The utilisation of reed (*Phragmites australis*): a review

J.F. Köbbing[1], N. Thevs[1] and S. Zerbe[2]

[1]Institute of Botany and Landscape Ecology, University of Greifswald, Germany
[2]Faculty of Science and Technology, Free University of Bozen-Bolzano, Italy

SUMMARY

Reed (*Phragmites*) is a wetland plant genus that has been utilised by man since ancient times. It is a tall, thin, highly productive grass (*Poaceae*) with an above-ground biomass of up to 30 t ha^{-1} y^{-1}. Due to its world-wide dominance, it is often cheap and readily available as a raw material. Reed has been used for centuries as a fodder plant in summer, and the stems have traditionally been harvested in winter as a raw material for crafts and for construction materials including roofing. It became popular for pulp and paper production in the middle of the twentieth century and, in recent years, has been used in sewage water treatment and as a source of renewable energy that is unlikely to compete with food production. This article explores the global extent of reedbeds and potential yields; and catalogues historical uses of reed, forgotten applications and new opportunities for its utilisation. Quality requirements, products and related stand management (such as harvesting time) are also reviewed.

KEY WORDS: application; products; pulp; renewable energy; thatching

INTRODUCTION

Phragmites (from this point onwards "reed"), is one of the most widely distributed wetland plant genera worldwide. It is a highly productive grass (*Poaceae*) with an above-ground net primary production ranging from less than 3 t ha^{-1} y^{-1} to as much as 30 t ha^{-1} y^{-1} (Allirand & Gosse 1995). Reed can be found all over the world except in Antarctica, but its core distribution area (mostly *Phragmites australis* Trin. ex Steud) is Europe, the Middle East and America (Haslam 2010). It is characteristic of wet sites, most often with water level ranging from slightly below the soil surface to one metre above ground level (Brix 1988, Ostendorp 1993, Ailstock 2000), and grows mostly at the shores of lakes and gulfs, along riverbanks and on nutrient-rich peatlands. It can grow in deeper water if sufficiently clear, and has been collected from depths up to about 4 m in the highly transparent oligotrophic waters of the Stechlinsee (Brandenburg, Germany) (J. Kvet pers. comm.). Small stands can also be found at desert margins with water table from around four metres below to three metres above the ground surface (Thevs *et al*. 2007). Reed grows mostly in fresh water, but also in brackish or (up to 16 %) salt water (Ostendorp 1993, Ailstock 2000).

Only the rhizomes are perennial (Björk 1967) and, in cooler climates, the above-ground part of the plant dies at the end of the growing season. At this time the nutrients are re-located from the stems and leaves back to the rhizomes and stored for the next growing season. Although reed can be grown from seed, vegetative propagation is much more common (Huhta 2009). It has a strong ability to spread from rhizomes, and parts of rhizomes deposited from moving water can initiate new reed stands. It is a pioneer plant that often occurs in mono-specific stands (Ostendorp 1993, Ailstock 2000). As it can propagate very rapidly in new areas and grow to a height of several metres, it is seen as a threat to other aquatic vegetation in parts of North America (Chambers *et al*. 1999, Tewksbury *et al*. 2002, Derr 2008).

Reed has been used by man since prehistoric times. We can find references to the use of reed for roof thatching along the North and Baltic Sea coastlines since the last ice age (Schaatke 1992), in Germany from as early as 66 BC (Ostendorp 1993) and in North America during the period 600–1400 AD (Saltonstall 2002.). Probably the best-known and well-described reed users are the Marsh Arabs of the Tigris and Euphrates valleys (Thesiger 1964). There is also important literature on historical reed use in general (Haslam *et al*. 1999, Haslam 2010) and about particular areas like the Danube Delta (Rodewald-Rudescu 1974) and South Africa (Tarr *et al*. 2004).

Today, the appeal of wetlands is enhanced by our recognition of their wide range of supporting, regulating, cultural and provisioning ecosystem services (Millennium Ecosystem Assessment 2005) such as water purification, regulation of the water cycle, supply of biomass as raw material, and providing areas for recreation. In many countries, wetlands have been encompassed by legislative protection and degraded wetlands have been restored (Kusler & Kentula 1990, Hodge & Mcnally 2000, Wichtmann & Joosten 2007, Cui *et al*. 2009). When protection and restoration measures are applied, it is often necessary to find uses for the biomass produced by the wetland vegetation and new sources of income for affected local communities. Moreover, the rising demand for food and energy biomass renders wetland plants like reed increasingly interesting from an economic perspective. Reed is potentially important in the renewable resources market because it is highly productive of raw material (biomass, especially for energy) and is unlikely to compete for land that is useful for food production.

Against this background, we provide here a review of options for use of the above-ground biomass of reed, as one of the most abundantly available wetland plants.

REED BIOMASS HARVESTING AND GLOBAL YIELDS

In most areas and for most applications, reed is harvested in winter. This minimises conflict with nature conservation (e.g. breeding birds) and is compatible with various applications. It can also reduce harvesting costs if the climate is cold enough to enable harvesting from frozen wetlands, which is comparatively easy. Where the ground does not freeze in winter, reed may be harvested traditionally using allen-scythes; or special equipment with large (low ground pressure) pneumatic tyres or tracks, and even mowing boats, may be employed (Kirs 2011, Ympäristö Ojansuut Oy 2011). The exact harvesting time is highly dependent on weather and may be delayed by wind, snow or rain.

Regular winter harvesting of reed increases its vitality, producing strong and vigorous stands (Hanson & Graneli 1984, Huhta 2009). The annual removal of above-ground biomass reduces insect and fungus populations, and leads to higher light levels and less oxygen consumption by decomposer organisms within the stand (Hansson & Graneli 1984, Brix 1988, Schäfer & Wichtmann 1999, Hansson & Fredriksson 2004, Kask *et al*. 2007). On the other hand, it increases the risk of frost damage during cold nights (Björndahl 1985).

Harvesting in summer provides reed biomass with higher nutrient content than in winter (Květ & Ostrý 1988, Gryseels 1989, Hansson & Fredriksson 2004, Asaeda *et al*. 2006) which is desirable when it is to be used as fodder, as in many regions of central Asia (e.g. Thevs *et al*. 2007, Zerbe & Thevs 2011). Summer harvesting may also be applied as a conservation measure, for example to provide space for ground-nesting birds.

Allirand & Gosse (1995) calculated the global area of reedbed at ten million hectare. Table 1 summarises our own literature review of reedbed areas and biomass yields obtained from reed stands. Some of the sources are rather old but, if we assume that only half of the total area identified still exists, it would exceed four million hectares. If we could harvest only half of it, yielding 5 t ha^{-1}, the quantity of biomass made available would be 10 million tonnes annually.

Yield is determined mainly by climate (radiation, temperature), the water supply, soil and water salinity, and nutrient supply. A high rate of eutrophication supports the production of above-ground biomass (Graneli 1990, Huhta 2007, Kask *et al*. 2007). Experiments conducted by Bornekamm & Ragath-Atri (1986) showed a rapid increase in below-ground and above-ground biomass with increasing nitrate supply, but reverse results for surplus phosphorus. Nonetheless, reed occurs in some oligotrophic (nutrient-poor) waters although not under dystrophic conditions (Haslam 2010). Reed growing on non-submerged saline sites sometimes has a dwarf habit (Thevs *et al.* 2007).

UTILISATION TODAY: QUALITIATIVE AND QUANTITATIVE PROPERTIES

People have used reed for thousands of years. Some applications such as the manufacture of schnapps, coffee and boats are less popular today than they have been in the past (Holzmann & Wangelin 2009). Current possibilities for reed utilisation can conveniently be divided into industrial, energy, agricultural and water treatment uses. An overview is provided in Table 2.

