush	6230	Single bush	S
Tree row or alley	63*x*2 and 63*x*3[b]	Group of trees in line (distance between crowns<5 m)	L
Tree group	63*x*1[b]	Group of trees (bushes absent)	A
Fruit tree (plantation)	6370	Group of fruit trees (commercial)	A
Single trees	6410, 6420, 6430	Single tree (open grown)	S

[a] 4,790 is a combination of 47.2 and 9280 in the BfN classification key

[b] *x* indicates all numbers from 1 to 7

Table 1). As we did not have the resources (or the permits) for destructive sampling that would have allowed us to derive our own biomass production values, we performed a literature review. However, literature on biomass production potentials of TOF is—contrary to forest biomass—very rare, and we were only able to build three different classes of annual biomass production (per m^2): single objects (S), linear objects (L), and ample objects (A).

- For class S (single objects), we used a value of 3 tons of dry woody biomass (oven-dry) per hectare and year, corresponding to 0.3 kg m^{-2} $year^{-1}$ (cf. Ref. [27]). We will use the unit kg m^{-2} $year^{-1}$ from here onward and do always refer to oven-dry woody biomass.
- For class L (linear objects), we used a value of 0.7 kg m^{-2} $year^{-1}$ (cf. Refs. [28, 27, 29]).
- For class A (ample objects), an annual biomass production of 0.66 kg m^{-2} $year^{-1}$ was used. This value was calculated via the assumption of an equal share of copses (0.5 kg m^{-2} $year^{-1}$; cf. Ref. [28]) and groves or tree groups (0.83 kg m^{-2} $year^{-1}$; cf. Ref. [29]) as they are all occurring in our dataset.

From literature, we found that a typical beech dominated forest in the Göttingen district would yield about 0.37 kg m^{-2} $year^{-1}$ [30], and a short rotation forest on agricultural land is expected to yield between 0.6 and 2 kg m^{-2} $year^{-1}$ depending on water supply [31].

In the following, we multiplied the polygon area of each classified TOF object with the class-specific annual biomass production per square meter to derive the total annual biomass production per object. The study areas total annual biomass production was then estimated based on the sampling. Note that the final number reflects a theoretical (maximum) potential. Finally, we calculated the theoretical amount of energy that could be provided annually through total biomass production. This was based on the assumption of a constant energy content of the woody biomass (1 kg dry wood=19 MJ of energy; cf. Ref. [27]), assuming it will be combusted in large-scale combustion plants and taking into account estimated average losses of about 25 % due to conversion and transport of energy (conservative assumption based on Ref. [32]).

Area-Wide Mapping

In order to provide area-wide and spatially explicit information on biomass location, all TOF object geometries within the study area were manually digitized. Such information would, for example, be needed to assess their distribution or accessibility. For this task, we used free Quantum GIS [17] with the Open Layers plugin "Bing aerial maps." All images available through Bing maps and used in our study were aerial photographs taken in 2012 provided by the Digital Globe Foundation [33]. The ground resolution was 0.4 m or higher. The same mask as used in the sampling approach, excluding all urban areas and forest areas, was used to cut out open land. Via manual delineation of their crown outline (crown projection area), all TOF elements like single trees, bushes, vegetation along roads, hedges, or copses were visually identified on a fixed scale of 1:2,000 in the imagery and digitized. A protocol was set up defining the delineation procedure of the TOF polygons in all details. We attempted to standardize mapping to the extent possible. For example, it was defined that shadows of the vegetation were to be excluded from the polygons. In case of fuzzy outlines due to overlapping shadows, the shadow area was used to determine the outline of the object. Objects that could not be clearly separated from each other or that appeared to be a group (e.g., groups of bushes) were delineated as one single polygon. Digitization and classification of the TOF polygons were done in separate processing steps as there was no thematic information recorded during delineation of the polygons but geometry.

We used ArcGIS [34] to calculate area and perimeter of each polygon as well as diameter and area of the smallest enclosing circle (SEC) around each polygon. We classified all TOF objects according to one of the three groups identified in the literature in analogy to the field campaign (S, L, and A). Classification was at first based on the diameter of SEC. All objects with a SEC diameter (D_{SEC}) smaller than 20 m were considered single objects (class S) such as trees or bushes. All larger objects were tested for the ratio between half the polygons perimeter and D_{SEC} as a measure of lengthiness. We found that there was a uniform distribution of polygon shapes along the entire gradient of possible ratios with only a slight tendency toward higher abundance of longish objects (ratio near 1). Not surprisingly, there was no abrupt turn from longish to ample polygon shapes, but the full natural variety of shapes. We decided to use the arithmetic mean of the ratios of all 61,029 polygons, and visual inspection suggested that it splits the objects sufficiently well into either linear or ample ones. Objects with this ratio being between 1 and 1.3 were considered longish (e.g., tree rows, hedges: class L), while those with the ratio being larger than 1.3 were classified as ample objects (e.g., groves, groups of trees, or bushes: class A).

