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The use of conservation biomass feedstocks as potential bioenergy resources in the United Kingdom

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HIGHLIGHTS

- Estimated the amount of biomass available from conservation areas in the UK.
- Examined the combustion properties of the species available.
- Studied the combustion of wood logs, Reeds and charcoal in a stove.
- Most of the conservation biomass could be used as a domestic fuel.

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ABSTRACT

A number of countries have introduced energy policies to reduce the emission of carbon dioxide which, in the case of bio-heat, has resulted in increased use of small wood burning stoves and boilers, particularly in Europe. There are issues surrounding the supply of sustainable wood feedstock, prompting a desire to utilise local biomass resources. This includes biomass generated through the management of natural woodlands in nature reserves and conservation areas. These management practices can also extend to other areas, such as raised bog wildernesses and estuary Reed beds. We term the biomass from this resource as conservation biomass. This study is concerned with the viability of this resource as a fuel within the United Kingdom, and combustion tests were carried out using a small domestic stove. It was concluded that there is as much as 500 kt y^{-1} that could be used in this way.

1. Introduction

European policies and targets for reducing emissions of carbon dioxide have led to an increase in the use of biomass in stoves and boilers throughout Europe. As a consequence, there are potential problems surrounding the availability of sustainable supplies of wood feedstock in Europe. With the requirement of large quantities of imported biomass for electricity generation in the UK (DUKES, 2015), coupled with the desire to achieve security of supply, there is a growing necessity to use local biomass resources. Sustainable bio-heat remains a challenge in many European countries. Thus, small-scale combustion applications may have to be increasingly used, although with appropriate attention to environmental and sustainability issues (Gerssen-Gondelach et al., 2014). In 2014, the UK used approximately 4.9 Mt of fuel wood (DUKES, 2015) of which 354 kt of wood pellets and briquettes were produced using locally grown woods and recycled Grade A wood (Forestry Statistics, 2015). For small scale bio-heat, alternative feedstocks from local sources are an attractive option for both consumer and supplier; however, there are issues about where this is sourced. Particular areas of the countryside are designated with a protected status to ensure that their high value nature and wildlife is not altered or destroyed. Special Areas of Conservation (SACs) and Special Protection Areas (SPAs) within the UK represent a significant expanse of land, covering a range of environments such as forests, moorlands and wetlands.

Although the UKs woodlands have been historically managed, a declining use of wood products has resulted in many forested areas becoming neglected, negatively impacting upon biodiversity and their long-term ecology (Read et al., 2009). The biodiversity of an area can be preserved through a passive management approach, but inaction can result in the suppression of important habitat values and, as a result, can be detrimental to conservation. Therefore, active management, such as small scale felling within previously managed woodlands, or the removal of invasive species, can

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become an environmental necessity. UK sites with significant nature conservation value, such as Sites of Special Specific Scientific Interest (SSSIs), are currently undermanaged, with less than half of the reported areas undergoing positive conservation management. Consequently, management practices hold a great environmental importance (Bernes et al., 2014; Ditlhogo et al., 1992; DEFRA, 2014).

In addition to the existing unmanaged woodland located within the UK, there are other conservation areas that require regular upkeep, namely Reed beds, which are predominantly located on the UK's wetlands. In total, there are 5 kha of Reed beds located within the UK, which require intensive management to safeguard their preservation. The regular cutting of the Reeds is necessary ensuring the correct conditions for rare breeding and migratory birds are achieved, thus improving biodiversity. Cutting the Reeds is a common management practice; however they are often openly burned (Ditlhogo et al., 1992). The inefficient combustion is associated with high emissions of pollutants (Lemieux et al., 2004). In addition, open burning releases CH_4, N_2O and carbonaceous aerosols which are important drivers of climate change (Jacobson, 2014). The practice of harvesting Reeds over a prolonged period of time increases the density of the grown Reeds, but also decreases their shoot thickness (Cowie et al., 1992). Estimates of the above-ground biomass production in the existing literature indicates that Reeds can produce 14–15 t ha^{-1} annually, suggesting that undertaking the required management practices of Reed bed conservation could result in a potentially significant source of local biomass resource (Kuhlman et al., 2013; Kobbing et al., 2014). Other estimates indicate that the productivity in wetlands can be as low as 10% of this figure, similarly in grasslands it can be as low as 6 t ha^{-1} (Wichtmann and Schafer, 2007) while coppiced woodlands can achieve a productivity of 2–5 t ha^{-1} (Hytonen and Issakainen, 2001). As a result, the variability in conservation sites gives rise to a wide variety of different biomass forms that could be utilised in the production of bioheat (Kuhlman et al., 2013; Kask et al., 2013/2014; Wichtmann et al., 2014; Ranjitkar et al., 2014; Sommersacher et al., 2015). Consequently, conservation management practices can produce a considerable amount of biomass wastes that are currently disposed of by open burning. This product is therefore available on a sustainable basis as a by-product of management actions aimed at conserving habitats and their incumbent wildlife. However the amount available of this biomass is dependent upon the proportion left in situ to maintain the health of the habitat, a figure which can vary from 10% to 100% (Welfe et al., 2014). This data enables us to estimate an approximate value for the availability of 'conservation' biomass later in this paper.

Thus this study aims to examine the potential and fuel characterisations for some of these biomass feedstocks produced from conservation management processes. The resources considered include a variety of native broadleaved wood species and harvested common Reeds, sourced from Areas of Outstanding Natural Beauty (AONB), SSSIs, and dedicated nature reserves.

Table 1
Areas of Special Conservation and Special Protection in the UK.