Reed as an industrial material

Within industrial uses we include the large-scale uses of reed for thatching and paper production, the manufacture of construction and insulation materials, and a new use as a source of polymers.

Thatching

Thatching is the traditional and probably best-known use of reed in Europe. Indeed, according to Iital *et al*. (2012), reed and straw were the only roofing materials available along the seashore until the late 1800s.

Table 1. Reed areas and yields from winter harvest in different countries.

Site/region/country	Reedbeed area (ha)	Year	Harvested biomass (t ha^{-1} y^{-1})	total yield (t)	Reference
Europe					
Poland	60,000				Rodewald-Rudescu (1974)
South Finland	30,000 (15,000 harvestable)	2006	10	150,000	Komulainen *et al*. (2008)
South Sweden	230,000	2012	5	1,150,000	Iital *et al*. (2012)
Mecklenburg-Vorpommern, Germany	1,500	1997			Schäfer (1999)
The Netherlands	9,000 (2,850 harvested)				Van Der Sluis *et al*. (2013)
Lake Neusiedl, Austria	60,000 (36,000 harvestable)		7	28,500	Schuster (1985), Brunner (2008), Gamauf (2005) cited in Kitzler *et al*. (2012)
United Kingdom	7,700 managed for conservation	2013			Mills (2013)
Estonia	27,899 (12,970 harvestable)		7	88,368	Kask (2011)
Only lakes, Latvia	13,200 (10,826 harvestable)	2009/10	7.2	69,000	Cubars (2010)
Curonian Lagoon, Lithuania	4,995	2012			Iital *et al*. (2012)
Kaliningrad Oblast, Russia	200–300				
Regions and provinces of Russia	> 1,715,000	1959[2]			Krivitzki (1959) cited in Rodewald-Rudescu (1974)
Kazakhstan	2,000,000	1959[2]			
Uzbekistan	800,000–1,000,000	1959[2]			
Turkmenistan	1,000,000	1959[2]			
Azerbaijan	50,000–100,000	1959[2]			
Danube Delta, Romania	190,000 (125,000 harvested)	1965	5	625,000[1]	Rudescu *et al*. (1965) citied in DeLaCruz (1987)
Danube Delta, Ukraine	105,055		5	50,000	Rodewald-Rudescu (1974)
Hungary	26,200				Ruttkay (1964) cited in Rodewald-Rudescu (1974)
America					
Brackish, salt and tidal marshes, USA	1,800,000	1991			Chambers *et al*. (1999)
Asia					
NW, N, NE and coastal east China[3]	484,000	2004	5.5	2,600,000–2,700,000	Pöyry (2006)
North & South Korea	30,000 and 20,000				Rodewald-Rudescu (1958)
Iraq	17,300	2000			UNEP (2001)
Globally	>10,000,000				Allirand & Gosse (1995)

[1] Stand biomass was determined. [2] Total area of the former USSR was 5,500,000 ha. [3] The total reed yields calculated for China seem quite low in the experience of the authors, who have visited a single comparatively small wetland in Inner Mongolia that is supplying a paper mill with reed at a rate of up to 200,000 t per year.

Domestic production of reed has declined continuously over recent decades in most central European countries, where the annual demand now generally exceeds supply. In 2008, 6–7 million bundles[1] of reed were harvested in The Netherlands, 2.5 million bundles in Denmark, 1 million bundles in Germany and 0.8–1.5 million bundles in Estonia (Stenman 2008); in 1995, 0.3–0.5 million bundles were harvested in the UK (Hawke & Jose 1996). To compensate for shortfalls the UK imported 1.5–1.8 million bundles (75–80 % of usage) in 1989 and Germany imported 4.1 million bundles (80–85 % of usage) in 1997, mostly from eastern Europe (Dickie 2001, Mcbride *et al*. 2011, Schäfer 1999).

For thatching, dry reed (maximum moisture content 18 %) is required. Naturally dried winter harvested reed is suitable. Only long, straight and flexible stems can be used and, depending on the length (1.5 m, 1.8 m, 2.3 m) their diameter should be 3–12 mm (Hiss Reet 2011). Old and short stems, as well as other 'leftovers' such as leaves, must be removed. Inclusion of the stem base (butt) is desirable because it is the hardest and most decay-resistant part, but reed that has grown too long for thatching is often cut above the butt and consequently has shorter life expectancy (S. Haslam pers. comm.).

A 30 cm thick roof thatch requires 10–11 bundles per square metre, which means that up to 100 square metres of roof can be thatched with the yield from one hectare (Schaatke 1992, Haslam 2009). The roof weight of 30–40 kg m^{-2} is lighter than tiling, so does not require a strong base frame (Iital *et al*. 2012). Well constructed reed-thatched house roofs (slope > 45 °) should last at least 50 years, and perhaps up to 100 years (BRGA n.d., Iital *et al*. 2012). However, the lifespan of high-quality reed thatch that would previously have lasted for 100 years may now be reduced to as little as 30 years if exposed to acid rain and/or air pollution; and the thatching quality of many reed stands has deteriorated as a result of increased (including atmospheric) nitrogen inputs (Ostendorp 1990, 1995, 1999; van der Putten 1997, Guesewell & Kloetzli 2000).

[1] Thatching reed biomass is usually measured in bundles. The length of a standard bundle is 1.2–1.7 m, its circumference is (60–)62–64 cm (BRGA, n.d.), its diameter is 20 cm, and it weighs 4.5–6 kg. Depending on moisture content, one tonne of reed is equivalent to 160–220 bundles. Depending on yield and size of bundles, 750–1000 bundles per hectare can be harvested (White 2009, ELP & Ash 2010, Haslam 2010).

The cost of thatching in 2005 was €32 (500 EEK) per square metre in Estonia (Stenman 2008), and in 2007 it was €43–73 (£35–60) per square metre in the UK (Haslam 2010) and €70–80 in Finland (Rauvola 2007). The cost of the reed is around €2.5 (£2) per bundle (Dickie 2001).

Construction and gardening

Winter-harvested reed stems are widely used to make garden fences (e.g. in Europe) and indoor furnishings such as blinds, floor and wall coverings, panels and screens. They can also be used in construction, e.g. in the walls, floors and ceilings of houses.

Reed stems can be used to produce insulation material for walls and roofs. The heat conductivity (λ) 0.055 W m^{-1} K^{-1} (compare wood fibre and mineral wool which have heat conductivities of 0.040–0.052 W m^{-1} K^{-1} and 0.033–0.040 W m^{-1} K^{-1}, respectively). Reed combines a high volume-to-weight ratio with high air content, which makes it not only a poor conductor of heat but also a good conductor of humidity (FNR 2012a).Thus, it supports a good indoor climate in both winter and summer.

Reed panels (sometimes called Berger Panels) are fixed to the wall, and may be covered with cement or clay as reinforcement. The quality of reed required is lower than for roof thatching. Thick, long, dry stems are cleaned, compressed and knitted with wire at different thicknesses (Stenman 2008) 'endlessly' in a weaving loom so that panels may be cut to any required length. Standard insulation panels are knitted with 2 mm wire, they are 2–5 cm thick, and come in sizes 1.25 × 1.0 m and 1.25 × 2.0 m (Holzmann & Wangelin 2009). They cost around €0.45 m^{-2} in China (in 2007) and €6.5–10 m^{-2} in Austria (in 2013) (Hansmann 2008, Reichel 2013). To make one square metre of panel, the materials required are 0.6–0.8 kg of wire (depending on the number of wire rows included), and 13 kg of reed m^{-2} for 3 cm thick panels or 20 kg of reed m^{-2} for 5 cm thick panels (Rodewald-Rudescu 1974).

