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# Reed canarygrass (*Phalaris arundinacea*) outperforms *Miscanthus* or willow on marginal soils, brownfield and non-agricultural sites for local, sustainable energy crop production

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## ABSTRACT

Growing biomass on non-agricultural land could potentially deliver renewable energy services without displacing land from food production, avoiding the social and environmental conflicts associated with bioenergy. A variety of derelict underutilized and neglected land types are possible candidates, sharing a number of challenges for agronomy, including contaminants in soils, potential uptake and dispersion through energy use. Most previous field trials have grown woody biomass species during phytoremediation. Five one-hectare brownfield sites in NE England, were each amended with c.500 t ha<sup>-1</sup> of green-waste compost, planted with short-rotation coppice willow, *Miscanthus*, reed canarygrass and switchgrass,<sup>1</sup> and then harvested for 3–5 years.

Critical issues for the economic and environmental viability of energy production on brownfield land were investigated: The yields achieved on non-agricultural land; the potential for fuel contamination; the suitability for use and potential markets for any biomass produced. RCG appears best suited to the challenging soil conditions found on non-agricultural land, outperforming other species in ease of establishment, cost, time to maturity, yield and contamination levels. Invasive spreading and low melting ash compositions were not observed. Annual yields of 4–7 odt ha<sup>-1</sup> from the second growth season were found consistently across a range of previously-developed, capped or former landfill sites, with a gross annual energy yield of 97 GJ ha<sup>-1</sup> at contamination levels acceptable for domestic pellets. The analogy with marginal agricultural land suggests that this species and approach could help boost biomass production while avoiding the natural capital “nexus” related to global food-fuel-land-water limits.

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<sup>1</sup> Hereafter abbreviated as SRC, MC, RCG, SG respectively.

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## 1. Introduction

Biomass is the commonest form of renewable energy [1] and combustion of ligno-cellulosic energy crops as a renewable heat source presents an available technology and a cost effective means of reducing greenhouse gas emissions, addressing climate change and meeting renewable energy targets: As an example, in the UK the Renewable Energy Review [2] found biomass boilers to offer the lowest minimum abatement cost (-£150/t CO<sub>2</sub> in 2020) among a range of low carbon heat technologies. However, the widespread utilization of biomass for heat or power generation in the UK and elsewhere has been tempered by concerns over the sustainability of biomass and biofuels in general [3]. Discussion of the economic, social and environmental impacts of biofuel production and use has centred on three aspects [4,5]: Firstly, the net carbon reduction benefit of using bioenergy when the whole life-cycle energy balance, fossil fuel use and greenhouse gas emissions of production and transport are considered [6,7]; secondly, the additional demand from direct utilization of food crops for liquid biofuels manufacture, or the potential for purpose-grown “energy crops” to compete indirectly with food production on agricultural land, together impacting on global food supplies or price [8], water and land availability - the so-called “land-fuel-water” nexus [9]; thirdly, negative impacts on the environment through land use change or deforestation from biofuels production, or indirect land use changes from displaced agriculture [7,10,11]. Using locally available non-agricultural land for energy crop production [12,13] could potentially circumvent each of these concerns, while offering a sustainable reuse option for brownfield sites, with improved habitat and amenity value at many sites [14–17].

To date, the existing field-scale demonstrations of biomass production on brownfields, contaminated land or landfills have mainly involved growing woody biomass as short rotation coppice or forestry [14,18–23], more rarely oil seed crops or perennial grasses [24–26]. Paradoxically, the majority of contaminated sites, whether brownfield or greenfield, are affected by heavy metals or mineral oils [27], which together with other prevailing site conditions might compromise economic viability by reducing yields [20,22]. Biomass production may be a secondary consideration to pollutant control [28], accompanying various forms of phytoremediation [29] or “gentle” remediation of contaminated sites [30]. The processing and utilization of recycled organic wastes may be used to add value to the biomass operation [14], which can be part of the long-term management of damaged land [31]. However, a real or perceived consequence of growing biomass in contaminated soils is the potential for it to become contaminated, which could reduce the value or suitability for use of the woody biomass [32,33]. This might occur directly by contaminant uptake (i.e. phyto-extraction [29]), or indirectly, by cross-contamination from adhering soil dust during growth or forage harvesting [15]. This would detract from the economic viability and environmental validity of the approach [31], unless an adequately productive energy crop can be identified with an acceptably low level of contamination to allow both its safe cultivation on these challenging

sites and subsequent suitable use, ideally in an existing market.

This paper uses the results of five full scale multi-season field trials in NE England to assess the potential of RCG as an energy crop grown on brownfield land, comparing the actual yields achievable on non-agricultural sites, quantifying the potential uptake of toxic elements from contaminated soils and investigating the resultant biomass fuel quality and uses.

## 2. Materials and methods

Five 1 ha brownfield trials were established in 2007 as part of an EU Life Programme demonstration project “Biomass, Remediation, re-Generation (BioReGen): Reusing Brownfield sites for Renewable Energy Crops” [34] in order to directly compare the suitability of SRC, MC, RCG and SG for growth on non-agricultural land. The five field trial sites were selected on the basis of adequate size, absence of scrub and apparent suitability for cultivation, using desk studies of historic maps to establish their previous use (Table 1). During walkover surveys three or more non-systematic surface soil samples were collected over a depth interval of 0–0.1 m to determine potential contamination, baseline nutrient status and physicochemical properties in the surface soil available for cultivation (Table 2).