Region	SAC		SPA	
	No. sites	Area (ha)	No. sites	Area (ha)
England	230	1,068,476**	81	1,054,353
Scotland	236	939,727**	152	1,205,988
Wales	85	590,864	17	172,149
England/Scotland*	3	112,564	1	43,637
England/Wales*	7	95,132	3	209,247
Northern Ireland	54	85,831**	16	114,052
Total	615	2,892,594	270	2,799,426

* Areas that cross the border,
** Includes Sites of Community Importance (SCIs).

2. Materials and methods

2.1. Source of the fuels

The sources of all of the conservation fuel in the UK are set out in Table 1. We have studied typical samples in particular locations described below and the samples studied are listed in Table 2. In addition to the raw (unprocessed) biomass samples, charcoal (biochar) produced from the peat grown Willow has been investigated, whilst both biochars and briquettes had been produced using the harvested Reed. The separate carbonising (charring) and briquetting processes were undertaken for us using traditional heated kiln methods.

The Humberhead Peatlands National Nature Reserve is considered the largest area of raised bog wilderness in lowland Britain and is located in South Yorkshire. The site is classified as both a SAC and a SPA due to its habitat and consequent role as a breeding

Table 2
Description of samples used in the study.

Type	Sample name	Site type	Sample type
Woods	Ash (*Fraxinus excelsior*)	Woodland (AONB[3])	Heartwood, bark
	Birch (*Betula pendula*)	Peat (SAC[1])	Heartwood, bark, homogenised
	Hazel (*Corylus avellana*)	Woodland (AONB[3])	Heartwood, bark
	Willow (*Salix caprea*)	Peat (SAC[1])	Homogenised
	Willow (*Salix caprea*)	Floodplain (SSSI[2])	Heartwood, bark
	Willow SRC (*Salix viminalis*)	Short rotation coppice	Homogenised
	Willow billets (*Salix* spp)	Tidal estuary	Heartwood, bark
	Willow char 1	Peat (SAC[1])	Traditional thermal kiln
	Willow char 2	Peat (SAC[1])	Traditional thermal kiln
Herbaceous	Reed raw (*Phragmites australis*)	Tidal estuary	Common Reed as harvested
	Reed char 1	Tidal estuary	Traditional thermal kiln
	Reed char 2	Tidal estuary	Traditional thermal kiln
	Reed washed	Tidal estuary	Lightly washed in room temp. distilled water
	Straw raw (*Triticum* spp)	Agricultural land	Wheat straw as harvested
	Washed straw	Agricultural land	Lightly washed in room temp. distilled water
	Peat turf	Peatland in Ireland	Cut bog peat, air dried

[1] Special Area of Conservation.
[2] Site of Specific Scientific Interest.
[3] Area of outstanding natural beauty.

site. Both the peat grown Willow and Silver Birch samples were sourced from a natural regenerated woodland area, which spans 200 ha. As the site has developed naturally, there is no uniformity in the tree ages, ranging from young saplings to well established specimens. Of the samples analysed, those taken from this site were the stem wood of juvenile Willow and Silver Birch trees. The woodland is established on peat soil, in an area that has historically undergone extensive peat extraction for use as a fuel. The composition of peat is dependent upon an array of environmental conditions. As a result, peats tend to have higher contents of N, S, Al and Ca, whilst the Ca content can vary greatly from site to site.

Alternatively, the Ash and Hazel wood samples, as described in Table 2, were sourced from an AONB. Their extraction was part of a thinning regime to improve access throughout the woodland, resulting in the samples originating from the stem wood of older, more established trees. The Willow samples, sourced from the Floodplain and Tidal Estuary sites, were produced following pollarding and the removal of branches as a management tool to help maintain the local habitat.

The Reeds were sourced from Blacktoft Sands as part of a regular, mechanised cutting regime of the Reed beds. This process is required to maintain an appropriate habitat for the conservation of the visiting birds. Common Reed grows predominantly in saturated marsh areas. This means that the surrounding environmental conditions, such as nutrient availability and the depth and salinity of the water, impact the growth and composition of the biomass. Other than the Reed briquettes and chars, the biomass samples used in this research were delivered with no additional processing following harvesting. On receipt of the harvested samples, they were stored in a covered, outdoor fuel store in separate, breathable containers.

2.2. Fuel characterisation

Prior to analysis, the fuels and chars were milled using a Retsch SM100 cutting mill and a Retsch PM100 ball mill before being milled to <90 μm in a SPEX 6770 cryogenic grinder to produce a homogeneous flour from each fuel. This type of equipment was used because of the high silica content of the Reeds. The bark was separated from the majority of the wood fuels and analysed separately. However in the case of Birch and Willow, the fuel logs were homogenised as received, including the bark.

Proximate analysis of the samples was undertaken using thermal gravimetric analysis (TGA) using a TA Thermogravimetric Analyzer Q5000 and using 3 mg sample sizes and standard procedures. The temperature was raised to 105 °C (to give the moisture loss), then 900 °C (to give the loss of volatile matter) in nitrogen, before being cooled to 550 °C and combusted in air, to give the ash content. In addition to calculating the proximate values, TGA also gives a detailed overview of the thermochemical behaviour during the process; this data was obtained from single runs.

The Ultimate analysis (C, H, N) was carried out using a CE Instrument Flash EA1112, the experiments being carried out in duplicate; the oxygen was calculated by difference as given in BS ISO 17247. The higher heating value (HHV) was calculated using data from the Ultimate analysis by means of the following equation (Friedl et al., 2005), on a dry ash free basis:

$$\mathrm{HHV} = \frac{3.55\mathrm{C}^2 - 232\mathrm{C} - 2230\mathrm{H} + 51.2(\mathrm{C} \times \mathrm{H}) + 131\mathrm{N} + 20600}{1000}$$

where C, H, N are the mass% of carbon, hydrogen and nitrogen, respectively, all on a dry basis. The inorganic content of the fuels was determined after digestion via atomic absorption spectroscopy (AAS), using a Varian 240 fs AAS. The chlorine contents of the fuels were determined using a single mercuric nitrate titration.