Granulate panels are made by mixing chopped winter-harvested reed (including both stems and leaves, as well as any 'leftovers' from thatching) with glue or clay. Standard granulate panels are 110 cm × 60 cm × 3 cm thick and can be used as insulation or plaster base, or to construct partition walls (Reichel 2011, Sumalowitsch 2011). They can be purchased in Austria for around €19 m^{-2} (Holzmann & Wangelin 2009, Reichel 2011).

Table 2. Overview of the different possibilities for utilisation of reed.

Use	Harvest time	Requirements	Treatment	Output	Price
Industrial material					
Roof thatching for all house types, minimum roof slope 45°	Winter	High quality, long, straight, flexible, annually moved, moisture content <18% (dry)	Leaves etc. removed by combing, Stems packed in uniform-length bundles, dried if necessary	40 cm thick = 20 bundles/ m^2 1 m^2 needs 1–1.2 ton of reed	Reed €2.5 per bundle (UK), thatching €32–80 m^{-2} (Europe)
Construction and gardening Walls, panels, mats, fence plaster base, Insulation	Winter	Long, thick, straight stems only	Compressed and knitted in a weaving loom, fixed to the wall and covered with clay	λ= 0,055 W m^{-1} K^{-1} Size 1.25 m x 1.0/2.0 m 1 m² panel = 20 kg (5 cm thick) or 13 kg (3 cm thick) of reed, 0.6-0.8 kg wire	6–10 €/m² (Austria), 0.45 €/m^2 (China)
Granulate panel		Chips or clippings for granulate panels, also leftover	Chopping and mixing with glue	Size 110 cm x 60 cm	19 €/m^2 (Austria)
All kinds of paper & pulp	Winter	Dry reed, depending on the kind of paper the whole plant can be used	Chopping & pressing For some paper kinds removal of sheets Mixing with wood pulp	1 ton of paper pulp =3.3–3.5 tons of reed	n.d.
Polymerisation for textile or plastic	Winter	Whole plant	With help of chemical separated into components, the cellulose is used to for products	-	Experimen-tal stage
Energy					
Combustion	Winter	Whole plant, low quality required; moisture content 15–20%; low nutrient and ash content, mixed with wood chips	Chopping and pressing to pellets, bailing or bulks	Pellets or briquettes 16.2–16.5 MJ/kg	€12–20 MWh^{-1} (Estonia)
Biogas	Summer	Whole plant, low quality required; wet/high moisture content	Chopping	1kg reed = 0.4–0.5 m^3 biogas with max. methane content of 55–60%	n.d.
Biofuel	Winter	Whole plant can be used	Different treatment to extract cellulose and convert to glucose	-	Experimental stage
Agriculture					
Fodder and litter	May-October	Soft, sweet shoots grazed before flowering	Directly grazed	-	n.d.
	May and June		Cut and stored in a dry place	Nutritional value of 13.31 kg reed = 1 kg oats	n.d.
Fertilizer/ compost	(Late) summer	Green sludge from biogas production	Digestion in a biogas plant	-	n.d.
	Summer	Chopped reed	-	-	n.d.
	Summer	Moisture content above 35%; mix with other garden waste	Composting	-	n.d.
Water treatment	Whole year	Wetlands with a stream	Regular harvesting maintains reedbed and purification function	04–1.0% N 0.2–0.9% P and 0.1–0.6% K	Highly variable

Pulp and paper

Reed biomass is a source of cellulose and hemicellulose. The cellulose content of reed, which ranges from 33 % to 59 % depending on environmental factors (Rodewald-Rudescu 1958), can be used for semi-chemical and chemical pulps (for an overview see Chivu 1968b). Generally speaking, only the leaves have to be removed for semi-chemical pulp, and all above-ground parts of the plant can be used in papermaking (Chivu 1968a).

Reed is favoured for paper production because it has a high proportion of short fibres (Chivu 1968b), although cellulose pulp made from short-fibre reed must be mixed with a certain proportion of long softwood fibres to achieve satisfactory paper density and tear resistance (Chivu 1968a, DeLaCruz 1987). Paper with up to 30 % reed content is of good quality and suitable for almost all uses (Chivu 1968a, Hurter 2001), whilst paper with reed content up to 80 % can be used as wrapping paper (Haslam 2010).

Reed paper mills have operated in Turkey, Sweden, Egypt Romania, Iraq, Italy, the former German Democratic Republic and the U.S.S.R., and still exist in China and probably India (Savcor 2006, FAO 1985, Wayman 1973). The best-known paper enterprise, producing several thousand tonnes per year, was in the Danube Delta (Rodewald-Rudescu 1958, 1974). Reed pulp and paper are no longer produced in Europe, due to lack of reed supply in addition to economic and environmental reasons; but in China the quantity of reed used for paper production in 2004 was 2.5–2.7 million tonnes and is increasing (Zhu *et al*. 1998, Pöyry 2006).

The dry (15 % moisture content) reed biomass (stems and leaves) is harvested in winter. The reed is chopped and pressed into bales after harvest to reduce its volume, facilitating storage of a year-round supply for the pulp and paper mill, which runs continuously, and reducing transport costs.

One tonne of paper pulp requires 5.3 m³ of softwood, 4.1 m³ of beech wood or 3.3–3.5 tonnes of reed (Chivu 1968b, Zhu *et al*. 1998), and Rodewald-Rudescu (1974) calculates requirements of four tonnes of reed per tonne of artificial fibre cellulose and three tonnes for normal cellulose. The result of an investigation by the authors in Inner Mongolia (China) was that reed as raw material for paper production costs up to €90 t^{-1} (≈750 CNY t^{-1}) at the factory gate.

Polymerisation

Reed, like other types of biomass, can be used as a raw material for bio-based plastics. Also, like wood and bamboo, it has a high (ligno-) cellulose content which can be utilised to produce functional polymers (e.g. stimuli-responsive polymers and biomimetic materials) (FNR 2012b). The cellulose can otherwise be used as a raw material for pulp and paper (see above) or textiles. By-products like lignin (22–23 %) and pentosan (23–27 %) must be extracted (Holzmann & Wangelin 2009).

The raw material (reed) is milled, then treated with various chemicals under high pressure and temperature to separate out the lignin, hemicelluloses and (especially) the cellulose (BMELV *et al*. 2012), which are then used for different applications. One of these is the manufacture of viscose/rayon, which can be spun into yarn and used for textile products. This process is still at an experimental stage and, although it is less energy intensive than cotton production, the high usage of chemicals and the sewage treatment remain challenging. Other applications include the manufacture of plastic from cellulose, and the conversion of cellulose and hemicelluloses by fermentation to glucose and, thence, to ethanol and biogas (BMELV *et al*. 2012). Because these processes are still being researched, no information is yet available about raw material efficiency and prices.

Energy

Reed biomass can be used as an energy source in three ways, namely by combustion, biogas production and biofuel production. All stems and leaves can be used regardless of length or diameter (Wichmann & Wichtmann 2009, ELP & Ash 2010).

Combustion

Heat and power can be generated by combustion or co-combustion of winter-harvested reed with low moisture content, in both simple burners and gasification power plants. The lowest moisture content of 15–20 % is achieved by harvesting in late winter (March–April) (Paist *et al*. 2003, Komulainen *et al*. 2008). The nitrogen, phosphorus and ash contents are also low because minerals and nutrients are stored in the roots at this time of year. Ash content, which is significantly lower (2–4 %) in winter than in summer (4–6 %) due to loss of leaves (Boltryk & Malszkiewicz 2007, Kask *et al*. 2007), is an important factor in relation to the corrosion of equipment and the regulation of emissions. The ash content of reed is higher than that of wood but, at most, half that of straw (Kronbergs *et al*. 2006).