Accessibility

In order to determine the accessibility of TOF objects as an indicator for harvesting and transport costs, we extracted all objects within a distance of 5 m to the next road that is accessible for vehicles. This was possible based on spatial information obtained from the area-wide mapping approach. A 5-m distance was assumed to be feasible for most management activities based on expert appraisals and can be considered a conservative number. We used ATKIS data on the road network of the study area that included all types of roads, from federal highways to unpaved roads. The data was initially provided as line shape and was converted into a polygon shape using a case-specific buffer with its width based on information on the actual road width that was available for each line segment. The shape file of the road network was then buffered (5 m), and all TOF objects reaching into this buffer were identified. For each TOF, object information on road type of that road in the buffer that had the highest hierarchical level was appended to the attribute table. We used this data to investigate which types of roads were to be used to access TOF objects and how these TOF objects would contribute to the overall biomass supply.

Results and Discussion

On the sample plots, we identified 1,971 TOF objects covering a total of 972,403 m^2 (2.18 % of the sampled area; standard error±0.25 %, cf. Ref. [12]). Total area under TOF according to our definition was thus estimated to be 24.37 km^2 with an estimated total TOF biomass production of 16,670 tons for the entire study area. This corresponds to the theoretical amount of biomass that could be harvested per year in a sustainable manner, i.e., without taking out more than is being produced in the same area.

In the area-wide mapping approach 61,029 polygons were detected and classified, covering a total of 24.35 km^2. This equals 2.17 % of the total area investigated. Based on the biomass production classes (S, L, and A), we calculated a total annual TOF biomass production of 16,055 tons in the study area. The difference of only 614.84 tons (3.68 %) between both approaches indicates high consistency among the results.

Regarding the identification of TOF objects, we argue that the interpretation of aerial photographs should be considered more error prone than our field survey, even though both processes are subjective to a certain degree. However, it should be emphasized that costs and efforts of an area-wide mapping are inevitable if spatially explicit information on the biomass distribution in the area, its accessibility, or any further assessment of ecosystem services is desired.

Temporal coincidence of data sources is always an issue when integrating field surveys and remotely sensed datasets. However, for our study, we noticed only marginal changes in the existence of certain TOF objects between 2010 (image acquisition commercial data), 2011 (field survey), and 2012 (Bing aerial imagery). Instead, we observed that digitization quality was much more affected by the seasonality in the open-access imagery. Differences in the possibility to determine a polygon's outline certainly existed between leave-off and leave-on images, with the latter being easier interpreted. The actual image resolution (0.4 m) was sufficiently high in the open-access imagery of the study region, and we faced no problems in the identification of even smallest TOF objects in the landscape. All TOF objects found in the field survey were previously identified in the imagery without difficulties.

Thanks to modern heavy machinery as used in agricultural or forest management, TOF objects in the investigated landscape can certainly be considered accessible, in general. However, it is a matter of fact that the distance to the nearest road certainly affects the costs of harvest and transport of the material, e.g., due to higher fuel consumption of vehicles operating off-road. Accessibility analysis revealed that 38,274 out of 61,029 polygons (62.7 %) can be reached from a road being 5 m or less apart. We considered this a distance for which transport of harvested material could be provided by machinery that operates on roads and which is not specifically made for off-road use. Such road-accessible TOF contributed about