2.3. Pyrolysis analysis

Pyrolysis gas chromatography mass spectrometry (Py–GC–MS) was performed using a CDS 5000 series pyrolyser coupled to a Shimadzu 2010 GC–MS. Approximately 2 mg of biomass fuel was pyrolysed at 500 °C. The products were separated on an Rtx 1701 60 m capillary column, 0.25 id, 0.25 μm film thickness, using a temperature program of 40 °C, a hold time of 2 min, ramped to 250 °C, and a hold time of 15 min. Assignments of the main peaks were made from mass spectral detection by using a NIST05a MS library. Only the peaks with a high degree of certainty (over 90%) are included.

2.4. Domestic stove combustion tests

A Waterford Stanley Oisin Multifuel stove was used to study combustion of all the fuels is shown in Fig. 1 and is rated as having a maximum thermal output of 5.7 kW and an efficiency of 79%. There is one primary air supply which is manually controlled via a damper, which is shown in Fig. 1. The general arrangement of the stove and measurement equipment was in accordance with BS EN 13240, as described previously (Mitchell et al., 2015). The stove was mounted on an electronic scale and sampling ports were installed in the 125 mm diameter flue at a height of 1.43 m.

One batch of a known mass of fuel was tested on each run, with no re-loading. The total energy content of each load was fixed at 25 ± 5 MJ. The damper was adjusted to give approximately 150% excess air, as recommended by the appliance manufacturer, which was kept constant for all fuels. Flue gas composition was monitored using a Testo 340 analyser for O_2, CO_2, CO, NO, NO_2 and flue gas temperature. Particulate matter (PM) was determined using a gravimetric method in which 25 L of flue gas was passed through two Whatman GF/F glass microfibre (0.7 μm) filter papers held at 70 °C. Samples were taken at 10 min intervals in order to monitor the change in emissions over time. The emissions factors were calculated in g per kg of fuel burned and are reported as the arithmetic mean of three runs.

Scanning electron microscope (SEM) analysis was carried out using a Hitachi SU8230 scanning electron microscope. Particle

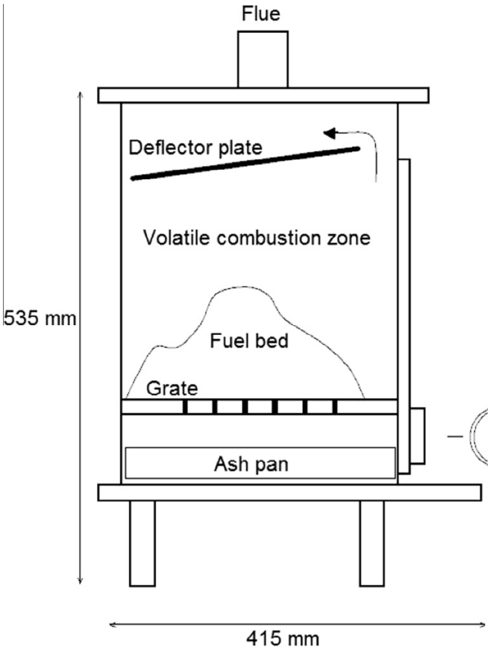

Fig. 1. Diagram of the stove.

Table 3
Ultimate (daf), proximate (db), HHV and inorganic composition (db) of the fuels.

Sample	C %daf	H %daf	N %daf	O %daf	Volatile %db	FC %db	Ash %db	HHV MJ/kg db	K ppm db	Fe ppm db	Na ppm db	Mg ppm db	Mn ppm db	Al ppm db	Ca ppm db	Cl % db
Ash bark	50.5	5.9	0.6	42.4	85.6	5.3	9.1	18.21	2215	78	260	977	44	664	43,813	0.06
Ash wood	47.7	6.1	0.1	46.0	90.0	9.5	0.5	18.84	956	0	201	365	2	847	1876	0.04
Birch bark	54.6	5.9	0.7	38.3	80.6	17.8	1.6	21.77	2235	172	98	687	290	332	4313	0.09
Birch wood	45.8	5.7	0.3	48.1	92.5	7.0	0.5	18.02	740	62	185	833	129	1155	3123	0.05
Birch (H)	48.4	6.5	0.2	44.7	91.2	7.4	1.4	19.04	621	25	905	504	140	142	1105	0.00
Hazel bark							10.2	15.59	1531	49	630	605	131	995	35,805	0.17
Hazel Wood	48.1	6.1	0.3	45.3	91.2	7.4	1.4	18.83	680	26	183	353	23	521	2443	0.09
Willow bark 1	53.4	5.5	1.8	38.7	73.3	20.0	6.7	19.90	6666	0	104	898	5	516	9036	0.11
Willow wood 1	45.8	5.8	0.2	48.0	89.0	10.2	0.8	18.00	3295	24	446	743	7	577	3046	0.06
Willow bark 2	47.6	5.3	1.1	45.5	74.9	19.9	5.2	17.94	5247	79	474	2465	135	817	14,213	0.16
Willow wood 2	48.6	6.1	0.2	45.0	89.9	9.1	1.0	19.12	1063	0	383	469	15	482	1911	0.11
Willow SRC	48.4	6.3	0.4	44.6	88.2	9.7	2.1	18.90	2223	51	677	587	25	225	5487	0.00
Willow (H)	47.6	6.3	0.5	45.2	88.1	9.4	2.5	18.51	2656	52	851	851	10	95	6773	0.07
Willow char 1	90.2	2.3	0.5	6.9	11.5	84.5	4.0	32.33	5480	51	745	1780	88	339	13,445	0.25
Willow char 2	76.3	4.6	0.9	18.0	38.6	56.2	5.2	29.26	4840	26	1291	1455	271	160	13,869	0.26
Reed briquette	45.4	5.7	0.5	33.9	79.5	6.2	14.3	18.02	2003	126	9841	1523	58	404	2643	0.18
Reed char 1	80.0	1.6	1.0	4.2	11.0	75.9	13.1	28.10	2294	283	4227	1121	145	510	1189	0.17
Reed char 2	73.6	2.2	1.0	8.6	12.1	73.5	14.4	26.48	1910	331	3859	1261	153	454	1360	0.12
Reed raw	44.9	6.1	0.4	43.8	85.3	10.1	4.6	17.82	576	50	1954	601	45	391	774	0.09
Reed washed									391	43	3913	783	35	561	235	0.11
Straw	44.3	6.2	0.5	43.0	82.3	12.0	5.7	17.62	6431	26	1589	717	44	369	3626	0.06
Straw washed	43.5	6.1	0.4	42.3	81.2	11.3	7.5	17.25								0.11
Peat turf	61.3	2.4	2.2	29.1	67.0	31.3	1.7	26.02	137	9392	1395	1955			25,250	0.29