The low density (20–60 kg m^{-3}) of reed biomass means that it occupies more space in storage and transport than other energy fuels. Therefore, the use of reed for direct combustion is most appropriate at a local scale, involving transport over distances not exceeding 50 km (Iital *et al*. 2012). In general, for economic viability, the energy density must increase with the required transport distance. This can be addressed by chopping and compressing the material into bales, briquettes or pellets (White 2009) with respective densities up to 140–170 kg m^{-3}, 705 kg m^{-3} or 1200 kg m^{-3} (Kronbergs *et al*. 2006, Iital *et al*. 2012) to increase the energy density and facilitate transport to the power plant.

The average primary energy content of reed pellets, briquettes and bales (moisture content 20 %) is 14 MJ kg^{-1} (Iital *et al*. 2012), which makes reed comparable to other forms of biomass for combustion (e.g. the calorific value of wood pellets is 17 MJ kg^{-1} whereas that of oil is 42.5 MJ kg^{-1}, BIOMASS Energy Centre 2013). Assuming a heating value of 16.2 MJ kg^{-1} (4.5 MWh t^{-1}) and a productivity of 5 t ha^{-1} y^{-1}, an energy yield of 20 MWh ha^{-1} y^{-1} can be achieved, which is equivalent to the annual energy consumption of one detached house in Finland (Graneli 1984, Kask *et al*. 2007, Komulainen *et al*. 2008). Even better results can be achieved by mixing up to 60 % reed with wood chips (Barz 2006), or by co-generating heat and electricity.

Reed that is harvested in summer and autumn must be dried before burning. Dried summer mass (moisture content 20 %) has a calorific value of 13–18 MJ kg^{-1} (3.7–5 MWh t^{-1}) (Graneli 1984, Paist *et al*. 2003), giving a heating value comparable to that of winter reed if the energy used for drying is not taken into account.

The maximum price that can achieved for reed as a source of energy (district heating plant) in Estonia is €12–20 MWh^{-1}, depending on the quality of the raw material and the availability of alternatives (Komulainen *et al*. 2008).

Biogas

Energy production from reed may otherwise be achieved by digestion in a biogas plant. For this purpose, green summer (May–October) reed with high nutrient content is required. Reed harvested in early summer or autumn has a lower biogas potential (Kask 2011), partly due to its higher lignin content (Hansson & Fredriksson 2004).

The process involves anaerobic digestion of chopped reed by bacteria, which generates methane that can be used for heat and electricity production. One kilogram of green reed biomass yields 0.4–0.5 m^3 of biogas with a maximum methane content of 55–60 % (Komulainen *et al*. 2008). Its calorific value is around 6 MWh m^{-3} (Iital *et al*. 2012). Winter reed is not suitable for fermentation due to its high carbon:nitrogen (C:N) ratio and low content of moisture and nutrients, which are necessary for bacterial decomposition (Iital *et al*. 2012). A by-product of the digestion is sludge that can be used as an agricultural fertiliser (Hansson & Fredriksson 2004, Komulainen *et al*. 2008).

Biogas production from summer-harvested reed is not widespread because it is difficult to access wet areas in summer and there are potential conflicts with nature conservation. Indeed, no information has been found for this review about the operation of a reed biogas plant.

Biofuel

A third potential method for energy generation from reed is the production of biofuel (biomass to liquid = BTL). This might be bio-ethanol, bio-diesel or bio-hydrogen for use in vehicles (Wichmann & Wichtmann 2009). Reed is a so-called “second generation” biofuel. This term is used for biofuels that are produced from non-food biomass (e.g. reed) or agricultural residues, in contrast to the “first generation” fuels, which were derived from food crops (e.g. maize).

Glucose is the raw material for biofuel production, and can be obtained from reed cellulose (31.5 % hemicellulose and 49.4 % cellulose) after pre-treatment to break the lignin seal and hemicellulose sheathing (Tutt & Olt 2011). This research is still at an experimental stage and studies are very limited. However, because reed resists the conventionally used enzymatic hydrolysis (Szijártó *et al*. 2009), it produces the lowest glucose yield (46.42 %) of all types of non-food biomass that have been analysed (e.g. *Miscanthus* 59.80 %, hemp 58.06 %) (Tutt & Olt 2011). When other methods were investigated to increase the glucose yield, the best results were obtained from (1) a wet oxidation pre-treatment, (2) enzymatic conversion into glucose, and (3) conversion of cellulose to ethanol by saccharification and fermentation (Costa-Ferreira *et al*. 2007, Szijártó *et al*. 2009). The conversion rate of cellulose to glucose thus achieved was 82.4 %.

Agriculture

The third major use of reed biomass is in agriculture. As a wild wetland plant, reed has been used for centuries for grazing by animals and also harvested as a fodder plant.

Fodder

Reed is still widely and commonly used as a fodder plant for water buffalo, cows, sheep, cattle, goats and donkeys; for example in Scandinavia, the

Netherlands and China (Häkkinen 2007, Thevs *et al*. 2007, Hansmann 2008, Huhta 2009, White 2009). Its high content of nitrogen, potassium (10.9 g kg^{-1}) and manganese (2.65 g kg^{-1}) makes it a particularly good fodder plant for ruminants (Baran *et al*. 2002). The nutritional value of 13.31 kg of reed is equivalent to that of one kilogram of oats (Rodewald-Rudescu 1974). Although it has a lower nutritional value than other fodder plants, it was (and is) cheap and easily available in some parts of the world, and large animals can eat shoots up to 50–75 cm tall (Haslam 2010).

We can distinguish two ways in which reed is used as a fodder plant. The first is grazing, which often occurs in spring and summer (April–October) if the shoots are green and soft (Hansmann 2008, Huhta 2009) and the water level is low enough for the stands to be accessible. However, grazing substantially disturbs plant growth, leading to significantly lower biomass production and smaller shoots in the subsequent grazing season (Thevs *et al*. 2007). The second is summer harvesting (in May and June) and storage as winter feed for livestock (Hansmann 2008). Some winter-harvested reed is used as animal litter (Schuster 1985).

Fertiliser/ compost

Reed can be used as a soil conditioner in agriculture, for example in rice cultivation (Thesiger 1964). Only summer-harvested reed contains sufficient nutrients to be useful as fertiliser (Hansson & Fredriksson 2004), but if it is harvested in summer, nutrients are removed in the biomass and this may lead to oligotrophication of the site and lower biomass growth in the following year. There are three methods for using reed as a fertiliser:

1. The easiest and cheapest method is to chop the reed and spread it directly onto the fields (Schuster 1985). A substantial disadvantage is the low availability of nutrients to crops due to the high C:N ratio (about 39, whereas the optimum is 15–30). Therefore, this technique is seldom applied.

2. Chopped reed is mixed with garden waste with high nitrogen content to reduce the C:N ratio to a value between 15 and 30, then composted. The moisture content must exceed 35 % (ELP & Ash 2010).

3. The nutrients in the green sludge remaining after anaerobic digestion of reed (for biogas) are readily available to plants. Iital *et al* (2012) calculate that the sludge generated by harvesting 5 ha of reedbed for biogas production would be sufficient to fertilise 2–4 ha of agricultural land.

The results of Hansson & Fredriksson (2004) show that the biogas alternative is more favourable, with approximately 56 % of total nitrogen available to plants as opposed to 30 % in the compost alternative. Experiments from the UK demonstrate feasibility for manure use but highlight issues about legislative constraints on private composting (White 2009). No data have been found about economic feasibility of composting.

