# Provenances and properties of thatching reed (*Phragmites australis*)

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## Abstract

The common wetland plant reed (*Phragmites australis*) is a traditional thatching material and reed thatched houses are substantial cultural parts of the Baltic and North Sea landscapes. Durability of reed and thus life expectancy of thatches is partly determined by properties of the building material. However, there is no comprehensive research work about properties of thatching reed. Therefore this study was performed and a total number of 214 reed bunches from German and Dutch providers was characterized concerning provenances, harvest years, morphological properties and chemical composition.

Examined reed bunches originate from 12 different countries in Europe and Asia and were predominantly harvested during the winter seasons in the sampling year or the year before. Mean culm diameters of bunches varies between 2.4 and 7.7 mm. Main dry matter component is crude cellulose (51.5 ± 2.3 %), followed by crude hemicellulose (26.9 ± 2.3 %) and crude lignin (11.9 ± 1.3 %). Crude ash shows a range from 0.69 to 8.07 %, and especially high calcium content seems to be related to considerable contamination with cattail (*Typha* spec.). C/N ratio varies noticeably between 76 and 963 with a mean of 290.

Results indicate the high variability of thatching reed concerning the values of its properties, probably because of multiplicity of influencing factors. With its exceptional large sample size, this study provides the informational background for further research about durability of thatching reed and life expectancy of reed thatches.

**Keywords:** *Phragmites australis, provenance, culm diameter, lignin, nitrogen, thatch, durability*

## Zusammenfassung

### Provenienzen und Eigenschaften des Dachdeckmaterials Reet (*Phragmites australis*)

Die weitverbreitete Sumpfpflanze Schilf (*Phragmites australis*) wird noch heute als Dachdeckmaterial verwendet, und insbesondere im Nord-und Ostseeraum sind Kulturlandschaften durch die traditionellen Reetdachhäuser geprägt. Als Baumaterial biologischen Ursprungs unterliegt Schilf zersetzenden Prozessen, wobei die Widerstandsfähigkeit und damit die Dauerhaftigkeit des Materials von dessen Eigenschaften bestimmt werden. Da bisher nur wenig über die Variabilität des Baumaterials bekannt ist, wurden insgesamt 214 handelsübliche Reetbunde hinsichtlich der Herkunftsländer und Erntejahre, morphologischer Eigenschaften und der chemischen Zusammensetzung untersucht. Die Reetbunde stammen aus zwölf verschiedenen europäischen und asiatischen Ländern und wurden vornehmlich während der Wintersaison des Jahres der Probenahme bzw. des vorangegangenen Jahres geerntet. Die mittleren Halmdurchmesser betrugen 2,4 bis 7,7 mm. Hauptbestandteil der Trockenmasse von Reet ist Rohcellulose (51,5 ± 2,3 %), gefolgt von Hemicellulose (26,9 ± 2,3 %) und Rohlignin (11,9 ± 1,3 %). Der Anteil an Rohasche liegt zwischen 0,69 und 8,07 %. Das C/N-Verhältnis reicht von 76 bis 963 und beträgt im Mittel 290. Aufgrund des sehr großen Stichprobenumfangs liefert die Studie grundlegende Informationen für weitere Untersuchungen über die Dauerhaftigkeit von Dachdeckerreet und die Lebensdauer von Reetdächern..

**Schlüsselworte:** *Phragmites australis, Herkunft, Halmdurchmesser, Lignin, Stickstoff, Reetdach, Dauerhaftigkeit*

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# 1  Introduction

Common reed (*Phragmites australis* (Cav.) Trin. ex Steud.) has been used as thatching material for at least a thousand of years (Frahm, 1972; Schattke, 1992) and reed thatched houses are a cultural heritage and in particular part of the Baltic and North Sea landscapes. However, since some decades early deterioration of reed thatches has been reported for western and middle Europe and its cause has been discussed (Kirby and Rayner, 1988; Kirby and Rayner, 2001; Haslam, 1989; Anthony, 1999). Moisture on roofs is said to support deterioration (Haslam, 1990) beneath constructional characteristics of roofs such as pitch (Anthony, 1999). As an important factor for deterioration also reed quality had been identified (Haslam, 1989; Haslam, 1990; Schwarz et al., 2008). Quality is assumed to be related to procedural, chemical and morphological properties, bending strength and in particular to life expectancy, reflected as resistance or durability against environmental conditions or degradative organisms (Haslam, 1989; Haslam, 1990; Schwarz et al., 2008). During growth process at least chemical and morphological properties are influenced by many factors, as is known for reed bed management (Björndahl, 1985; Guntli, 1989; Asaeda et al., 2003), conditions of climate (Rodewald-Rodescu, 1974; Kuehl and Kohl, 1992), soil and eutrophication (Dinka, 1986; Ksenofontova, 1988; Schaller et al., 2012, Li et al., 2014a), water (Koppitz et al., 2004) and salinity (Hartzendorf and Rolletschek, 2001; Chen et al., 2006). Moreover, these parameters vary by ecotype (Kühl et al., 1999; Čurn et al., 2007; Hansen et al., 2007; Achenbach et al., 2012) or cutting height (Guntli, 1989) and are reported to be highly variable even within a few square meters (Schieferstein, 1997), so single reed beds can provide very different qualities (Boar et al., 1999). Until now there are neither extant studies about the range of single properties of traded reed bunches in Germany and elsewhere, nor is there a general consensus which reed properties define its suitability as thatching material.