### 2.1. Site preparation & planting

Sites were prepared using the results of smaller scale single species or hand-cultivated trials planted between 2004 and 2006 [15,35,36]. From these a generalized approach was developed for in situ cultivation of non-agricultural sites, requiring surface incorporation of c.500 t ha<sup>-1</sup> (fresh mass at 20–30 % H<sub>2</sub>O) of green waste compost produced to BSI PAS100 specification [37,38] and supplied from stock from a single composting site (Premier Waste Management Ltd, Joint Stocks, Coxhoe, County Durham). To do this any standing vegetation was first mown and sprayed with glyphosate. Ploughing and disking was used to break open the soil. Compost was applied using a back-end spreader, then incorporated by further disking to a maximum depth of c.0.1 m. All crops were planted in spring 2007 using standard agricultural equipment and conventional UK planting methods for energy crops: For SRC 0.2 m cuttings were step-planted (Coppice Resources Ltd) at a rate of 15,000 ha<sup>-1</sup> using a conventional double-row layout (alternate 0.75 m and 1.5 m machine aisles, along row spacing 0.59 m) using single commercial hybrid clones (*S. schwerinii* x *S. viminalis*), either Tora (SW910007) or Torhild (SW930725) [39]; MC rhizomes (*Miscanthus x giganteus*) were planted at a rate of c. 20,000 ha<sup>-1</sup> using a modified potato planter (Bical Ltd). Both SG (Ernst Seeds, variety Shawnee, 10 kg ha<sup>-1</sup>) and RCG (uncertified seed, Advanta, 20 kg ha<sup>-1</sup>) were sown from seed by broadcast spreading, followed by firming with a Cambridge (multi-segmented, rib-edged) roller. Finally, the sites were protected from rabbits (*Oryctolagus cuniculus*) and deer (*Cervus elaphus*) by erecting an enclosing wire mesh fence with a buried lower edge. Thus planting mimicked current UK deployment methods for commercial energy crops at agricultural sites.

**Table 1 – Details of previous uses, ground conditions preparation and planting at trial sites.**

Site name (abbreviation)	NGR	Area (ha)	Previous use(s) <sup>a</sup>	Dominant soil type, contaminant, nutrient or site issue(s) <sup>b</sup>	Compost application rate and method	Energy crops planted
Haverton Hill (HH)	NZ489225	0.67	Cleared site in industrial estate Shipyards & railway land Made ground on estuary tidal flats	Sandy clay loam Heavy metals, PAHs Low SNS Granular made ground & obstacles	500 t ha <sup>-1</sup> in situ incorporation for grasses, (250, 500, 750 t ha <sup>-1</sup> subplots for SRC)	Reed canarygrass & switchgrass (var. Shawnee), <i>Miscanthus</i> , SRC (var. Torhild)
Tees Barrage (TB)	NZ461188	0.77	Clay soil capped riverside embankment of industrial made ground Iron and steelworks & slag heap Marshalling yard & railway Reclaimed tidal flats	Sandy clay loam Heavy metals & PAHs below cap Low SNS, P, TOC (±S) Raised free-draining embankment	500 t ha <sup>-1</sup> in situ incorporation for grasses, (250, 500, 750 t ha <sup>-1</sup> subplots for SRC)	Reed canarygrass & switchgrass (var. Shawnee), <i>Miscanthus</i> , SRC (var. Torhild)
Binchester (BC)	NZ238319	0.68	Haulage yard & storage compound Coal stocking yard Drift mine (fireclay?) Collieries with spoil tips, coke ovens, gasometer & railways Agricultural	Sandy clay loam As, PAHs Low SNS, P, (±K) Compacted dolomite, coal dust & burnt shale beneath applied soil, mineworkings No rabbit fencing	Compost & screened soil mixing ex situ at 2:3 volume ratio & loose tipped (depth c.30 cm) (equivalent to 735 t ha <sup>-1</sup> compost)	Reed canarygrass & switchgrass (var. Shawnee), <i>Miscanthus</i> , SRC (var. Torhild)
Rainton Bridge (RB)	NZ336490	1.0	Sub-soil and clay-capped vacant industrial plot Sewage farm sludge & filter beds Agricultural	Clay Clean subsoil over clay cap Low SNS, P, K & TOC Water-logging in winter	500 t ha <sup>-1</sup> in situ incorporation for grasses, (250, 500, 750 t ha <sup>-1</sup> subplots for SRC)	Reed canarygrass & switchgrass (var. Shawnee), <i>Miscanthus</i> , SRC (var. Tora),
Warden Law (WL)	NZ367504	1.23	Restored and planted, topsoil and clay capped amenity land Unlined council landfill (construction, demolition & dredging fill) Sand and gravel pits Railway & incline with (steam) winding engine crossing agricultural area	Clay loam Clean topsoil over clay cap Low SNS, P, K & S Exposed hilltop site Incomplete rabbit fencing	375 t ha <sup>-1</sup> in situ incorporation for grasses, (250, 500, 750 t ha <sup>-1</sup> subplots for SRC)	Reed canarygrass & switchgrass (var. Shawnee), <i>Miscanthus</i> , SRC (var. Tora),

<sup>a</sup> As determined from desk studies (most recent former use first).