composition was analysed by energy dispersive spectroscopy (EDS) using an Oxford Instruments X-Max silicon drift detector with an 80 mm^2 crystal. Samples were iridium coated.

Experiments were not carried out with blends of the different fuels. But it is possible to estimate emissions of NO_x and PM on the basis of an 'additivity' rule, that is, the emission of the blend is approximately the sum of the emissions of the individual components on a pro rata basis (Sommersacher et al., 2015; Mitchell et al., 2015).

3. Results and discussion

3.1. Fuel characterisation

The proximate, ultimate, and higher heating value (HHV) results for a number of fuels, woods, bark, Reeds, a briquetted Reed, straws and biochars from woods and Reeds are given in Table 3. These show a large variation in their properties. Compared to the raw fuel, the briquetted Reed showed a lower volatile content and a higher ash content which is probably due to the processing conditions.

Unlike the Reed char samples, the two Willow chars significantly differed from one another due to different reaction conditions. A higher proportion of the volatiles (38.6%) remained in char 2, compared with Willow char 1 (11.5%) and the two Reed chars (11.0% and 12.1%). The carbonisation process increases the HHVs of the conservation biomass feedstocks, as shown in Table 3, producing results comparable to bituminous coal. Significant differences were also observed between the wood and bark samples. In all cases, the bark contained higher values for elemental and fixed carbon, nitrogen and HHV than the heartwood. The peat turf sample was found to contain high levels of both moisture (>30%) and fuel nitrogen (2.2%). The heartwood samples of the peat-grown Willow (Thorne Moor) contained 0.5% nitrogen, whereas the Willow analysed from non-peated sites contained 0.2–0.4% nitrogen. This highlights the importance of the nitrogen content of the soil on the biomass composition.

The variation in fuel types is demonstrated by the Van Krevelen diagram shown in Fig. 2. Of particular note is the fact that the barks are more carbonaceous, that is more aromatic, than the woods. These have a higher HHV when considered on a daf basis. On average the bark content was about 13 wt%.

The differences in the inorganic content of the fuels are shown in Table 3. The herbaceous feedstocks generally contained higher levels of Na, Mg and Cl whereas the wood fuels generally contained more K and Ca. The inorganic content of the Reed samples are principally affected by their growing conditions in brackish estuarine water; the Reed briquette had a higher level of sodium compared to both the untreated Reed and the Reed chars. Both of the Reed chars contained significantly higher trace elements. The exceptions to this were the Reed briquettes which contained high levels of Na, Mg and Ca. It is believed that this is due to possible contamination from binding agents during the briquetting process. The briquettes were produced from biomass sourced from the same site as the raw Reeds analysed within this study. Additionally, washing the Reed for 15 min was found to reduce the content of K, Fe, Mn and Ca.

The barks contained substantially higher levels of all inorganics, particularly Ca and K. The existence of metallic elements within wood can often be directly related to the surrounding environment of the tree, with its roots often absorbing the existing available inorganics, before distributing them throughout the remainder of the tree. Fe is found at higher concentrations in the bark, but levels were much lower than the other inorganics. Bark can be contaminated by inorganic impurities, such as soil and sand. Calcium was

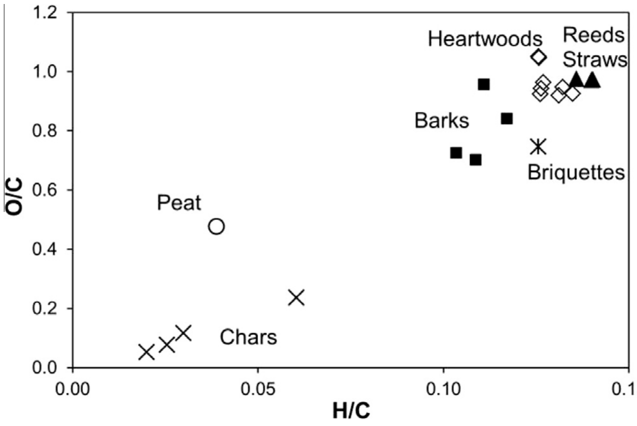

Fig. 2. Van Krevelen diagram for the fuels.

found to be the dominant inorganic species in the analysed wood fuels, particularly prominent in the bark of the ash and hazel samples. These samples were both sourced from the same woodland area, suggesting that the sites soil may have been calcium rich. Interestingly, in both the ash and hazel samples the calcium content of the heartwood was comparable to the other wood species analysed; however the calcium concentrations within their bark is considerably higher.