The intention of this research work is therefore to give a first overview about the building material reed by a) analysing the provenances and harvest dates, b) measuring different morphological parameters, c) determining contents of several chemical constituents and d) analysing correlations between single reed properties of 214 customary thatching reed bunches.

# 2  Materials and Methods

## 2.1  Source of samples

The investigated bunches of thatching reed originate from different producing countries and sites. Bunches were collected and offered by official reed producers and traders in Germany and the Netherlands between 2010 and 2012. Few of the bunches were declared for discharge by providers because of beginning or advanced decay after delivery or storage. Additionally all providers were asked to fill questionnaires about harvest areas and years as well as environmental, soil and storage conditions.

## 2.2  Sample preparation

Starting at the bottom of each bunch, multiple parts with a circumference of about 40 cm and a height of 55 mm were cut off. On these parts, morphological parameters were calculated as demonstrated by Wöhler-Geske et al. (2013) and Wöhler-Geske (2014). About 100 g of culms were milled and sieved for 1 mm. Milled reed was used for determination of chemical properties.

## 2.3  Determination of morphological parameters

Different morphological parameters were determined, calculated or estimated. Before bunches were cut, conicity was calculated as ratio of bunch circumference at a height of 0.8 m and circumference at bunch basis. Also length of bunches from basis to panicles was measured. Directly after cutting, circumference and weight of undried parts were determined and thus packing density in $kg\,m^{-3}$ was calculated.

Image analysis was used to estimate mean diameter of culms of a bunch and mean culm wall thickness amongst other parameters according to Wöhler-Geske et al. (2013) and Wöhler-Geske (2014) as described as follows. Cut bunch parts were scanned, and resulting bitmaps were used to develop analysis algorithms (Halcon, version 7.1.2, MVTec Software GmbH, Munich). For detection of culms, it is searched for circles with a certain quantity of pixels above a predefined threshold concerning brightness. Decrease in brightness around this primary circle was used to determine diameter and wall thickness of culms. Diameters and wall thicknesses of identified culms were averaged for every examined bunch.

Reference for the determination algorithms was obtained by manual measurement of culm diameters and culm wall thicknesses including leaf sheaths using ImageJ (ImageJ 1.44p, Wayne Rasband, National Institutes of Health, USA). In total, mean culm diameters of 34 bunches were used as reference. To estimate mean culm diameter and mean culm wall thickness of other bunches, a regression equation between manually (ImageJ) and program determined (Halcon) parameters was used. Coefficient of determination ($R^2$) for estimating the mean culm diameter of a bunch was 0.971. Culm wall thicknesses were calculated basing on culm diameters with a determination coefficient of 0.865, since direct determination by Halcon showed poorer results.

Additionally, density of undried samples without culm lacunae and gaps between culms was estimated in two different ways of calculating cutting surface of culms. On the one hand, cutting surface was estimated by calculation including previously determined mean diameter and wall thickness. On the other hand, cutting surface was estimated by Halcon mediated quantification of culm areas in bitmaps by analysis of brightness in the same way as described for identification of culms and determination of diameter and wall thickness.

Halcon based image analysis was also used to determine dimensionless levels in RGB color model. Bitmaps were decomposed for red, green and blue channels, and mean intensity of colors was determined within the area of identified reed culms.

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## 2.4 Determination of chemical composition

Chemical constituents were determined according to standard methods described in VDLUFA Methodenbuch III (2007), such as crude ash (method 8.1), nitrogen (4.1.2) and carbon (4.1.2). Neutral detergent fibre (NDF and organic NDF) and acid detergent fibre (ADF and organic ADF) were analyzed according to a procedure to Van Soest et al. (1991). The procedure enables the determination of different components of the cell wall. Thereby the complete amount of cell wall components is obtained by digesting (boiling) the feed sample in a so called neutral detergent solution and results in the neutral detergent fiber fraction (NDF). The residue after digestion in a solution with sulfuric acid is called the acid detergent fiber (ADF) and contains mainly cellulose and lignin. Finally the remaining sample is treated with sulfuric acid of a higher concentration, resulting in a decomposition of cellulose leaving mainly lignin. This fraction is called acid detergent lignin (ADL). Organic fibre fractions (oNDF and oADF) were determined because aerobic degraders are assumed to incorporate only organic fractions during decay. Contents of cellulose, hemicellulose and lignin were calculated as differences between NDF and ADF content. Concentrations of carbon and nitrogen were determined according to Dumas by using a CHN analyzer.