<sup>b</sup> Abbreviations: PAH = poly-nuclear aromatic hydrocarbons, SNS = soil nitrogen supply (from total leachable N), TOC total organic carbon (mainly from organic matter).

**Table 2 – Composition of receiving soils, compost and amended soils for potentially toxic elements and nutrients (average and range). Figures in bold are statistically different for the amended soils compared to the receiving soils at the 99% level.**

	Receiving soils (n = 26 <sup>a</sup> or 20 <sup>b</sup> )	Compost (n = 6)	Amended soils (n = 25)	Compost limits [37], soil limits for pH > 7 [49]
<i>Contaminants</i>				
As (mg kg <sup>-1</sup> )	13 (7–47)	8.7 (7.9–10.3)	13 (7–24)	
B (mg kg <sup>-1</sup> )	1.5 (0.3–5.1)	10.0 (8.4–12.3)	3.1 (1.6–6.0)	
Cd (mg kg <sup>-1</sup> )	0.33 (0.10–0.93)	0.43 (0.41–0.45)	0.41 (0.18–1.06)	1.5, 3
Cr <sup>T</sup> (mg kg <sup>-1</sup> )	31 (11–50)	24 (18–42)	24 (14–46)	100
Cu (mg kg <sup>-1</sup> )	68 (23–277)	51 (42–59)	53 (26–124)	200, 200
Pb (mg kg <sup>-1</sup> )	137 (23–498)	96 (88–106)	106 (43–333)	200, 300
Hg (mg kg <sup>-1</sup> )	0.20 (0.03–0.74)	0.28 (0.22–0.37)	0.18 (0.06–0.60)	1.0, 1.0
Ni (mg kg <sup>-1</sup> )	29 (17–45)	19 (15–32)	27 (16–46)	50, 110
Zn (mg kg <sup>-1</sup> )	196 (57–636)	146 (137–159)	185 (81–600)	400, 450
<i>Nutrients</i>				
N <sub>T</sub> %	0.24 (0.08–0.52)	1.0 (0.7–1.1)	<b>0.49</b> (0.25–0.91)	
P <sub>T</sub> (mg kg <sup>-1</sup> ) %	0.037 (0.009–0.065)	0.18 (0.15–0.20)	<b>0.084</b> (0.05–0.15)	
K <sub>T</sub> (mg kg <sup>-1</sup> ) %	0.14 (0.03–0.29)	0.67 (0.53–0.82)	<b>0.24</b> (0.15–0.37)	
N <sub>A</sub> (NH <sub>4</sub> <sup>+</sup> + NO <sub>3</sub> <sup>-</sup> ) (mg kg <sup>-1</sup> )	3.6 (0.5–16.9)	270 (37–593)	7.3 (1.9–27.8)	
P <sub>A</sub> (mg L <sup>-1</sup> )	11 (4.2–40)	101 (75–114)	51 (27–94)	
K <sub>A</sub> (mg L <sup>-1</sup> )	147 (7–497)	3710 (3210–4400)	<b>1110</b> (510–2120)	
OM %	4.6 (1.6–11.2) <sup>c</sup>	32 (27–37)	<b>10.8</b> (5.2–17.7)	
SMN 10 (kg ha <sup>-1</sup> N <sub>A</sub> to 0.1 m)	3.2 (0.5–14)	n/a	44 (5–208)	

<sup>a</sup> For soil contaminant suite analyses.  
<sup>b</sup> For nutrient suite analyses.  
<sup>c</sup> n = 11 for OM (excludes the HH site).

## 2.2. Site layout, replication and control

The planting of all four energy crop species was replicated at each of five sites. For SRC three different compost application rates were replicated at four sites, namely 250, 500 and 750 t ha<sup>-1</sup> [17,38]. The lowest figure corresponded to the prevailing maximum annual permitted rate for spreading on land used for agriculture resulting in benefit to agriculture or ecological improvement (here used as a control), with the rates increased by factors of two and three permitted only for the reclamation or improvement of industrial or other previously developed land incapable of beneficial use without treatment [40]. In the trial site corresponding most closely to the ideal layout (at Rainton Bridge, Houghton-le-Spring, Sunderland, Fig. 1) the 100 m × 100 m plot was divided into four equal 100 m × 25 m strips for each crop, here trending NNW–SSE, with two perpendicular 25 m wide strips of lower (250 t ha<sup>-1</sup>) or higher (750 t ha<sup>-1</sup>) compost application at each end, with a central 50 m wide standard compost application area (500 t ha<sup>-1</sup>), also giving an overall average rate of 500 t ha<sup>-1</sup>. At other sites logistical and geographical constraints meant that compost rate variations for crops other than SRC were not possible. While the intended compost application rate for the RCG trial areas was 500 t ha<sup>-1</sup>, it fell to 375 t ha<sup>-1</sup> at one site (WL). This was due to the exact size of the sites achieved during preparation being unknown when the amounts of waste-derived compost to be used were registered in advance. Conversely, for smaller sites another legal