Similar to the Reed, the carbonisation process was found to concentrate the inorganics in the Willow chars. The example peat turf sample used was found to contain relatively high levels of Fe, Na and Ca, which suggests that the peat-grown wood species assimilate particular inorganics during growth. This could mean that potential combustion issues related to the inorganic content of peat could also be witnessed when using peat-grown wood fuels, similarly to that of nitrogen content and the consequent emissions of NO_x.

The thermogravimetric data obtained for the woods, barks and two wood charcoals are shown Fig. 3(a) and the data for the straws, Reeds and chars are shown in Fig. 3(b). Individual information for the different fuels is not indicated, but the general trends are clear. From Fig. 3(a) it is clear that there is a significant difference in the rate of devolatilisation between the woods and the barks, this resulting from the high lignin and high inorganic content of the bark, which lowers the volatile content and increases the ash content. It is seen from Fig. 3(a) that most fuels decompose rapidly at temperatures above 300 °C, whereas bark decomposition occurs in three stages. For example the weight derivative for pyrolysis stage of hazel bark shows three distinct peaks at 340 °C, 489 °C and 661 °C. The first peak is at a comparable temperature for volatile loss in the other fuels, but the additional two peaks were not seen on any other fuel.

From Fig. 3(b) it is seen that there are differences between the straws and the untreated Reed, whilst both are different to the woods in Fig. 3(a). This behaviour is consistent with that observed in other studies (Amaral et al., 2014; Mitchell et al., 2015). The Reed briquette contains a binder which changes the rates of devolatilisation. The properties of the chars in Fig. 3(a) and (b) behave in a way compatible with their composition (cf Table 3).

3.2. Pyrolysis GC–MS analysis

Pyrolysis GC–MS chromatograms for the woods and their barks are shown in Supplementary Figs. S1 and S2 respectively. Similar measurements were made for the heartwood and bark of the peat grown Silver Birch samples, however these are not shown here. The corresponding peaks are a result of the decomposition of the cellulose and lignin components and follow the pattern previously seen for pine (Fitzpatrick et al., 2008).

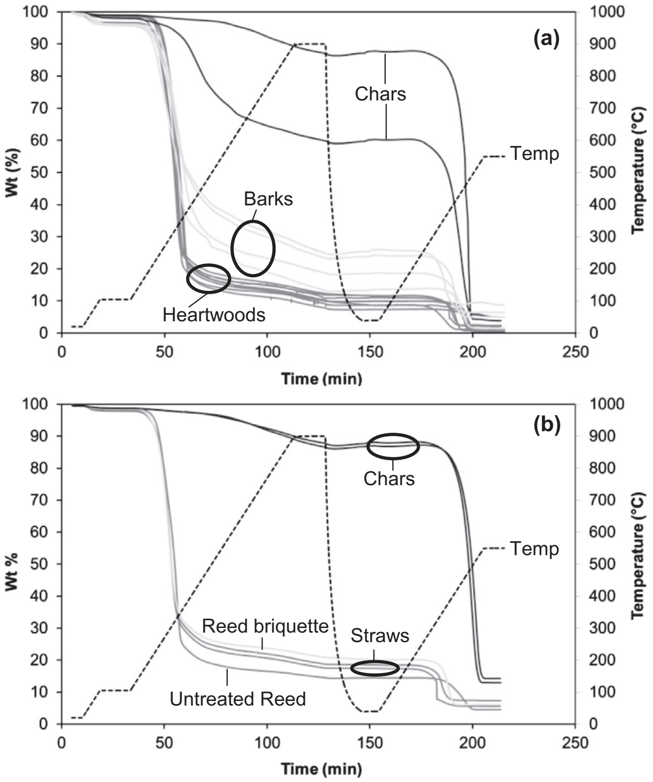

Fig. 3. TGA results for (a) the woody biomasses and (b) the herbaceous biomasses.

Generally the heartwoods exhibit the same fingerprint while the bark differs greatly. Similar compounds were found in both heartwood and barks materials for all trees, but there are differences in the abundance of certain species; different patterns are shown for the cellulose and hemicellulose derived compounds and those from lignin. These differences have been quantified by using ratios of certain key species; it should be noted that many of the complex species cannot be quantitatively determined so the ratio method overcomes this difficulty.

The species examined are firstly acetic acid (hydroxyl acetaldehyde) designated (a) in Supplementary Figs. S1 and S2, and furfural (F), both of which are decomposition products of cellulose. The other species, such as furan, are in small concentrations, whilst the major decomposition species CO, H_2 and CO_2 are not seen by GC–MS. The second group are the lignin decomposition species. Previous work suggests that the lignin decomposition species are largely responsible for the smoke formation in the flame (Fitzpatrick et al., 2008) so it is of interest to examine these more closely. They have been designated as guaiacyl (G) and syringyl (S) where S/G defines the lignin core, eugenol (E) which we use as a marker of the lignin deposition products. The lignin decomposition indicators are defined as A, B and C; these are the methoxy, allyl, vinyl or propenyl phenolic compounds of various types depending on the biomass. Some of the barks, such as hazel bark, generate much higher molecular weight compounds – and in this case heneicosane, a C_{21} n-alkane which is a waterproofing agent. The two Willow heartwoods from different sites exhibit the same fingerprint; however the two Willow barks do not. This might be attributed to site conditions. In particular, the potassium and calcium contents are significantly different and weathering can also affect the bark composition. The values of the ratios of these compounds are given in Table 4.