Furthermore bunches were analyzed for mineral substances silicium (Si), magnesium (Mg), phosphor (P), calcium (Ca), potassium (K) and sulphur (S) by X-ray fluorescence adapted to a procedure of Schnug and Haneklaus (1999). Values were tested for plausibility and eliminated if not plausible (n = 1).

## 2.5 Statistical analysis

All sample subsets were tested for normality by using Kolmogorov-Smirnov and additionally skewness and kurtosis tests.

To quantify relationships between parameters, Pearson product-moment correlation was used.

# 3 Results

## 3.1 Provenances and harvest years

Countries of origin could be located for almost 99 % of bunches, and bunches originated from 12 different countries in Europe and Asia. Provenances of reed from Dutch and German providers are largely similar, except for the lack of Dutch reed at the German market (Figure 1). In total, three-quarter of bunches were harvested either in Germany, Netherlands, Turkey, Romania or China. For 45 % of bunches, also single districts of origin were known, primarily concerning bunches from Germany, Netherlands and Turkey.

Information about harvesting years was definite for less than 40 % of all bunches. For another 56 %, identification of harvesting years was only approximation. The oldest stored bunch was indeed harvested about 1990, but for more than 85 % of bunches the harvest was performed between years 2009 and 2011. Separate harvesting months were only known for 15 % of all bunches with February (7.9 %) and January (3.3 %) as most prevalent months. Harvesting time spanned from October to March.

Providers did not give any utilizable information about environmental, soil and storage conditions.

## 3.2 Morphological parameters

Reed bunches yet visually appeared to be different not only in culm diameters, but also in severity of contaminations (Figure 2). Some bunches showed considerable contaminations with typical reed bed plants like cattail (*Typha* spec.), rush (*Juncus* spec.) or sedges (*Carex* spec.). However,
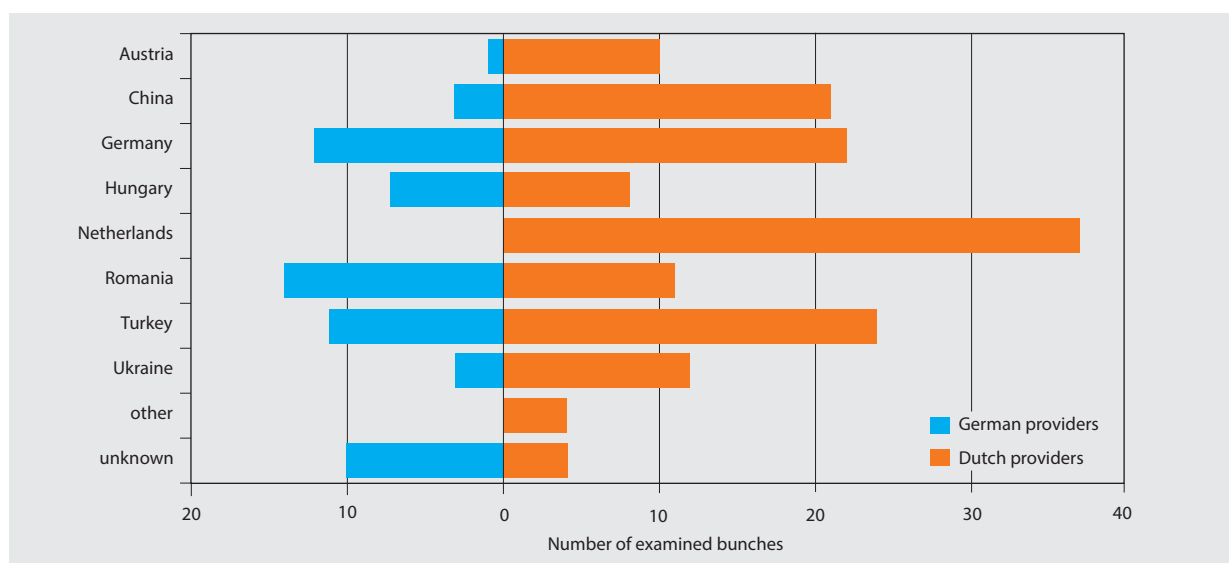