**Fig. 1 – Optimum field trial design as illustrated by the Rainton Bridge brownfield site (54.834317°N, –1477743°E) showing NW–SE trending strips for SRC, MC, RCG, SG and perpendicular zones of different compost amendment rates averaging 500 t ha<sup>-1</sup>. Locations and planting layout for other sites can be displayed in Google Earth by opening the kmz file provided as supplementary data.**

requirement was to fully utilize all waste-derived material delivered to site, in order to achieve recovery. Furthermore at one smaller site (BC) where *ex situ* incorporation and soil tipping was deployed, the equivalent rate was  $735 \text{ t ha}^{-1}$ . From analysis of samples of the compost received at each site the application rate of  $500 \text{ t ha}^{-1}$  corresponds to average total N ( $N_T$ ) total P ( $P_T$ ) and total K ( $K_T$ ) additions of 3165, 571 and  $2114 \text{ kg ha}^{-1}$  respectively. However, compost is a slow release source of N, so current UK guidance for application to agricultural soils assumes that only 6% of  $N_T$  and 15% of  $P_T$  may become available in the first year application, with up to 80% of  $K_T$  being water soluble and available over one to three years [41]. Assuming a similar rate of mineralization will indeed occur in previously uncultivated brownfield soils, the estimated N released over the first year is  $190 \text{ kg ha}^{-1}$ . Thus  $500 \text{ t ha}^{-1}$  of compost should provide in excess of the optimum bag fertilizer N applications that are recommended for agricultural land [42] of  $40 \text{ kg ha}^{-1}$  before planting RCG and 100 to  $50 \text{ kg ha}^{-1}$  annually in subsequent years, for autumn or spring harvesting regimes respectively.

### 2.3. Field survey methods

Bespoke field survey methods were required to provide comparative yields for each species, appropriate to its growth habit. These were designed to reflect standard agricultural practice in terms of the harvesting seasons, harvesting intervals and field conditions, together allowing collection of representative samples for gravimetric determination of oven dry mass and physio-chemical fuel analysis.

For SRC it is common practice to “top” the first year growth with a flail or blade mower at 0.1 m to encourage multi-stem regrowth, then to coppice and harvest on a 2–3 year cycle during winter dormancy [43]. Accordingly, all willows were cut by hand at 0.1 m above ground in winter after the first and third growth seasons with all cuttings collected and bagged, ensuring that cuttings were not allowed to touch the soil surface. Cuttings were chipped in bulk on site using a cleaned-down garden shredder (Makita GSP5500 5.5 hp) before homogenization and subsampling 50 L portions in lidded polypropylene buckets for drying or analysis. At all sites the maximum stem height for every established tree was recorded together with the number of cuttings growing on each measured row, in order to compare establishment rates with the number expected for full establishment ( $15,000 \text{ ha}^{-1}$ , average along row plant spacing 0.59 m).

MC is commonly cut annually after dormancy in spring following the second or third growth year [44], so all establishing stems were cut by hand to 0.1 m above ground level after the 2nd and 3rd growth seasons, chipped and subsampled, following the same methods as described for willow.

RCG is typically mown and baled annually while dormant, in either autumn or in spring after overwintering [42,45]. Growth was initially assessed in autumn (Nov–Dec '08) using a  $0.25 \text{ m}^2$  quadrat frame within which growth above 0.1 m was cut by hand, taking care to avoid soil contact, bulking the material from 10 sites in each plot before oven-drying, weighing and then fuel analysis. RCG was also subsequently harvested mechanically (Mar '09) using a tractor, grass mower and round baler, from which actual harvestable yields were

calculated from bale numbers, average bale masses and samples of mown biomass collected for oven drying (25 L portions, lidded containers as above). Spring bales were stored in a Dutch barn for approximately 3 weeks, followed by resampling for fuel analysis (in 50 L portions as above). This was repeated following regrowth (Oct '09) to compare with the earlier overwintered harvest. Autumn cut biomass was stored outside to determine the effects of field storage, prior to subsampling for analysis in Feb 2010.

Modified soil sampling methods were also needed for sampling brownfield sites for a combination of contaminants and nutrients from a single sample. For determination of nutrient status and fertilizer requirements it is usual to use a representative bulked sample with 25 subsamples in a W-pattern, using a  $1 \text{ m} \times 2.5 \text{ cm}$  diameter gouge auger to obtain a continuous sample of the full depth of the soil horizon (to 0.6–0.9 m) in 2 or 3 depth layers for N or to 7.5–15 cm for other major nutrients in grass or arable fields [46]. In contrast, spatial composite samples are not normally recommended for investigations of land affected by contamination [47]. Given that some sites were known to be capped (WL, RB, TB) the following protocol was developed. A garden spade was used to remove a block of soil  $0.2 \text{ m} \times 0.2 \text{ m} \times 0.1 \text{ m}$  depth. Vegetation was removed during disaggregation, the soil homogenized using a stainless steel trowel and subsampled in 1 L soil pots for separate contaminant and nutrient suite analysis with delivery to the laboratory by courier as soon as possible after collection.