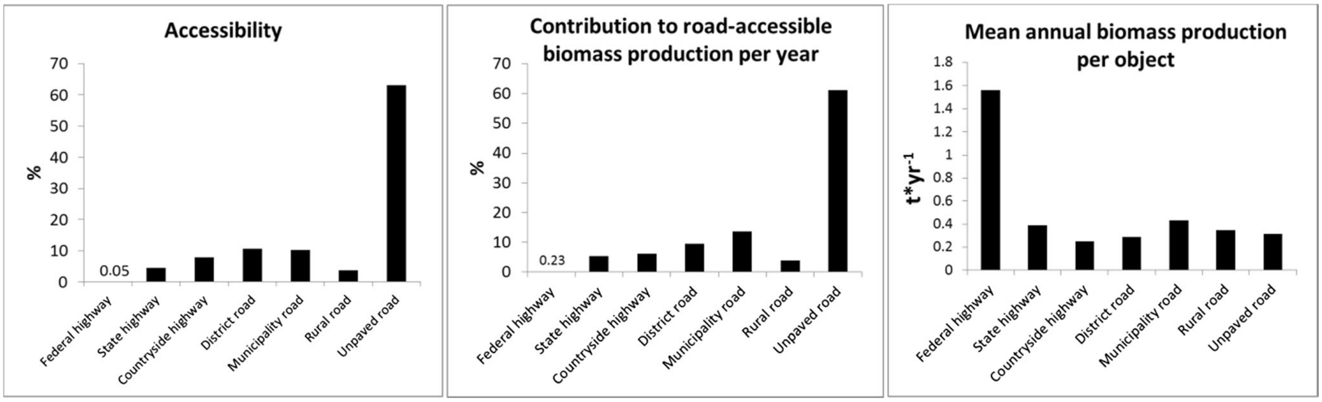

Fig. 3 *Left*: Percentage of all TOF objects that can be reached via roads of different hierarchical levels. *Middle*: Percentage of total road-accessible biomass supplied by TOF objects accessed via roads of different hierarchical levels. *Right*: Mean biomass production of TOF accessible via roads of different hierarchical levels. In our study area, large TOF polygons (green along roads) were located at the federal highways, causing high values of mean biomass per object

74.3 % to the total TOF biomass supply. For about 63 % of those TOF objects, the nearest road was unpaved. However, these objects could supply about 61 % of the total biomass and are hence of great importance. Only a very small proportion of TOF objects would be directly accessible from federal highways (0.05 %). Interestingly, these objects were found to be of greater biomass production than the mean (1.56 tons year^{-1} vs. mean: 0.51 ton year^{-1}), which is due to the large and nonfragmented area of green along roads that is found along federal highways in the study area. Objects accessible from unpaved roads were comparably small (mean: 0.3 ton year^{-1}) making their management less efficient when compared to those located at federal highways (see Fig. 3).

Furthermore, it was found that 39.3 % of all road-accessible TOF objects were of class S (single objects: trees and bushes), 5.2 % belonged to class A (ample), and 18.1 % to class L (linear) objects. In contrast to the abundance values, the importance of class A and class L objects was high, as they supply most of the biomass production accessible within 5 m to the next road (97.7 % in total). This is because, on average, only 0.01 ton year^{-1} of biomass were provided by single class objects due to their small size, while class L objects provide 0.58 ton year^{-1} and class A object 1.76 ton year^{-1}, on average. A great proportion of the road-accessible TOF objects were located at unpaved roads and this was also where most of the biomass gain was produced (Fig. 3, middle). TOF objects of type A (ample objects) were found to provide largest biomass supply per object (Fig. 4, middle and right) due to their size and biomass density. However, they were rarely accessible from the existing road network in the study area (Fig. 4, left).

Based on the mean biomass production rates estimated from both approaches (16,363 tons), we calculated that about 311 TJ (about 86 GW h) of energy could be produced annually from TOF in the study area. In the administrative region of Göttingen, a total end-use energy of about 25,168TJ is consumed annually [35, 36]. Taking into account conversion losses of approximately 25 % [32], just about 0.93 % (233 TJ) of the region's energy consumption could be covered in the theoretical case that all annual TOF production could be mobilized and used energetically. Note that this number reflects the theoretical maximum potential and does not take into account that only around 74 % of this biomass potential is road-accessible and that energy is to be invested for harvesting, transporting, and processing the biomass. A realistic contribution of TOF to the total energy consumption in the study region will, therefore, be considerably lower than the above 0.93 %. Apart from accessibility, a utilization ratio of the calculated total mean annual biomass production would