**Figure 1**

Provenances of investigated reed bunches delivered by German (blue) and Dutch (orange) providers. Of a total number of 214 bunches, 61 were offered by German providers and 153 by Dutch providers. Reed bunches were harvested in different countries primarily in winter season of the sampling year or the year before.
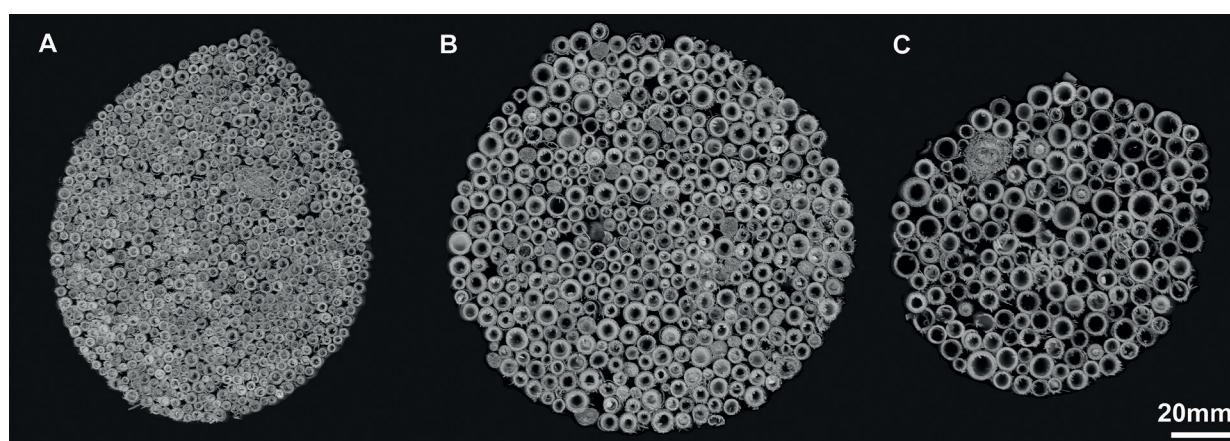
**Figure 2**

Exemplary scan displays of basic sections of different bunches. Displays were used to determine morphological parameters. **A** Bunch with a mean culm diameter of 3.4 mm, mean culm wall thickness of 0.3 mm and packing density of 235 kg m$^{-3}$, little contamination by cattail (*Typha* spec.). **B** Bunch with a mean culm diameter of 5.4 mm, mean culm wall thickness of 0.6 mm and packing density of 187 kg m$^{-3}$, obvious contamination by rush (*Juncus* spec.). **C** Bunch with a mean culm diameter of 6.3 mm, mean culm wall thickness of 0.7 mm and packing density of 160 kg m$^{-3}$, little contamination by cattail (*Typha* spec.).

morphological parameters such as mean culm diameter or density were calculated and estimated for all bunches. Mean culm diameter of bunches varied between 2.4 and 7.7 mm and mean culm wall thickness between 0.2 and 0.8 mm (Table 1). Length of bunches was 184 ± 32 cm. Dimensionless conicity ranged between 0.4 and 1.1 with a mean of 0.8, showing prevalent cone-shaped form of most bunches.

**Table 1**

Characteristic values of morphological properties of samples (n = 214).

| Morphological parameter | Range | Mean | Standard deviation | Variation coefficient [%] |
|---|---|---|---|---|
| mean culm diameter [mm] | 2.4 - 7.7 | 4.3 | 1.0 | 22.9 |
| mean culm wall thickness [mm] | 0.2 - 0.8 | 0.4 | 0.1 | 24.8 |
| length of longest culm of bunch [cm] | 98 - 267 | 184 | 32 | 17.5 |
| conicity | 0.4 - 1.1 | 0.8 | 0.1 | 14.0 |
| density, estimated by solid geometry [kg/m³] | 447 - 1225 | 788 | 122.7 | 15.6 |
| density, estimated by quantification of bright areas [kg/m³] | 219 - 448 | 320 | 40.3 | 12.6 |
| packing density [kg/m³] | 128 - 291 | 200 | 27.6 | 13.8 |
| red level in RGB color model | 128 - 209 | 173 | 14.4 | 8.3 |
| green level in RGB color model | 96 - 186 | 144 | 15.4 | 10.7 |
| blue level in RGB color model | 76 - 167 | 124 | 15.5 | 12.4 |

Results from two different methods for estimating density differed considerably. On the one hand, density of undried material, which was calculated including diameters and wall thicknesses, accounted for about 788 ± 123 kg m$^{-3}$. On the other hand, density by quantification of bright areas was about 320 ± 40 kg m$^{-3}$. Of all levels in color model (red, green and blue), blue level showed highest variation. However, all levels were highly correlated (r ≥ 0.980).

### 3.3 Chemical composition

With a proportion of about 52 % of dry matter (dm), crude cellulose was the main component in thatching reed (Table 2), followed by hemicellulose (about 27 % dm) and lignin (about 12 % dm). Crude ash content was about 3 % dm. Single supplementary mineral substances spanned from 0.01 % to 0.83 % dm with silicium as dominating mineral substance. Nitrogen content varied between 0.05 and 0.67 % dm, whereas C/N showed slightly higher variations and extended from 76 to 963 with a mean of 290. All mineral substances as well as ash, N and C/N showed high variation coefficients of about 50 % and nearly all of these constituents were not normally distributed and right-skewed. However, cell wall components and C showed normal distribution, skewness and kurtosis.