For baseline sampling of the brownfield site soil conditions the number of samples varied slightly between sites due to complexity of previous use, heterogeneity of made ground, layout or history of site access. For contaminant suite analysis the total number of samples per site was as follows: Warden Law 4, Rainton Bridge 3, Binchester 10, Tees Barrage 6, Haverton Hill 3. Subsamples were all analysed for nutrients except for 6 of the samples from Binchester. Routine analysis for organic matter was added part way through the process so only those samples from Warden Law, Rainton Bridge and two samples each from Binchester and Tees Barrage were included. As the compost was delivered over a 5 week period in April–May, a sample from the stockpile at each site was collected for full analysis, with two from Binchester due to suspected heterogeneity. Subsequently, all of the amended sites were resampled over a three-day period in early August, with five samples analysed for all determinants from each site, allowing statistical comparison with the unamended sites (Table 2).

### 2.4. Analytical methods

Soil samples were submitted to an accredited commercial laboratory (NRM Laboratories, Bracknell, UK) for soil contaminant, nutrient and physio-chemical analysis suites, including potentially toxic elements, speciated total petroleum hydrocarbons, PAHs, phenols, total and available major nutrients (N, P, K, Ca, Mg), pH, conductivity, total organic matter and particle size analysis (Table 2). Oven dry biomass yields were determined gravimetrically by oven drying (at  $105 \text{ }^\circ\text{C}$ ) 50 L subsamples of chipped material until no further mass loss occurred (University of Teesside, Middlesbrough, UK). Fuel

analysis was performed on undried bulk samples submitted to an accredited commercial laboratory (Knight Energy Services, Scotland), including gross and net calorific values, C, H, N, fixed C, S, Cl, F, PTEs, ash content, elemental ash composition, ash fusion temperatures, slagging and fouling indices.

### 3. Results

#### 3.1. Soil contaminants and nutrients

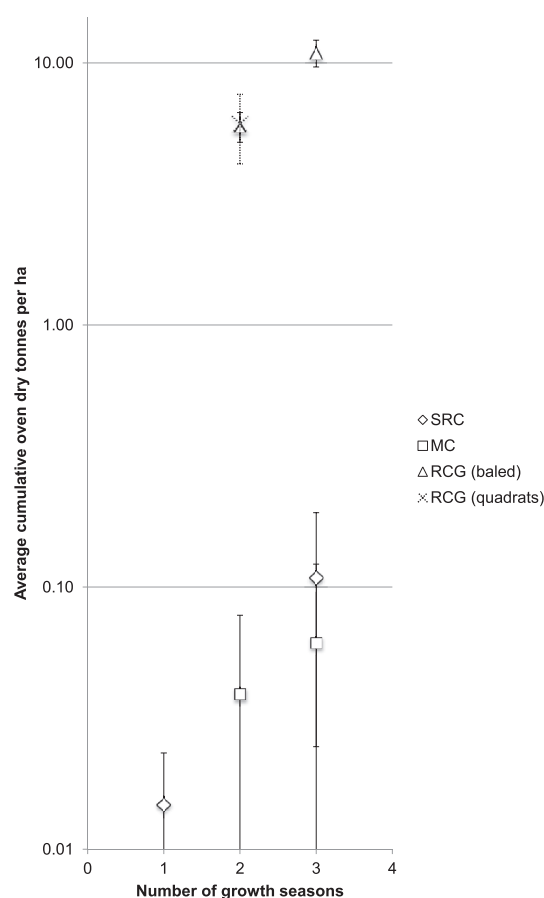
The amended soils have been compared to the original receiving soils, together with the compost (Table 2). Overall averages for the receiving soils were calculated by equally weighting the samples from a particular site, since the number of samples per site varied in some cases. Key parameters considered were a suite of nine potentially toxic or phytotoxic elements As, B, Cd, Cr<sup>T</sup>, Cu, Pb, Hg, Ni, Zn, total and available major nutrients (N, P, K) and organic matter. These were used to establish the level of contamination before and after incorporation of the compost amendment, and the effect of compost addition on nutrient content, availability and likely long-term nutrient availability. A two-tailed t-test showed that the amended and unamended soils were statistically different at the 99% confidence level for B, N<sub>T</sub>, P<sub>T</sub>, K<sub>T</sub>, K<sub>A</sub>, and OM (i.e. the null hypothesis, that both receiving and amended soils are samples of same population, is rejected for these determinants, but cannot be rejected for the remainder). These results show that the compost provides a source of major nutrients and organic matter (see Ref. [38]), which are otherwise low in the brownfield soils, although short-term availability remains limited for N and P. The levels of contaminants in the compost are lower or similar to those in the receiving soil, other than for B. Boron phytotoxicity effects may occur in soil at hot water soluble concentrations of more than 5–8 mg L<sup>-1</sup> [48], whereas the range of concentrations observed here corresponds to 5–7 mg L<sup>-1</sup> in the lower density compost before dilution. The composition of the resulting growth medium after application is an intermediate between that of the receiving soil and the compost, so the amended and cultivated soils are not significantly changed in terms of their contaminant burden compared to the uncultivated surface soil baseline conditions. Some sites were capped or had established adventitious plant and soil cover, so cultivation might have increased levels of contamination at the surface. Levels of contaminants were found to be below those of interest for human health risk assessment and the applicable regulatory guideline values at the time of site preparation [17]. The maximum concentrations of contaminants found exceed the “safe” levels permitted from sewage sludge application for the prevailing pH for B, Cu, Zn and Pb [49], but the average concentrations of these potentially phytotoxic elements fall well below these limits. Hence the use of these sites for food production could be inappropriate but widespread phytotoxic effects on energy crops were not anticipated.