Table 4
Relative abundance of compounds in heartwood and bark samples obtained by Pyrolysis–GC–MC.

	F/a	E/F	S/G	A/E	B/E	C/E
Ash wood	6.8	1.7	1.1	0.6	1.6	1.0
Birch wood	7.6	1.9	3.6	1.0	1.3	1.6
Hazel wood	7.1	0.8	3.1	2.5	2.50	4.3
Willow wood	7.0	2.0	1.8	0.7	0.6	1.5
Ash bark	0.6	4.1	1.5	0.6	0.8	0.6
Birch bark	0.6	2.3	0.5	0.8	0.4	0.6
Hazel bark	0.2	1.6	0.3	0.7	1.1	2.6
Willow bark (no 1)	0.2	2.1	0.05	0.6	0.1	0.2

A number of issues are clear. The thermal decomposition of the cellulose from woods, as given by F/a, are to the barks; in the latter there is an extensive conversion to acetic acid, presumably aided by the high levels of the metals present. The values of S/G are different, the lower values for the bark is more like values for a grass, the wood being a more interconnected lignin The values of E/F show the higher level of lignin in the bark, in line with the ultimate analysis, and associated with this is the curious variations of the lignin decomposition products. The amount of the lignin decomposition products A, B and C are similar with the woods but vary considerably with the barks. It is clear that these types of pyrolysis GC–MS analyses give an insight into the chemistry. However, as seen previously (Mitchell et al., 2015), the best indicators of smoke forming tendency are C/H ratio and the volatile content.

3.3. Domestic stove tests

Three fuels were combusted in the stove; these were Ash wood logs, Reed briquettes and lump wood Willow charcoal. These are representative of the range of fuels available; log wood is a reasonably good biomass fuel, charcoal is a relatively expensive processed fuel and the Reed briquette is typical of a low grade fuel. These combustion experiments were made on a batch basis in order to observe how the emissions of PM, NO_x and CO change over time in one cycle. The results are shown in Fig. 4.

The results are generally consistent with those observed previously by us using a similar stove (Mitchell et al., 2015) and with the predictive model of Sommersacher et al. (2012). The profiles show substantial differences in the combustion properties of the fuels. The average burning rate for the Willow char ($0.73\ \mathrm{kg\ h^{-1}}$) was much lower than the Ash wood logs ($1.22\ \mathrm{kg\ h^{-1}}$) and the Reed briquettes ($0.82\ \mathrm{kg\ h^{-1}}$). However, the average value for the Reed briquettes was slightly skewed by a very long smouldering time compared to the wood logs. In one of the tests the briquettes were still visibly glowing and exuding heat after 4.5 h; this is a desirable feature compared with logs.

The Willow char, due to a combination of its relatively small size and its lower overall mass (for the same energy content), had the shortest total run time. As a result of the carbonisation process and reduction in volatile content, the char showed a rapid decrease in burning rate and concentrations of particulate matter (PM) following ignition. The duration of the chars flaming phase was shorter than that of the other fuels, lasting less than 20 min. This is significant with regards to the emission of PM as, during the flaming phase, large quantities of carbonaceous soot are produced from the volatiles. There is a gradual increase in the PM emissions rate as the combustion approaches the peak of the flaming phase, which is proportional to the volatile content of the fuel (Mitchell et al., 2015), before decreasing as it moves into the smouldering phase. The relative duration of the smouldering phase for the charcoal is much higher than the other fuels, as the small amount of remaining volatiles (approximately 11%) are rapidly driven off. Consequently, the total PM emissions are lower than that of the wood logs and Reed briquettes, where the volatile combustion is more dominant. Fig. 4 also shows a small secondary peak in both the PM emissions and burning rate for both the Ash logs and Reed briquettes. This is due to the fragmentation of the fuel and increase in burning rate. This causes an increase in NO_x and CO formation. NO_x emissions are strongly correlated with flaming combustion (dominated by NO), accordingly reducing over the course of the run. NO_x emissions were much higher for the Reed briquettes than for Ash logs, which is consistent with the higher fuel- nitrogen content as shown in Table 3 as is expected (Sommersacher et al., 2012; Mitchell et al., 2015; Amaral et al., 2014; Fournel et al., 2015). Willow char however does not follow that pattern: it has similar nitrogen content to the Reed briquettes, but during the combustion test it had slightly lower NO_x emissions. This is probably due to the fact that the wood char present reduces the NO to $N_{2.}$

As expected, CO shows a strong negative correlation with flaming combustion (Mitchell et al., 2015). There is a rapid increase in the concentration of CO when the smouldering phase commences, indicating that the CO emissions are chiefly determined by the relative duration of the smouldering phase for each fuel. CO emissions are lowest for the wood logs, which have the highest volatile content. Of these, the highest was the Willow char, which had only a 20 min flaming phase. A summary of the emission factors derived here for flaming conditions are compared with those for the open burning of biomass given in the literature in Table 5. These emission factors are used because this condition is similar to open burning combustion.

The data in Table 5 shows that a substantial reduction of PM emissions is achievable when the fuel is burned in a domestic appliance, compared to open burning, a current practice associated with the under-utilised conservation biomass feedstocks (Lemieux et al., 2004; McMeeking et al., 2009; Akagi et al., 2011). NO_x emissions are largely unchanged compared to open burning, as is the CO emission for the wood logs. The CO emission factors for the Reed briquettes and Willow char are higher than the reported values for open burning. This will be due to differences in fuel type since the Reed briquette tends to form a char after the early stages of combustion and the behaviour thereafter is similar to charcoal fuel; chars form carbon monoxide more easily because combustion occurs on the carbonaceous surface. A further difference between stove and open burning is that air entrainment into the plume formed in the latter case reduces the carbon monoxide concentration (Akagi et al., 2011).