Water treatment

The use of mainly artificially constructed wetlands for sewage water treatment is quite common (Vymazal 2010). Non-point source pollution (mainly N and P) is removed from the water by leading it through beds of different kinds of aquatic plants (Kusler & Kentula 1990, Brix 1994, Wild 2001, Sarafraz *et al*. 2009).

Water is purified by reedbeds in two different ways. First, whole reed stalks initiate bacterial activity by conveying air (i.e. oxygen) to the roots *via* the aerenchyma (Kronbergs *et al*. 2006). N is removed mainly by ammonification, nitrification coupled with denitrification, ammonia volatilisation and cation exchange for ammonium, while P is removed by chemical adsorption and biological transformation (Sarafraz *et al*. 2009). Secondly, nutrients are removed from the wetland by harvesting the above-ground biomass. Nutrient accumulation in the upper part of the reed plant peaks in July or August (Hansson & Fredriksson 2004, Komulainen *et al*. 2008) and is later reversed when nutrients are returned to the roots and sediment for storage until the next growing season. Only 10–20 % of the nutrients present in August remain in the dead above-ground shoots over winter (Graneli 1990, Hedelin 2001). Therefore, the extraction of nutrients by harvesting is highly dependent on the cutting time. The dead above-ground biomass is cut mostly in winter when the ground is frozen. Winter harvesting of a reedbed in south Sweden with a standing crop of 7.4 t ha^{-1} and harvestable crop of 5 t ha^{-1} y^{-1} extracted 20 kg ha^{-1} y^{-1} nitrogen, 1 kg ha^{-1} y^{-1} phosphate and 8 kg ha^{-1} y^{-1} potassium. Summer harvesting of the same reedbed yielded 10 t ha^{-1} y^{-1} of biomass and removed 92 kg ha^{-1} y^{-1} of nitrogen, 9 kg ha^{-1} y^{-1} of phosphate and 66 kg ha^{-1} y^{-1} of potassium (Graneli 1990, cf. Table 3). One positive side effect of removing biomass from the wetland is the reduction of secondary pollution arising from both plant decomposition and sedimentation. On the other hand, harvesting of reed may negatively influence water quality, as it removes the reed stalks which pump up nutrients from the roots (Huhta 2009).

Table 3. Overview of nutrient extraction in above-ground biomass by summer and winter harvesting of natural wetlands. n.d. = no data.

Country	Sweden[1]		China[2]		Finland[3]		Estonia[4]		Seasonal ranges
Habitat	Coastal and littoral stands		Eutrophic lake		Coast of the Baltic sea		Lake reed		
Harvest time	Feb	Aug	Nov–Jan	Sep	Mar	Jul	Winter	Summer	*Winter* Summer
Yield of dry mass (t ha^{-1} y^{-1})	5	10	10	20	4.5	5	8.1	7.4	*4.5–10* 5–20
N (%)	0.2	0.24	n.d.	n.d.	0.33	1.0	0.3	1.0	*0.2–0.33* 0.24–1.0
P (%)	0.02	0.08	0.028	0.09	n.d.	0.095	n.d.	n.d.	*0.02–0.028* 0.08–0.095
K (%)	0.16	0.5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	*0.16* 0.5

[1]Graneli (1990), [2]Hedelin (2001), [3]Komulainen *et al*. (2008), [4]Kask (2011).

CONCLUSIONS

Even today, reed is a valuable raw material for a multitude of products. Each product has specific requirements in terms of stem length, thickness, dryness or freshness, moisture content, ash and nutrient content. All of these requirements depend primarily on the time of harvest. Other factors influencing the quality of reed are location, nutrients, climate, frequency of harvesting, water availability and management.

At local scale, reed can be a sustainable substitute for fossil energy sources like oil and coal. It may also replace wood for cellulose production. With human population growth and the economic development of many countries, the demand for such raw materials will increase. Where economic growth leads to accidental or unavoidable eutrophication of lakes and wetlands, the exploitation of reed may offer the dual advantages of increased yields and beneficial enhancement of the water purification functions of wetlands. In the management of reedbeds, harvesting should be balanced with their other important services and functions (e.g. bird habitat, recreation, flood protection) and the aim to conserve the wetland as a whole.

Compared to first-generation biofuel crops (corn, rape, sunflower etc.), reed has two large advantages as a source of renewable energy. The first is that agricultural land is not used to produce the energy crop. The second relates to preservation of the carbon stocks in peatlands which, when drained, release large amounts of greenhouse gases due to peat decomposition (Frick *et al*. 2011, Wichtmann & Joosten 2007, Wichtmann 2008). Because reed can grow as a peat-forming plant on fens and other less-acidic minerotrophic mires, commercial use of peatland reed stands could reduce the likelihood that such peatlands will be drained, and thus contribute directly to the limitation of greenhouse gas emissions. Reed might also be planted on appropriate re-wetted peatlands to simultaneously achieve carbon capture and reed biomass production.

ACKNOWLEDGEMENTS

We thank the Kurt-Bode-Foundation for funding the Project “Sustainable Water Management and Wetland Restoration in Settlements of Continental-Arid Central Asia” (SuWaRest), within which this study was undertaken. Furthermore, we thank the Fachagentur für Nachwachsende Rohstoffe (FNR) (Agency for Renewable Resources) for covering additional personal costs. Special thanks to Francesco Patuzzi from the University of Bozen-Bolzano for valuable comments on the energy part. This article is based on a presentation made by J. Köbbing at the international conference on the utilisation of emergent wetland plants “*Reed as a Renewable Resource*”, held on 14–16 February 2013 at the University of Greifswald, Germany.

REFERENCES

Ailstock, S.M. (2000) Adaptive strategies of Common Reed *Phragmites australis*. In: *The Role of* Phragmites *in the Mid-Atlantic Region, Princess Anne, MD, April 17*, Environmental Center, Anne Arundel College, Arnold, MD. Online at: http://www.aacc.edu/envcenter/file/adaptivestrategiesphragmitesaustralis.pdf.

Allirand, J.-M. & Gosse, G. (1995) An above-ground biomass production model for a common reed (*Phragmites communis* Trin.) stand. *Biomass and Bioenergy*, 9(6), 441–448.

Asaeda, T., Rajapakse, L., Manatunge, J. & Sahara, N. (2006) The effect of summer harvesting of *Phragmites australis* on growth characteristics and rhizome resource storage. *Hydrobiologia*, 553(1), 327–335.

Baran, M., Váradyová, Z., Kráâmar, S. & Hedbávn, J. (2002) The Common Reed (*Phragmites australis*) as a source of roughage in ruminant nutrition. *Acta Veterinaria Brno*, 71, 445–449.

Barz, M. (2006) Energetic utilization of Common Reed for combined heat and power generation. In: Barz, M. & Ahlhaus, M. (eds.) *Use of Bioenergy in the Baltic Sea Region*, Proceedings 2nd International Baltic Bioenergy Conference, 02–04 November 2006, Fachhochschule Stralsund, Germany, 166–173.

BIOMASS Energy Centre (2013) Typical calorific values of fuels. Online at: http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,20041&_dad=portal&_schema=PORTAL.

Björk, S. (1967) Ecological investigations of *Phragmites communis*. Studies in theoretical and applied limnology. *Folia Limnologica Scandinavica,* 14, 1–248.

Björndahl, G. (1985) Influence of winter harvest on stand structure and biomass production of the common reed, *Phragmites australis* (Cav.) trin. ex steud. in Lake Takern, Southern Sweden. *Biomass*, 7(4), 303–319.