#### 3.2. Yields of RCG on brownfield sites

The overall results of the growth trials in terms of the relative productivity of the three candidate species over the first three

growth seasons are summarized in Fig. 2. SG failed to establish at any site. It is clear that in this timeframe and in these soil conditions RCG outperforms MC and SRC, with average cumulative yields roughly two orders of magnitude greater than those of other crops over the first two harvests. Error bars indicate that this difference is significant and consistent across the four sites, including any effects on yield from the internal divisions with different compost amendment rates. Neither SRC nor MC showed the expected increase in biomass productivity in the third season, indicating that growth-limiting conditions persisted in the shallow surface amended soils. Since nutrients were adequate and phytotoxicity limited this suggests water availability was a possible factor.

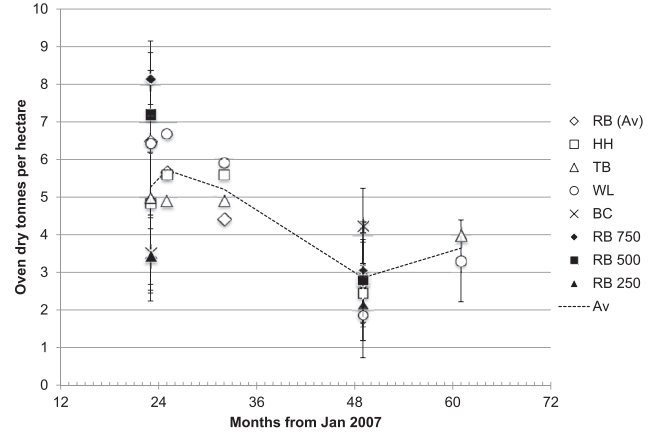
The performance of RCG at individual sites over five years is shown in more detail in Table 3. Site averaged yields in the first or second harvests are in the range 3.5–6.7 oven dry (od) t ha<sup>-1</sup> for the standard amendment rate of 500 t ha<sup>-1</sup> or for area-weighted averages. Where compost application rate was varied by ± 250 t ha<sup>-1</sup>, the yield increased or decreased in sympathy. A wider internal variation in yield is illustrated by overlapping error bars (1 standard deviation) for individual 0.25 m<sup>2</sup> quadrat areas (Fig. 3). However, averaged yields for all sites (Table 3) are not statistically different (two-tailed t test) for the first and second harvests (growth years 1–2 and 3



**Fig. 2** – Average cumulative yield (in oven dry tonnes per hectare) for SRC, MC and RCG (by quadrat survey of standing crop and baled harvest yield) for growth seasons 1 to 3 (2007–2009). Error bars show 1 standard deviation from the mean (see Table 3).

**Table 3 – Yield data for individual energy crop trial sites, component compost amendment rate plots, growth seasons and sampling dates (oven dry tonnes per hectare). Figures in italics are area-weighted averages calculated from figures for sub-plots.**

Site	Compost rate plot t/ha	SRC year 1 Jan '08 odt ha <sup>-1</sup>	SRC year 2–3 Dec '09–Feb '10 odt ha <sup>-1</sup>	MC year 1–2 Feb–Mar '09 odt ha <sup>-1</sup>	MC year 3 Feb '10 odt ha <sup>-1</sup>	RCG year 1–2 Nov–Dec '08 odt ha <sup>-1</sup>	RCG year 1–2 bales Mar '09 odt ha <sup>-1</sup>	RCG year 3 bales Oct '09 odt ha <sup>-1</sup>	RCG year 4 quadrats Jan '11 odt ha <sup>-1</sup>	RCG year 5 quadrats Jan '12 odt ha <sup>-1</sup>
Rainton Bridge	750	0.020	0.068	0.019	0.004	8.15	4.41	3.05	—	—
	500	0.017	0.067	0.025	0.014	7.20	—	2.80	—	—
	250	0.015	0.045	0.017	0.019	3.45	—	2.19	—	—
Tees Barrage	750	0.003	0.027	—	—	—	—	—	—	—
	500	0.006	0.041	0.010	0.008	4.85	4.90	3.09	3.98	—
	250	0.004	0.018	—	—	—	—	—	—	—
Haverton Hill	750	0.023	0.167	—	—	—	—	—	—	—
	500	0.026	0.213	0.147	0.075	5.00	5.60	2.45	—	—
	250	0.021	0.197	—	—	—	—	—	—	—
Warden Law	750	Grazed by pests	0.015	—	—	—	—	—	—	—
	500	—	0.022	—	—	—	—	—	—	—
	250	—	0.014	—	—	—	—	—	—	—
Binchester	375	—	—	0.016	0.015	6.45	6.70	1.88	3.31	—
Average	735	0.015	0.079	0.049	0.028	5.26	5.73	5.47	2.87	3.65



**Fig. 3 – Yield (in oven dry tonnes per hectare) of RCG for growth seasons 2 to 5 (2008–2011) for 5 brownfield trial sites measured by quadrat surveys or from harvested bales (see Table 3).**

respectively) whether they were determined by quadrat sampling or by cutting and bailing all available biomass, or whether in autumn or in spring after overwintering and expected losses. Lower yields ranging 1.9–4.0 odt ha<sup>-1</sup> in the fourth and fifth harvests (growth years 4 and 5) when averaged are not distinguishable from one another but are significantly different (at the 99% and 95% levels respectively) from the site averaged yield in year 3.