Overall the environmental impact from burning in stoves is less than for open burning and of course energy is made available for heating, cooking and potentially for electricity generation. The benefit from burning Reeds is not as advantageous however.

3.4. Ash analysis

There were significant differences in the properties of the residual ash resulting from the combustion tests. These are summarised in Fig. 5 and are separated into two categories; under-gate and over-grate losses from the different fuels. The under-grate losses are defined as that which can pass through the grate spacing of 13 mm and are dominated by fine ash particles. The over-grate losses are those that are too large to pass through and consisted mostly of unburnt fuel particles.

Fig. 5 shows that the total ash losses are lowest for the Ash wood logs and highest for the Reed briquettes. This is consistent with the ash contents, given in Table 4, which are 0.5 wt%, 6.2 wt % and 4 wt% for the Ash logs, Reed Briquette and Willow Char, respectively. Unlike the other fuels, the majority of the ash losses for the Reed Briquettes are over-grate, which is attributed to them largely retaining their size and shape after combustion. In this case,

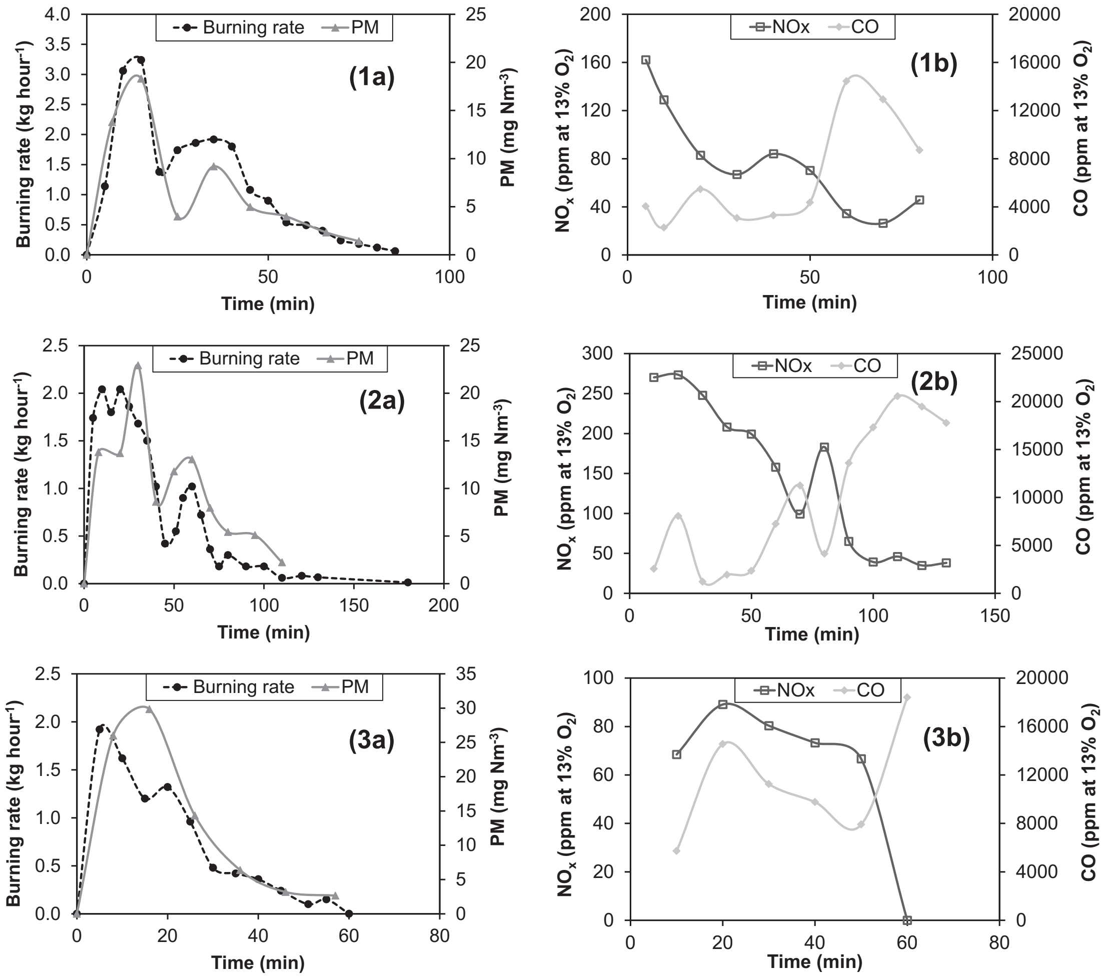

Fig. 4. Plots of (a) burning rates and PM emissions and (b) NO$_x$ and CO emissions for: (1) Ash logs, (2) Reed briquettes and (3) Willow char during combustion in a domestic stove.

Table 5
Emission factors (g kg^{-1}) for the open burning of two biomass types compared with those for a domestic stove (under flaming condition) from this study.

Biomass type	PM	NO$_x$	CO
Temperate forest – open burning, Akagi et al. (2011)	5–20	2–4	57–121
Common Reed –open burning, McMeeking et al. (2009)	36	6–10	31–63
Stove-Ash wood logs [this study]	3	3	69
Stove-Reed briquette[this study]	2	9	94
Stove-Willow charcoal [this study]	2	3	105

the over-grate losses contain a significant amount of fused clinkers which, on average, represented 5–10% of the total mass of residual ash; the largest example of clinker measured approximately 40 mm in length. As shown in Table 3, the Reed contains higher levels of ash, especially silica, with the amount varying between seasons. The ash content can be higher in the summer months, influencing their slagging and fouling behaviour (Kask et al., 2014). The characteristic ash melting temperatures for *P. australis* have been reported as low as 800 °C for sintering, 1100 °C for softening and 1200 °C for melting, but these values depend on the source of the Reeds as well as the part of the plant where the sample is taken (Patuzzi et al., 2012). In order to confirm the reasons for the observed ash fusion, samples of the Reed briquette ash and the wood log ash were analysed by SEM EDX and the results are given in Table 6.