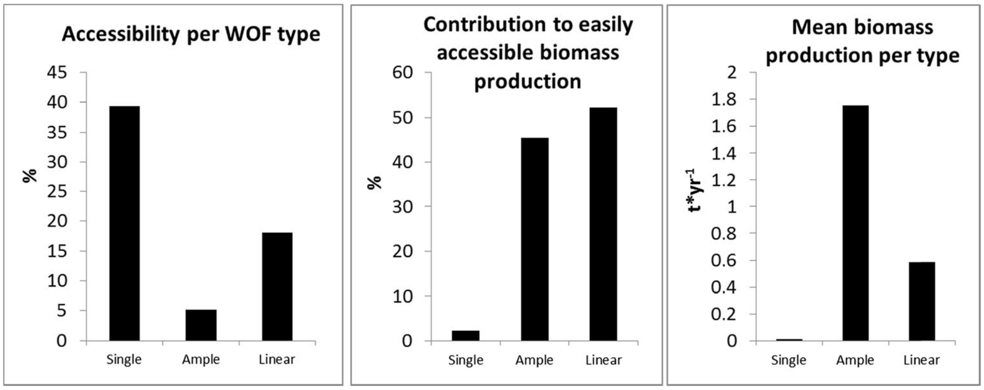

Fig. 4 *Left*: Percentage of road-accessible TOF objects in the study area separated by biomass production classes. *Middle*: Percentage of the total road-accessible TOF biomass production in the study area that was contributed by the three different biomass production classes. *Right*: Mean biomass production of all road-accessible TOF objects separated by biomass production classes

depend on many additional factors, e.g., market prices, regional governance goals, supply chains, and conservation status. Assessing it is far beyond the scope of this paper.

Comparing annual biomass production from TOF to forests (numbers provided in Section "Field Sampling") revealed that there are noteworthy growth rates for TOF, maybe partly due to fertilizer inputs from adjacent fields and beneficial light conditions for trees growing in open areas. However, biomass production rates of TOF range on the lower end of the spectrum achievable in short rotation forest on agricultural land.

Conclusion and Outlook

Our study indicated that biomass production rates of TOF can be determined for large areas through sampling approach as well as through area-wide mapping. However, there are certain pros and cons for each of the approaches. If a cost-efficient estimation of a region's overall biomass production potential from TOF is the primary goal of a study, the sampling approach is in favor. It is of lower economical and labor costs and sampling protocols can easily be adjusted in order to fulfil the needs of a given study on various levels of detail.

In cases where spatially explicit information on biomass distribution is needed, an area-wide mapping approach should be considered. Compared to the sampling approach, it is much more time-consuming and expensive, especially if aerial images are to be purchased. Here, we see large potential for open-access imagery embedded in free software and argue that inventory costs could be reduced by avoiding the use of commercial imagery and software. The quality, appropriateness, and consistency of open-access imagery are to be evaluated with respect to the specific study purpose. It was found to be suitable for the mapping approach of woody vegetation presented here and imagery with resolution similar or equal to that used in our study is now available for many regions of the world free of charge.

From the analyses of accessibility we conclude that single objects, such as trees or bushes scattered in the landscape, contribute a relatively low amount to the potential biomass supply of TOF. They should be of low priority in case of a TOF ranking for management importance for biomass production. While they are often road-accessible (39.3 %), they contribute less than 3 % to the biomass production of all road-accessible TOF objects in the study area. It may be suggested, therefore, to focus on the management of linear and ample objects, with the linear objects being of special importance due to their large contribution to the overall biomass in the study area (45.5 %). Furthermore, they seem to be easier to reach from existing roads when compared to ample objects (18.1 vs. 5.2 %).

Anyway, it was found that an almost negligible proportion (<1 %) of the primary energy need of the administrative area of Göttingen could be covered from the theoretical production potential of TOF identified in the area. Despite the low amount of energy supply, a large proportion of the existing TOF are already under some kind of management, e.g., to ensure traffic safety. Common practices include pruning of trees, shrubs, or coppicing of hedges. Our field survey exhibited a TOF proportion of more than 50 % showing clear signs of management (coppicing or pruning; data not shown). The costs related to these management activities might be reduced by the development of management plans and utilization chains for the harvested biomass, e.g., through its energetic use.

Overall, our study clearly indicated that the practical relevance of TOF for energetic use is very minor, and there is no considerable contribution of TOF biomass for the production of renewable energy to be expected in the study area.

Acknowledgments We would like to thank the administrative board of the *Landkreis Göttingen* for their support and for providing us with the permission to visit all sample sites during our field work. Special thanks go to Prof. Dr. R. Bürger-Arndt for her support during the project. The work was funded by the German Federal Ministry of Education and Research (BMBF) and is part of the BEST Research Framework (http://www.best-forschung.de). We owe our sincere thanks to the helpful comments of three anonymous reviewers.

Conflict of Interest The authors declare that they have no conflict of interest.

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