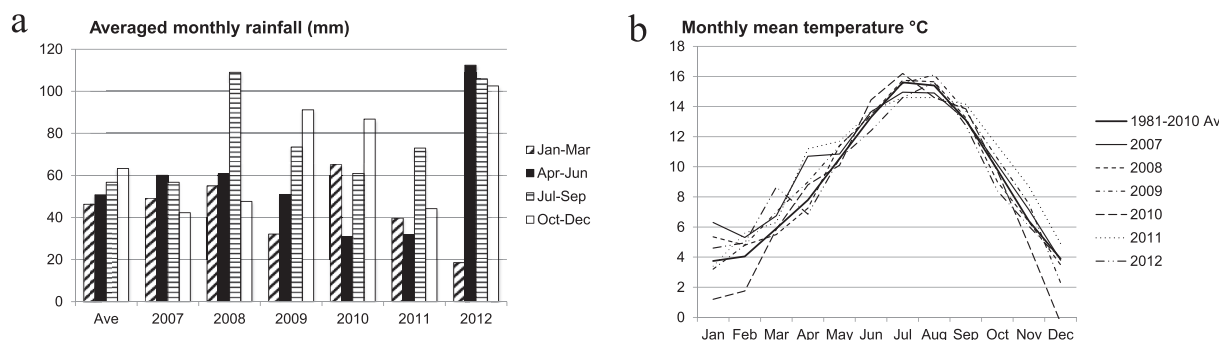
Thus, over the 5-year timescale of the project, the yields of RCG appear to decline from c 5.5 to about c.3 odt ha<sup>-1</sup>. During this period two harvests were taken and there was no additional fertilization, apart from the limited subsequent nutrient availability provided from degradation of the compost. Weed competition was observed to decrease from a maximum in the year of establishment. Averaged monthly rainfall data for the nearest weather station (at Durham [50]) indicate that both 2010 and 2011 showed dry conditions during the spring and early summer growth period (Fig. 4a). In 2010 the mean monthly temperatures were unusually low early in the year and again over the following winter (Fig. 4b), so thatching by lying snow could potentially have affected early growth and the overwintered yields.

### 3.3. Effect of brownfield soils on biomass contamination and fuel properties

To ascertain whether growth in brownfield soils has led to unacceptable levels of PTEs in the biomass, the fuel analyses have been used to compare each energy crop to one another and to the respective limits set for pelletized biomass and its use in different contexts (Table 4) [51,52]. In general, commercial or residential use can require lower levels of any detrimental characteristic than industrial use, with intermediate levels used to define intermediate grades in each case for woody biomass pellets.

#### 3.3.1. Potentially toxic elements

Concentrations of all PTEs in energy crops from the BioReGen trials are lower than the acceptable limits for commercial or



**Fig. 4** – Monthly rainfall data averaged by quarter (a) and monthly mean temperatures (b) for the nearest Met Office station historic data [50].

residential use of the resultant biomass pellets (Table 4), with the exception of Cd and Zn levels in SRC or MC. The highest levels of Zn and Cd are both found in SRC, for which average contents are above the threshold for residential/commercial use [51,52], with the highest values also unsuitable for industrial use Fig. 5. For MC the highest concentrations of Zn or Cd found here are at the limit for commercial/residential use. This indicates that uptake of Zn, Cd and possibly Cu, from equally or more contaminated soils would be an issue for use of the resulting biomass where either SRC or MC were grown. The lower concentrations of Zn and Cd found in RCG grown in the same soils (Table 4) make this suitable for pellets for all uses.

Comparing average soil compositions (Table 2) and biomass compositions (Table 4) indicates that Cd, B and possibly Zn may be concentrated by SRC, whereas in RCG only B is at higher levels than in the soil. This confirms earlier results [15,17] and suggests that any additional environmental dispersion of soil contamination through the food chain from energy crop production of RCG at a brownfield site over that occurring through voluntary vegetation is limited.

### 3.3.2. Ash content

Ash content is a key parameter for alternative biomass fuels, since compared to the maximum 0.7% in grade A1 pellets made from timber [51], the generally higher levels will require more frequent or effective removal from combustion systems and additional disposal costs. As anticipated, RCG has the highest ash contents (average 8.6%), followed by MC (average 5%). In both fuels these average ash concentrations exceed the nominal thresholds for pellets of these feedstocks [52] so would need to be stated, possibly affecting value. Ash content is also relatively high in the SRC (2.1%), presumably the effect of small stem size from poor growth and the immaturity of the coppice, resulting in higher bark to core ratios, so this would only be suitable for the lowest grade industrial use.