BMELV, BMBF, BMU & BMWi (2012) *Roadmap Bioraffinerien im Rahmen der Aktionspläne der Bundesregierung zur stofflichen und energetischen Nutzung nachwachsender Rohstoffe (Roadmap Bio-refineries, Part of the Action Plan of the Federal Government for Raw Material and Energetic Use of Renewable Resources*). Die Bundesregierung, 108 pp. (in German). Online at: http://www.bmelv.de/SharedDocs/Downloads/Broschueren/RoadmapBioraffinerien.pdf?__blob=publicationFile.

Boltryk, M. & Malszkiewicz, D. (2007) Influence of reed blade length upon technical properties of reed-concrete. In: *Modern Building Materials, Structures and Techniques,* Full Papers of the 9th International Conference, May 16–18 2007, Vilnius, Lithuania. Online at: http://leidykla.vgtu.lt/conferences/MBM_2007/1pdf/Boltryk_Malas1.pdf.

Bornekamm, R. & Ragath-Atri, F. (1986) Über die Wirkung unterschiedlicher Gabe von Stickstoff und Phosphor auf die Entwicklung von *Phagmites australis* (Cav.) Trin. ex Steudel (About the impact of adding nitrogen and phosphorus to *Phagmites australis* (Cav.) Trin. ex Steudel). *Archiv für Hydrobiologie*, 105(4), 423–441 (in German).

BRGA (n.d.) *´Norfolk Reed´ Roofing Today. A Guide to the Benefits of Thatching with Reed*. Leaflet, British Reed Growers Association, Norwich, 6 pp. Online at: http://www.brga.org.uk/Publications.html.

Brix, H. (1988) Gas exchange through dead culms of reed, *Phragmites australis* (Cav.) Trin. ex Steudel. *Aquatic Botany*, 35(1), 81–98.

Brix, H. (1994) Use of constructed wetlands in water pollution control: Historical development, present status, and future perspectives. *Water Science Technology*, 30(8), 200–223.

Chambers, R.M., Meyerson, L.A. & Saltonstall, K. (1999) Expansion of *Phragmites australis* into tidal wetlands of North America. *Aquatic Botany*, 64(3), 261–273.

Chivu, I.A. (1968a). The use of reeds as raw material for pulp and paper production. In: FAO (ed.) *Pulp and Paper Development in Africa and the Near East,* Vol. 2, Food and Agriculture Organization of the United Nations, Rome, 227–289.

Chivu, I.A. (1968b) Practical experiment in the cropping of reeds for the manufacture of pulp and paper - economic results. In: FAO (ed.) *Pulp and Paper Development in Africa and the Near East,* Vol. 2, Food and Agriculture Organization of the United Nations, Rome, 877–899.

Costa-Ferreira, M., Sousa, J.M., Lageiro, M., Anatoly, S., Helena, P., Kádár, Z., Mátyás, S. & Kati, R. (2007) *Bioethanol Production Using Native Reeds From Portugal and Hungary – a Collaborative Study*. Poster, European Meeting Point - Energy for Development, October 10–12, Beja, Alentejo, Anguilla, Portugal. Online at: http://orbit.dtu.dk/en/publications/bioethanol-production-using-native-reeds-from-portugal-and-hungary-a-collaborative-study(0069b892-2e25-4d9c-9df9-59889507bc26).html.

Cubars, E. (2010) Analysis of reed-covered surface and of potential biomass in Latvia’s lakes. *Cofreen Project*, 1–2. Online at: http://www.cofreen.eu/index.php/en/project/publications/57-

analysis-of-reed-covered-surface-and-of-potential-biomass-in-latvias-lakes.

Cui, B., Yang, Q., Yang, Z. & Zhang, K. (2009) Evaluating the ecological performance of wetland restoration in the Yellow River Delta, China. *Ecological Engineering*, 35, 1090–1103.

DeLaCruz, A. (1987) The production of pulp from marsh grass. *Economic Botany*, 32, 46–50.

Derr, J.F. (2008) Common Reed (*Phragmites australis*) response to mowing and herbicide application. *Invasive Plant Science and Management*, 1, 12–16.

Dickie, I. (2001) *The Economics of Reedbed Management in the UK*. RSPB, Sandy, 16 pp. Online at: http://www.brga.org.uk/files/cgi-bin/Economics of Reedbed Management in the UK.pdf.

ELP & Ash, N. (2010) *New Opportunities for the Sustainable Management of Fens: Reed Pelleting, Composting and the Productive Use of Fen Harvests*. Final Report, Ecology, Land and People (ELP) for the Broads Authority, Norwich, UK, 66 pp.

FAO (1985) *Weed Control and Utilization of Aquatic Control and Utilization of Aquatic Plants of Lake Edku and Barsik Fish Farm - Egypt*. Report for Project TCP/EGY/4506 based on the work of G. Sainty, Food and Agriculture Organization of the United Nations, Rome. Online at: http://www.fao.org/docrep/field/003/R7236E/R7236E00.htm.

FNR (2012a) *Dämmstoffe aus nachwachsenden Rohstoffen* (*Insulation from Renewable Resources*). Fachagentur für nachwachsende Rohstoffe (FNR), Gülzow-Prüzen, Germany, 72 pp. (in German).

FNR (2012b) *Nachwachsende Rohstoffe in der Industrie* (*Renewable Raw Material in the Industry*). Fachagentur für nachwachsende Rohstoffe (FNR), Gülzow, Germany, 88 pp. (in German).

Frick, A., Steffenhagen, P., Zerbe, S., Timmermann, T. & Schulz, K. (2011) Monitoring of the vegetation composition in rewetted peatland with iterative decision tree classification of satellite imagery. *Photogrammetrie - Fernerkundung - Geoinformation*, 2011(3), 109–122.

Graneli, W. (1984) Reed *Phragmites australis* (Cav.) Trin. ex Steudel as an energy source in Sweden. *Biomass*, 4, 183–208.

Graneli, W. (1990) Standing crop and mineral content of reed, *Phragmites australis*, in Sweden - Management of reed stands to maximize harvestable biomass. *Folia Geobotanica*, 25(3), 291–302.

Gryseels, M. (1989) Nature management experiments in a derelict reedmarsh. I: Effects of winter cutting. *Biological Conservation*, 47(3), 171–193. doi:10.1016/0006-3207(89)90063-3.

Guesewell, S. & Kloetzli, F. (2000) Assessment of aquatic and terrestrial reed (*Phragmites australis*) stands. *Wetlands Ecology and Management*, 8(6), 367–373.

Häkkinen, J. (2007) Traditional use of reed. In: Ikonen, I. & Hagelberg, E. (eds.) *Read Up On Reed!*, Southwest Finland Regional Environment Centre, Turku, Finland, 62–72.

Hansmann, P. (2008) *"They Call Them Golden Sticks"- Socio-economic Explorations Around the Commodity of Reed*. Master thesis, Wageningen University, The Netherlands.

Hansson, L.A. & Graneli, W. (1984) Effects of winter harvest on water and sediment chemistry in a stand of reed (*Phragmites australis*). *Hydrobiologia*, 112(2), 131–136.

Hansson, P.A. & Fredriksson, H. (2004) Use of summer harvested common reed (*Phragmites australis*) as nutrient source for organic crop production in Sweden. *Agriculture, Ecosystems & Environment*, 102(3), 365–375.

Haslam, S.M. (2009) *The Reed*. Updated edition, British Reed Growers Association, Brown & Co., Norwich, UK, 38 pp.

Haslam, S.M. (2010) *A Book of Reed:* (Phragmites australis *(Cav.) Trin. ex Steudel, Formerly* Phragmites communis *Trin.*). Forrest Text, Cardigan, GB, 254 pp.