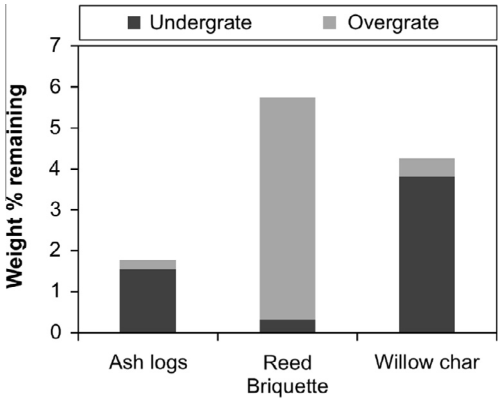

Fig. 5. Ash losses (over-grate and under-grate) after combustion for three fuels studied.

The results show that there was a high proportion of silica in the Reed briquette ash. There was also a relatively high proportion of sodium and aluminium in comparison to the constituents of the wood log ash. The relative carbon content of the wood ash was higher, indicating a poorer burnout efficiency. In addition, the proportion of potassium and calcium was higher in the wood ash, which is consistent with the results of the inorganic analysis of the raw fuel. These results are consistent with previous studies

Table 6
Bed ash analysis.

Element (wt%)	Reed briquette	Ash wood
C	6.8	19.3
O	44.7	44.3
Na	12.4	1.5
Mg	2.4	2.4
Al	0.2	–
Si	22.8	–
P	0.5	0.6
S	–	2.5
K	3.4	11.8
Ca	6.2	17.6
Fe	0.7	–
Total	100.0	100.0

(Kask et al., 2013/2014; Sommersacher et al. 2012; Bostrom et al., 2012) where it has been shown that the ratio of Si/(Ca + Mg) is important. The general trend is that as the content of Ca and Mg increases, the ash fusion temperatures also increase and thus reduce the tendency for slag formation; this is observed with the wood sample here. In the case of the Reeds, silica melts are observed, a result of the high silica content in the Reed and also due to possible contamination from sand and soil.

Due to their high inorganic content and ash melting tendency, Reed chars may not be suitable for residential combustion. They may be blended with other fuels, otherwise, chars made from wetland biomass such as Reed could be converted into biochar, improving soil productivity and carbon sequestration on agricultural lands (Cui et al., 2016).

3.5. Implications for the supply of biomass

There is little or no openly published information in the way that biomass is harvested from Conservation Areas in the United Kingdom, nor how much biomass produced in this way could be used as an indigenous energy resource. In order to estimate this values for the yield (2 t ha^{-1}) and the productivity (10%) given in the Introduction have been used on an overall average basis. Additionally, the suitability of the biomass as a fuel has been considered and estimated that 50% of the biomass is suitable as a fuel. Thus this gives on average a value of 0.1 t ha^{-1} that can be utilised. From the total area of Special Conservation and Special Protection given Table 1 this give a useable biomass yield of approximately 500 kt Mt y^{-1}. It is clear that these sources can provide a significant amount of biomass although the errors in this estimation are at least a factor of 2. However in some cases such as Reed the fuel may need upgrading by blending thus increasing the yield. These materials can be blended with good quality biomass and be suitable for domestic use, but would not be suitable for power stations. The quality of the biomass obtained is highly variable and is geographically dispersed in the UK, but the amount of available conservation material is considerable. Fuel improvements can be undertaken by washing, carbonising or through torrefication before blending the product with higher quality materials to make pellets or briquettes.

The increased ash contents of the bark samples, when compared to their corresponding heartwood, pose questions about the necessity for debarking. Increased concentrations of ash could have detrimental impacts during combustion, however due to the higher contents of carbon-rich lignin within the bark, debarking would result in a reduction of energy content. Peat-grown woods were found to contain marginally higher levels of nitrogen, iron and calcium than non-peat woods. It is recommended that all of the tree, including its bark, should be used if possible.

Pyrolysis GC–MS showed the woods were very similar. It was found that greater amounts of lignin derived aromatic hydrocarbons exist within the bark which, during combustion, could prompt increased levels of soot formation.

The high volatile levels of the untreated Ash wood logs resulted in them having the highest burning rate and PM emissions of the three fuels, during the stove combustion tests. Conversely, using wood-based biomass chars reduces particulate emissions, however the increased carbon content results in higher emissions of CO. In comparison to the other fuels, the Reed briquettes had intermediate levels of CO and PM emissions, although their levels of NO_x where the highest.

Maintaining biodiversity in conservation sites will require continual management and, as such, useable conservation biomass resource will continue to be produced. As current practices for dealing with conservation biomass include open burning, which has been shown to produce high levels of PM emissions, alternative ways of dealing with the resource should be identified.

4. Conclusions

(1) In the United Kingdom there is a considerable biomass resource available as a result of conservation management techniques, with about 500 kt y^{-1} that can be used as a domestic fuel.
(2) This is more environmentally acceptable than the current open burning option since the utilisation in domestic stoves provides usable heat and reduces emissions.
(3) The biomass resource contains a significant amount of a low grade material such as Reeds and soil contaminated wood.
(4) The lower grade material such as Reeds could be blended with higher grade saleable fuel for domestic heating as briquettes or pellets.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biortech.2016.04.057.

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