Moisture of samples accounted for about 8 %.

### 3.4 Correlations between properties of thatching reed

Few of morphological parameters showed correlations at high levels. Mean culm diameter and wall thickness correlated (r = 1.000), and both parameters were also slightly related to solid geometry estimated density (r = -0.535) and

**Table 2**
Chemical composition of samples (n=214).

| Chemical component | Range [%] | Mean [%] | Standard deviation [%] | Variation coefficient [%] |
|---|---|---|---|---|
| NDF | 80.32 - 93.88 | 90.30 | 1.83 | 2.0 |
| oNDF | 79.96 - 93.17 | 89.82 | 2.02 | 2.2 |
| ADF | 48.72 - 70.02 | 63.44 | 2.66 | 4.2 |
| oADF | 47 - 68.93 | 62.06 | 2.81 | 4.5 |
| Crude cellulose | 38.76 - 57.47 | 51.53 | 2.26 | 4.4 |
| Hemicellulose | 20.87 - 40.24 | 26.85 | 2.28 | 8.5 |
| Crude lignin | 8.43 - 17.17 | 11.91 | 1.31 | 11.0 |
| Crude ash | 0.69 - 8.07 | 2.94 | 1.26 | 42.8 |
| Mg | 0.009 - 0.059 | 0.020 | 0.008 | 38.9 |
| Si | 0.16 - 2.76 | 0.83 | 0.44 | 52.5 |
| P | 0.004 - 0.034 | 0.014 | 0.007 | 49.5 |
| S | 0.025 - 0.434 | 0.092 | 0.043 | 46.4 |
| K | 0.02 - 0.8 | 0.15 | 0.09 | 61.8 |
| Ca | 0.01 - 0.57 | 0.11 | 0.05 | 49.3 |
| N | 0.053 - 0.668 | 0.225 | 0.111 | 49.4 |
| C | 47.3 - 52.63 | 50.35 | 0.97 | 1.9 |
| C/N (dimensionless) | 76 - 963 | 290 | 172 | 59.5 |

conicity (r = 0.456). Additionally all color levels were strongly correlated (0.980 ≤ r ≤ 0.996), estimated densities correlated with each other (r = 0.802), packing density was related to solid geometry estimated density (r = 0.848) and density estimated by bright areas (r = 0.945). Less strong but significant correlations (r < 0.400) were observed for packing density and mean culm diameter or wall thickness, and wall thickness with density estimated by bright areas or red level, respectively.

Also many chemical components showed correlations. Strongest correlations were observed for NDF and oNDF (r = 0.960), ADF and oADF (r = 0.940) or cellulose (r = 0.870) or hemicellulose (r = -0.737), crude ash and silicium (r = 0.923), carbon and crude ash (r = -0.761) or silicium (r = -0.778), as well as nitrogen and C/N (r = -0.774). Slightly lower correlations were found for N and P (r = 0.642), C/N and P (r = -0.531), crude cellulose and hemicellulose (r = -0.630), crude ash and NDF (r = -0.567), ADF and Lignin (r = 0.525) or NDF (r = 0.534), respectively. Actually yet more constituents were correlated at a significance level of 0.01, but with much lower correlation coefficients. Also correlations of oADF and oNDF with other constituents were observed, but at the same levels as ADF and NDF, respectively.

Additionally, some chemical properties were correlated to morphological parameters. Highest correlation was observed for color levels and nitrogen (-0.719 ≤ r ≤ -0.705) as well as color levels and C/N (0.576 ≤ r ≤ 0.595). Conicity and ADF as well as cellulose showed positive correlation at the same levels, whereas hemicellulose or ADF were also slightly correlated to diameter as well as wall thickness.

# 4 Discussion

## 4.1 Provenances and harvest years

Countries of origin and approximate harvest years are known for almost all collected reed bunches, since producers, traders and thatchers are usually familiar to harvesting specifications and willing to provide these information. Information about typical origins of reed beneath other requested properties is given by the product data sheet published by the association of the German roofing industry (Zentralverband des Deutschen Dachdeckerhandwerks, 2010). In this data sheet, not only typical origins are listed, but also characteristics of culm length and diameter. Also it is disadvised to use reed with high humidity or obvious excessive infection with insects or fungi. However, suitability of reed as thatching material could be characterized by more than these properties.