Haslam, S.M., Klötzli, F., Sukopp, H. & Szczepański, A. (1999) The management of wetlands. In: Westlake, D.F., Květ, J. & Szczepański, A. (eds.) *The Production Ecology of Wetlands*, Cambridge University Press, Cambridge, 405–464.

Hawke, C.J. & Jose, P.V. (1996) *Reedbed Management for Commercial and Wildlife Interests*. Management Guides Series, RSPB, Sandy, 212 pp.

Hedelin, B. (2001) *The Effect of Reed Harvesting on the Phosphorus Budget of Lake Wuliangsuhai, P.R. of China*. Master thesis, Royal Institute of Technology (KTH), Stockholm, Sweden.

Hiss Reet (2013) Dachreet (Thatching reed). Online at: http://www.hiss-reet.de/produkte/dachreet/allgemein.html.

Hodge, I. & Mcnally, S. (2000) Wetland restoration, collective action and the role of water management institutions. *Ecological Economics*, 35, 107–118.

Holzmann, G. & Wangelin, M. (2009) *Natürliche und pflanzliche Baustoffe: Rohstoff - Bauphysik - Konstruktion* (*Natural and Plant Construction Materials: Raw Materials - Building Physics -*

Construction), Vieweg & Teubner, Wiesbaden, 225 pp. (in German).

Huhta, A. (2007) To cut or not to cut? - The relationship between Common Reed, moving and water quality. In: Ikonen, I. & Hagelberg, E. (eds.) *Read Up On Reed!*, Southwest Finland Regional Environment Centre, Turku, Finland, 30–38.

Huhta, A. (2009) Decorative or Outrageous - The significance of the Common Reed (*Phragmites australis*) on water quality. *Comments from Turku University of Applied Sciences*, 48, 1–33.

Hurter, R.W. (2001) *Nonwood Plant Fiber Characteristics*. TAPPI 1997 Nonwood Fibers Short Course Notes. Online at: http://www.hurter consult.com.

Iital, A., Klõga, M., Kask, Ü., Voronova, V. & Cahill, B. (2012) Reed harvesting. In: Schultz-Zehden, A. & Matczak, M. (eds.) *Compendium: An Assessment of Innovative and Sustainable Uses of Baltic Marine Resources*, Maritime Institute in Gdansk, Gdansk, 103–124.

Kask, Ü. (2011) Reed as bio-energy: opportunities to use it in boiler-houses and as biogas source. Seminar *Reed for Bio-energy and Construction*, 11.03.2011, Piikiö/Kaarina, Finland. Online at: http://www.roostik.ee/ettekanded/Ulo%20Kask_11.3.2011_Reed_Seminar_Tuorla.pdf.

Kask, Ü., Kask, L. & Paist, A. (2007) Reed as energy resource in Estonia. In: Ikonen, I. & Hagelberg, E. (eds.) *Read Up On Reed!*, Southwest Finland Regional Environment Centre, Turku, Finland, 102–114.

Kirs, V. (2011) Reed harvesting and latest machinery development in Estonia. *Cofreen Project Midterm Seminar 8.9.2011*. Online at: http://www.cofreen.eu/index.php/en/events/past/9-events/presentations/26-veiko-kirs-reed-harvesting-and-latest-machinery-development-in-estonia-892011-midterm-seminar.

Kitzler, H., Pfeifer, C. & Hofbauer, H. (2012) Combustion of reeds in a 3 MW district heating plant. *International Journal of Environmental Science and Development*, 3(4), 407–411.

Komulainen, M., Simi, P., Hagelberg, E., Ikonen, I. & Lyytinen, S. (2008) *Reed Energy - Possibilities of Using the Common Reed for Energy Generation in Southern Finland*. Reports from Turku University of Applied Sciences, 67, 81 pp. Online at: http://julkaisut.turkuamk.fi/isbn 9789522160355.pdf.

Kronbergs, E., Kaktis, A., Smits, M., & Nulle, I. (2006) Biomass condition for solid biofuel compositions. In: Barz, M. & Ahlhaus, M. (eds.) *Use of Bioenergy in the Baltic Sea Region*, Proceedings 2nd International Baltic Bioenergy Conference, 02–04 November 2006, Fachhochschule Stralsund, Germany, 83–92.

Kusler, J.A. & Kentula, M.E. (eds.) (1990) *Wetland Creation and Restoration: The Status of the Science*. Island Press, Washington DC, 616 pp.

Květ, J. & Ostrý, I. (1988) Mineral nutrient accumulation in the principal plant communities of the Rožmberk fishpond littoral. In: Hroudová, Z. (ed.) *Littoral Vegetation of the Rožmberk Fishpond and its |Mineral Nutrient Economy*, Studie ČSAV 9, Academia nakladatelství Československé akademie věd, Prague, 108 pp.

Mcbride, A., Diack, I., Droy, N., Hamill, B., Jones, P., Schutten, J., Skinner, A. & Street, M. (2011) (eds.) *The Fen Management Handbook*, Scottish Natural Heritage, Perth, Scotland, 13 pp.

Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-being: Wetlands and Water Synthesis*. World Resources Institute, Washington DC, 80 pp.

Mills, S. (2013) Sustainable management of reedbeds for conservation. Presentation at *Reed as a Renewable Resource (RRR)*, 14–16 February 2013, University of Greifswald, Germany. Online at: http://www.rrr2013.de/p/contributions.html.

Ostendorp, W. (1990) Die Ursachen des Röhrichtrückgangs am Bodensee-Untersee (Causes of reed reduction at Lake Constance). *Carolinea*, 48, 85–102 (in German).

Ostendorp, W. (1993) Schilf als Lebensraum (Reed as a habitat). Artenschutzsymposium Teichrohrsinger, *Beihefte zu den Veröffentlichungen für Naturschutz und Landschaftspflege in Baden-Württemberg* (*Supplements to the Publications for Nature Conservation and Landscape Protection in Baden-Württemberg*), 68, 173–280 (in German).

Ostendorp, W. (1995) Impact of winter reed harvesting and burning on the nutrient economy of reed beds. *Wetlands Ecology and Management*, 3, 233–248.

Ostendorp, W. (1999) Management impacts on stand structure of lakeshore *Phragmites* reeds. *International Review of Hydrobiology*, 84, 33–47.

Paist, A., Kask, Ü. & Kask, L. (2003) Composition of reed mineral matter and its behaviour at combustion. Poster, Reed Seminar, 21–22 August 2003, Salo, Sininen Talo, Finland. Online at: http://www.pilliroog.ee/Poster.pdf.

Pöyry (2006) *China: Technical Assistance for the Sustainable Development of the Non-wood Pulp and Paper Industry. Review of Fiber and Raw Material Availability by Province*. Technical Report, Module 3, Pöyry Forest Industry (Shanghai) Co. Ltd., 72 pp.

Rauvola, R. (2007) *Launch and Marketing of Thatched Roofs in Nauvo*. Turku University of Applied Science.

Reichel, F. (2013) Bauschilf (Construction reed). Online at: http://www.bauschilf.at/produkte.htm (in German).

Rodewald-Rudescu, L. (1958) Schilfrohr und Fischkultur im Donaudelta (Reed stalk and fish culture in the Danube Delta). *Archiv für Hydrobiologie*, 54(3), 303–339 (in German).

Rodewald-Rudescu, L. (1974) *Das Schilfrohr* Phragmites communis *Trinius* (*The Reed Stalk* Phragmites communis *Trinius*). Die Binnengewässer (Inland Waters), Vol. XXVII, E. Schweizerbart'sche Verlagsbuchhandlung (Nägele u. Obermiller), Stuttgart, 302 pp. (in German).

Saltonstall, K. (2002) Cryptic invasion by a non-native genotype of *Phragmites australis* into North America. *Proceedings of the National Academy of Sciences, USA*, 99, 2445–2449.

Sarafraz, S., Mohammad, T.A., Norr, M.J. & Laight, A. (2009) Wastewater treatment using horizontal subsurface flow constructed wetland. *American Journal of Environmental Sciences*, 5(1), 99–105. Online at: http://www.scipub.org/fulltext/ajes/ajes5199-105.pdf.

Schaatke, W. (1992) *Das Reetdach - Natürliches Wohnen unter sanftem Dach - Von der Uhrzeit bis heute (The Reed Roof - Natural Living Under a Soft Roof - From Primeval Times Until Today)*. Christians Verlag, Hamburg, 264 pp. (in German).

Schäfer, A. (1999) Schilfrohrkultur auf Niedermoor - Rentabilität des Anbaus und der Ernte von *Phragmites australis* (Reed cultivation on fens - Feasibility of growing and harvesting of *Phragmites australis*). *Archiv für Naturschutz and Landschaftsforschung*, 38, 193–216 (in German).

Schäfer, A. & Wichtmann, W. (1999) Sanierte Niedermoore und weitergehende Abwasserreinigung (Restored fens and largely sewage treatment). *Archiv für Naturschutz und Landschaftsforschung*, 38, 315–334 (in German).

Schuster, J. (1985) Schilfverwertung - Erntestudie (Reed utilization - harvesting study). *Grosina: AGN-Forschungsprogramm und seine Umsetzung im Raum*, 586–609 (in German).

Stenman, H. (2008) *Reed Construction in the Baltic Sea Region*. Reports from Turku University of Applied Sciences, 68 pp.

Sumalowitsch, E. (2011) Rohrwolf. Schilfprodukte aus der Nationalparkregion Neusiedler See (Rohrwolf. Reed products from the national park region Lake Constance) (in German). Online at: www.rohrwolf.com.

Szijártó, N., Kádár, Z., Varga, E., Thomsen, A.B., Costa-Ferreira, M. & Réczey, K. (2009) Pretreatment of reed by wet oxidation and subsequent utilization of the pretreated fibers for ethanol production. *Applied Biochemistry and Biotechnology*, 155(1–3), 386–396.

Tarr, J.A., Rooyen, M.W. & Bothma, J.D.P. (2004) The response of *Phragmites australis* to harvesting pressure in the Muzi swamp of the Tempe elephant park, South Africa. *Land Degradation & Development*, 15, 487–497.

Tewksbury, L., Casagrande, R., Blossey, B., Häfliger, P. & Schwarländer, M. (2002) Potential for biological control of *Phragmites australis* in North America. *Biological Control*, 23, 191–212.

Thesiger, W. (1964) *The Marsh Arabs*. Penguin Books, Harmondsworth, Middlesex, England.

Thevs, N., Zerbe, S., Gahlert, E., Mijit, M. & Succow, M. (2007) Productivity of reed (*Phragmites australis* Trin. ex Steud.) in continental-arid NW China in relation to soil, groundwater, and land-use. *Journal of Applied Botany and Food Quality*, 81(1), 62–68.

Tutt, M. & Olt, J. (2011) Suitability of various plant species for bioethanol production. *Agronomy Research Biosystem Engineering,* Special Issue 1, 261–267.

UNEP (2001) Partow, H. *The Mesopotamian Marshlands: Demise of an Eosystem*. Early Warning and Assessment Technical Report, UNEP/DEWA/TR.01-3 Rev. 1, Division of Early Warning and Assessment, United Nations Environment Programme, Nairobi, Kenya, 58 pp. Online at: http://www.grid.unep.ch/activities/sustainable/tigris/mesopotamia.pdf.

Van der Putten, W.H. (1997) Die-back of *Phragmites australis* in European wetlands: An overview of the European research programme on reed die-back and progression (1993–1994). *Aquatic Botany*, 59(3–4), 263–275.

Van Der Sluis, T., Rii, O., Poppens, R. & Lesschen, J.P. (2013) Reed resources in Poltava Oblast, Ukraine: biodiversity conservation and bioenergy production. Presentation at *Reed as a Renewable Resource (RRR)*, 14–16 February 2013, University of Greifswald, Germany. Online at: http://www.rrr2013.de/p/contributions.html.

Vymazal, J. (2010) Constructed wetlands for wastewater treatment. *Water*, 2, 530–549. Online at: http://www.mdpi.com/2073-4441/2/3/530/pdf.

Wayman, M. (1973) *Guide for Planning Pulp and Paper Enterprises*. Food and Agriculture Organization Forestry and Forest Products Studies, No. 18, 379 pp.

White, G. (2009) *The Future of Reedbed Management*. Information and Advice Note, Version 7, July 2009, RSPB, Sandy, 11 pp. Online at: http://www.rspb.org.uk/Images/Reedbed_management_tcm9-255077.pdf.

Wichmann, S. & Wichtmann, W. (2009) Bericht zum Forschungs- und Entwicklungsprojekt-Energiebiomasse aus Niedermooren (ENIM) (*Report on the Research and Development Project Energy Biomass from Fens*). Institut für Dauerhaft Umweltgerechte Entwicklung der Naturräume der Erde (DUENE), Greifswald, Germany, 190 pp. (in German).

Wichtmann, W. (2008) Standortgerechte Bewirtschaftung wiedervernässter Moore - Paludikultur (Site-adapted management of re-wetted fens - paludiculture). Seminar *Energetische Biomassenutzung in M-V-Folgen für die Landschaft und alternative Nutzungskonzepte*, Güstrow, 05 February 2009, LUNG Mecklenburg-Vorpommern (in German). Online at: http://www.lung.mv-regierung.de/dateien/lls_programm_09_02_05.pdf.

Wichtmann, W. & Joosten, H. (2007) Paludiculture: peat formation and renewable resources from rewetted peatlands. *IMCG Newsletter*, 2007-3, 24–28. Online at: http://paludiculture.botanik.uni-greifswald.de/documents/paludiculture_peat_formation_and_renewable_resources_from_rewetted_peatlands.pdf.

Wild, U. (2001) Cultivation of *Typha* spp. in constructed wetlands for peatland restoration. *Ecological Engineering*, 17(1), 49–54.

Ympäristö Ojansuut Oy (2011) Introduction to harvesting and harvesting equipment. Online at: http://www.hameenlinna.fi/pages/399506/Ympar isto-Ojansuut_2012_Tuulos.pdf.

Zerbe, S. & Thevs, N. (2011) Restoring central Asian floodplain ecosystems as natural capital and cultural heritage in a continental desert environment. In: Hong, S.-K., Wu, J., Kim, J.-E. & Nakagoshi, N. (eds.) *Landscape Ecology in Asian Cultures*, Ecological Research Monographs, Springer, Tokyo Dordrecht Heidelberg London New York, doi:10.1007/978-4-431-87799-8, 277–297.

Zhu, Z., Jiang, C., Zhong, M. & Huafu, W. (1998) *Status, Trends and Prospects for Non-wood and Recycled Fibre in China*. Working Paper No. APFSOS/WP/35, Asia-Pacific Forestry Sector Outlook Study, FAO Forestry Policy and Planning Division, Rome, Regional Office for Asia and the Pacific, Bangkok, 37 pp.

Submitted 31 May 2013, revision 12 Aug 2013
Editor: Olivia Bragg

Author for correspondence:
Jan Felix Köbbing, Ernst Moritz-Arndt University Greifswald, Institute of Botany and Landscape Ecology, Soldmannstr. 15, 17487 Greifswald, Germany
Tel.: +49 (0) 3834-864137, Fax: +49-(0) 3834-86-4114, E-mail: jan.koebbing@stud.uni-greifswald.de