According to the Product Data Sheet and Wichmann and Köbbing (2015), countries of origin of collected bunches are typical for reed traded in Germany. Only few of these bunches originated from countries which are not listed in the data sheet like France and Sweden. No samples were obtained from other countries mentioned in the Product Data Sheet and by Wichmann and Köbbing (2015) as Denmark, South Africa, Baltic States or Poland. Percentage of German reed is said to account for about 15 % of all 3 to 4 million traded bunches in Germany (Schwarz et al., 2008). This percentage was reflected by the samples collected from German providers.

Also for reed bunches obtained at the Dutch market, a huge percentage was imported. Main supplying countries were Turkey, Germany, China, Ukraine, Romania, Austria and Hungary, in accordance to suppliers presented by Wichmann and Köbbing (2015).

Harvest years are well documented for many of the collected bunches because of temporal proximity, whereas information about harvesting months was missing for most bunches. However, bunches with a higher age than two years were not traded at the reed market anymore, but stored for future analysis. Common cropping months were February and January. At this time finished senescence offers reed with increased portions of substances, which are hard to degrade for microorganisms (Kvêt, 1973; Rodewald-Rudescu, 1974; Mochnacka-Lawacz, 1974a; Dinka, 1986). However, cropping of reed beds after February is strictly forbidden in many states because of nature conservation determinations.

Unfortunately, reliable information about environmental, soil and storage conditions was not obtainable.

Only few of the bunches in this study were selected randomly. A majority of the analyzed bunches were selected systematically to cover the complete range of visible properties such as culm diameters, stem colors or other properties. These characteristics are assumed to be important for reed durability and procedural features (Schlechte, 2012). Since samples were not selected randomly using a stratified selection method, representativeness cannot be assured neither concerning reed markets nor concerning differences

between bunches of different proveniences. For this reason, a detailed analysis of reed basing on different proveniences was not realized.

## 4.2 Morphological parameters

Morphological parameters largely exhibited same ranges as reported in literature. Mean diameter and wall thickness of thatching reed was reported at similar levels by Anthony (1999) and Schwarz et al. (2008). However, in natural reed beds these parameters can exhibit higher amounts. For example Shorygina et al. (1965), Mochnacka-Lawacz (1974b), Ksenofontova (1988) or Kuehn et al. (2004) reported mean diameters between 10 and 12 mm for reed harvested in autumn and Rodewald-Rodescu (1974) actually detected samples with a diameter up to 32 mm. But also thinner reed has been found in autumn harvested natural reed beds (Van Ryckegem, 2005; Dinka et al., 2010). In contrast, wall thickness was rarely determined and measurements were exclusively performed manually by using calipers. Values reported by Schwarz et al. (2008) were in the same range as wall thicknesses of collected reed bunches, but those reported by Rodewald-Rodescu (1974) were higher.

Information about oven-dry density of thatching reed is more abundant, since density is assumed to influence reed resistance (Schlechte, 2012). Stephan (2008), Schwarz et al. (2008) and Wulf (2009) used liquid filled pycnometers for density determination. However, hydrophobic characteristics and hydrostatic uplift of reed could affect results. Therefore in this study, density was estimated using solid geometry and image analysis. Also Schlechte (2012) calculated density basing on solid geometry, probably after determining diameters and wall thicknesses by calipers. Nevertheless, reported results are contradictory. Stephan (2008) measured up to three times higher and Schwarz et al. (2008) even five times higher densities in wild reed than Wulf (2009) with a mean of 335 kg m$^{-3}$ in cultivated reed. Schlechte (2012) used mathematical methods and reported densities between 340 and 760 kg m$^{-3}$.

For this study, density of undried samples was estimated in two different ways. Results of the estimations differed considerably with means of 788 kg m$^{-3}$ and 320 kg m$^{-3}$. Based on a sample humidity of 8 %, results of estimations are comparable to all reported values. Density, which was estimated with solid geometry, is similar to this reported by Stephan (2008) and Schwarz et al. (2008). Density, which was estimated by quantification of bright culm areas, is nearly similar to values reported by Wulf (2009). Schlechte (2012) showed a density just between all reported values. These contradictory results reflect different estimation or determination methods with different error sources. Since density could be an important parameter for durability, further investigation for a standardized method with little error sources is needed.

Current investigated samples do not exactly represent the potential spectrum of morphological parameters. Especially diameter and wall thickness are partly lower than those reported for some reed beds. On the one hand, these parameters are highly influenced by environmental and genetic factors, on the other hand at least in Germany thinner reed is favoured for thatching due to its good procedural properties and appearance on roofs (Schattke, 1992). Also Kaminski (1939) argued for reed with low or medium culm diameter, since it would exhibit a higher durability than reed with thick culms.

## 4.3 Chemical composition

Every chemical component exhibits large variations in the analyzed sample. High variability has already reported in literature before and related to different environmental and physiological conditions. Also seasonal changes and growth stage are important for chemical composition of reed, as well as storage or transport conditions. Mineral substances and nitrogen are translocated into rhizomes during progression of growing season (Ho, 1981; Choi et al., 2005), resulting in decreased concentrations in aboveground organs (Kvêt, 1973; Mochnacka-Lawacz, 1974a; Ho, 1981; Dinka, 1986; Graneli, 1990; Schieferstein, 1997). Since especially nitrogen can facilitate decay in other plants (Taylor et al., 1989; Aerts and de Caluwe, 1997; Güsewell and Verhoeven, 2006), harvesting time is assumed to be very important. Additionally, concentrations can differ in dependence of examined reed organs (Kvêt, 1973; Mochnacka-Lawacz, 1974b; Ho, 1981; Ksenofontova, 1988; Graneli, 1990, Li et al., 2014a). For example, concentration of mineral substances is reported to be higher in leaves than in culms (Ho, 1981; Gessner, 2000; Dinka et al., 2004).

Few of presented components in collected bunches are detected in lower or higher concentration than reported for reed before. This is true for carbon and hemicellulose, which usually exhibit partly lower concentrations (Rodewald-Rodescu, 1974; Dinka et al., 2004; Schwarz et al., 2008; Dinka et al., 2010; Zhao et al., 2011).

Mean nitrogen content is noticeable low in analyzed bunches. Lowest detected nitrogen content is 0.053 % dm, and only Li et al. (2014b) reported samples in a similar range. Usually, *Phragmites* exhibits much higher contents (Ho, 1981; Graneli, 1990; Hietz, 1992; Zhao et al., 2011; Rodewald-Rudescu, 1974; Ksenofontova, 1988; Schieferstein, 1997; Dinka et al., 2004; Dinka et al., 2010). Nitrogen concentration is influenced by many factors including its concentration in soil or water (Dinka, 1986; Ksenofontova, 1988; Li et al., 2014a), growth stage (Dinka, 1986; Mochnacka-Lawacz, 1974a; Schieferstein, 1997) and thus harvesting time, and also infection by fungi (Engloner et al., 2000) can have an impact. Also stress such as submergence was shown to increase nitrogen containing amino acids (Koppitz et al., 2004). At least during growth, nitrogen content also seems to be influenced by height of examined sections (Schieferstein, 1997). However, in view of multiplicity of influencing factors and unusual high sample size, low nitrogen contents seem to be reasonable.

High carbon and low nitrogen contents result in extraordinary high C/N ratios up to 963 not only for few bunches. Highest ever reported C/N ratio of reed was about 250 (Schwarz et al., 2008; Dinka et al., 2010; Schlechte, 2012). For

wood, ratios between 500 and 1000 are already known (Ottow, 2011).

Mineral substances are low for some samples compared to values of harvested reed in literature (Dinka, 1986; Ksenofontova, 1988; Graneli, 1990; Hietz, 1992; Schieferstein, 1997; Gessner, 2000; Bragato et al., 2006; Sharma and Sharma, 2006; Dinka et al., 2010; Zhao et al., 2011). Also these dissimilarities may be due to unusual high sample size and variety of provenances of collected bunches. Concentrations in some samples are near or below detection limit of the used method. This is especially true for phosphor and already known (Schieferstein, 1997).

Despite environmental and growth conditions, also storage and transport conditions of reed bunches could have influenced variability of chemical properties. Indeed, providers gave identical information about conditions, at which bunches were stored or transported, so importance of these conditions for chemical composition of bunches could not be considered.

Current samples with noticeable low or high concentration and therefore outliers were detected for almost all constituents. Concerning bunches are frequently those, which show high contents of other reed bed plants, usually cattail (*Typha* spec.), or were declared for discharge by providers. Three outlier events were observed for calcium. Most of these outliers are related to high *Typha* content. Indeed, the most obvious difference regarding mineral substances between cattail and reed is represented by calcium content. Calcium content can be up to 14 times higher in cattail (Seidel, 1966). Other detectable outliers were associated with progressed decay, which was characterized by softness of culms and visible fungal infection. In particular, concentration of cell wall components cellulose, hemicellulose, NDF and ADF are known to decrease during progressing degradation (Dinka et al., 2004).

In general, lignin and cellulose degrading basidiomycetes are most important causative organisms for thatch decay (Schauer et al., 2013). Lignin is a substance with high recalcitrance against microorganisms due to its complex polymer structure (Ruiz-Duenas and Martinez, 2009), and by aggregation with cellulose, also protects this cell wall component from microbial degradation. For this reason, lignin content of reed is presumably a key factor for thatch durability (Schlechte, 2012). However, thermal pretreatment of thatching reed could improve resistance against biotic and abiotic decay additionally (Dosdall et al., 2015).

### 4.4 Correlations between single properties

Some of the morphological parameters such as solid geometry estimated density and diameter are correlated. Also Schwarz et al. (2008) reported such a correlation and assumed lower diameters as well as lower densities in secondary shoots in comparison to primary shoots, so maybe this correlation is not based on causality.

In different wood species, also color intensity can be useful to predict natural durability due to color changes in relation to content of degradation affecting phenolic extractives (Gierlinger et al., 2004; Kokutse et al., 2006; Amusant et al., 2008). Reed is not reported to contain noticeable concentrations of these or other resistant extractives. Nevertheless, there may be other constituents such as lignin or nitrogen, which could have an influence on decay resistance (Murphy et al., 1998; Aerts and de Caluwe, 1997; Xu and Hirata, 2005; Sanaullah et al., 2010) and show specific colors. For this reason, color intensity of reed samples were detected by image analysis. Remarkably, all color levels were highly correlated, so samples do not differ regarding single colors, but in color saturation.

The higher the color saturation of a sample, the lower seems to be its nitrogen concentration. This may be due to a low coloration of nitrogen containing inorganic substances such as nitrate and nitrite compounds. Organic substances like proteins or nucleic acids show low coloration, but degrade soon after cell death. Another explanation may concern mycelia, sporangia and spores of fungi. These tissues exhibit high nitrogen concentration because of high protein and chitin content. In bunches showing progressed decay, visible fungal tissues are often whitish. At least increasing nitrogen content in reed caused by colonisation by degrading organisms has been reported before (Gessner, 2000; Dinka et al., 2004). However, also with recent knowledge it is not possible to determine if and how this observed correlation is causally determined.

Also some of the chemical components in reed are correlated. However, statistical interpretation is difficult, since percentage is ratio scaled and has a defined upper limit. Major constituents will always be correlated to some extent. Observed correlations will be mixed correlations between those basing on authentic correlations with a real causal relationship and those basing on the percentage level.

However, correlation coefficients between many substances are significant. Highest correlations are observable for constituents, where one substance is a fraction or calculated of a second one, such as silicium and ash or NDF and oNDF. Another correlation is found for carbon and ash or silicium, respectively. This is the highest correlation for carbon, and correlations with the major carbon containing substances NDF and ADF are noticeable lower. Since carbon is rarely detected in reed, no correlations to other substances are reported until now. However, correlations between different mineral substances were reported by Ksenofontova (1988) and are also partly found in current study. Correlation is noticeable between nitrogen and phosphor, and at least in wheat leaves the phosphor content is not only influenced by its availableness in soil, but also by availableness of nitrogen (Evans, 1983). Contradictory to reports of Ksenofontova (1988), correlation between other mineral substances are much lower. Maybe harvest time is the cause for this difference. Ksenofontova (1988) performed harvest in August, when concentrations of minerals are still relatively high in aboveground organs, whereas samples of this study were harvested in winter, when most of mineral substances had already been translocated into belowground organs.

Mineral substances could be assumed to correlate with morphological properties, since good availableness of nutri-

ent substances in soil and therefore also in plants (Zingelwa and Wooldridge, 2009) should have a positive effect on linear and width growth. Ksenofontova (1988) found high correlations not only between root nitrogen or calcium content and morphological parameters of above-ground biomass harvested in August, but also correlation between diameter and calcium content of culms. However, only low correlations were found in collected winter harvested bunches since concentration of mineral and other components in aboveground biomass changes during seasons (Mochnacka-Lawacz, 1974b; Dinka, 1986), whereas most morphological parameters are constant. Finally, also different reed genotypes can show different properties at the same cultivation site (Achenbach et al., 2012).

A positive correlation is found for conicity and ADF. Additionally, bunches with high diameter exhibit lower contents of hemicellulose and higher ADF concentration. Culms with higher diameters use to be longer (Mochnacka-Lawacz, 1974a; Ksenofontova, 1988; Schieferstein, 1997) and require more stability, which is given by accumulation of lignin and cellulose. Maybe also secondary shoots have a significant influence on this correlation, since these shoots are assumed to be thinner and show different chemical profiles than primary shoots (Schwarz et al., 2008). Schwarz et al. (2008) did not only report differences between shoot types, but also correlations between density and cellulose or hemicellulose. Correlations in these dimensions could not be validated.

## 5 Conclusions

This study is the first one to provide information about an exceptional large sample size of thatching reed bunches concerning properties, which could determine the suitability of reed as thatching material. Even if the sample cannot be identified as representative for German or Dutch reed markets due to selective sampling and mixed willingness of potential providers to participate, the results still represent the range and variability of merchandised reed. Basing on these results, interested market actors can qualitatively classify their own thatching reed after analysis with regard to the Dutch and German markets. Moreover, this research work provides the informational background for further studies about durability of thatching reed and life expectancy of reed thatches or for revision of the product data sheet published by the association of the German roofing industry.

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