### 3.3.3. Non-metals

Two other potentially detrimental elements, S and Cl, are present in the grasses at levels above those specified for pellets [52]. Both contribute to acid gas emissions and are relevant to boiler corrosion issues [53]. All samples of MC exceed the concentration limit for S. For RCG this threshold is higher,

so although levels are higher they are still mostly below the limit. For Cl all RCG samples exceed the higher limit and MC average concentrations also exceed the slightly lower limit. Accordingly, energy grasses grown on made ground likely to contain sulphate (e.g. colliery spoil, slag) or chloride (e.g. in coastal areas, colliery spoil) would require testing before use [52] and this might limit use of the resultant biomass to industrial applications.

### 3.4. Fuel composition and combustion issues for RCG

In addition to the effects from uptake of PTEs, Cl or S from contaminated sites, inherent differences between RCG compositions and those of conventional energy crops could limit the potential use for combustion. In particular, high levels of K and Si, where not accompanied by Ca, can reduce ash fusion temperatures, leading to “slagging” issues related to adhesion and fusion of ash, in turn leading to various operational difficulties [53], including “fouling” of heat exchangers. Using the ash contents and ash analyses in Table 4 the average K content of the original biomass can be estimated as 0.47% for SRC, 0.62% for MC and 0.86% for RCG (assuming that these elements were conserved on ashing). Thus the grasses do indeed contain slightly higher levels of K in the actual biomass. However, averaged ash fusion tests [54] appear to show higher initial deformation and softening temperatures for RCG compared to MC and SRC. The lowest temperatures in each range are shown by SRC, including some well below 1000 °C, which are normally characteristic of non-woody fuels [53]. The average flow temperature measured is slightly lower for RCG, but still well above the likely combustion temperature.

The alkali content of the residual ash (Table 4) can also be used to give an indication of the slagging behaviour during combustion. CaO and K<sub>2</sub>O dominate ash from SRC, whereas that of the grasses is richest in SiO<sub>2</sub>, resulting in contrasting proportions of these elements and the two alkali metal oxides (Fig. 6). The Na<sub>2</sub>O–SiO<sub>2</sub>–K<sub>2</sub>O diagram illustrates the effect on the relative proportions of oxides, with much higher K<sub>2</sub>O:SiO<sub>2</sub> ratios in SRC ash compared to the grasses. The K<sub>2</sub>O–CaO–SiO<sub>2</sub> diagram also shows a marked separation between SRC and the grasses and corresponds to a well-studied ternary phase diagram used in glass-making [55] which can be used to



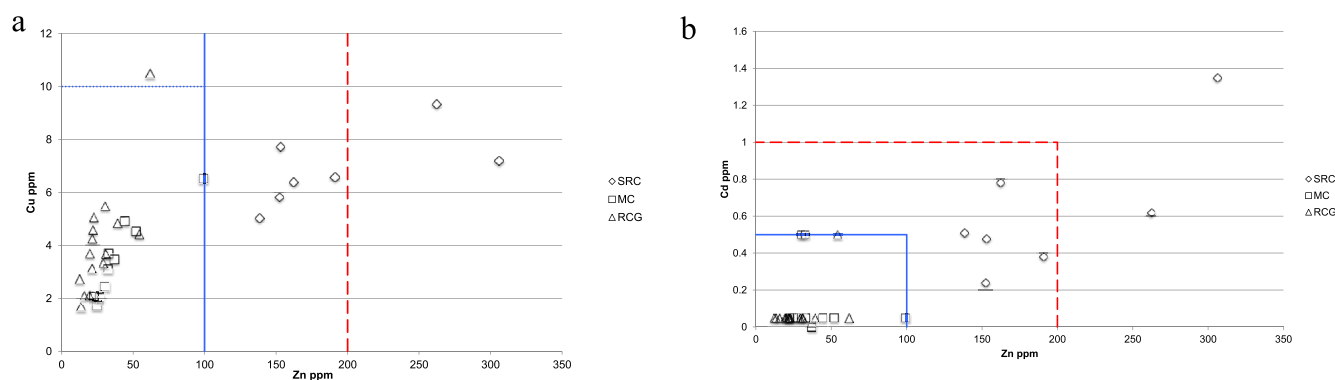
**Table 4 – Results of fuel testing of samples from full-scale growth trials at five brownfield sites.**

	SRC		MC		RCG	
	This study (n = 7)	Graded wood pellets for commercial or residential use (A1/A2/B), or industrial use (I1/I2/I3) <sup>a</sup> BS17225-2 [51]	This study (n = 10)	Graded miscanthus pellets for commercial residential or industrial use BS17225-6 [52]	This study (n = 15)	Graded reed canary grass pellets for commercial, residential or industrial use BS17225-6 [52]
<i>Fuel characteristics</i> (on dry basis) <sup>b</sup>						
Ash content (%)	2.1 (1.8–2.3)	0.7/1.2/2.0, 1/1.5/3	<b>5.0 (4.2–6.4)</b>	4/>4	<b>8.6 (5.5–12.3)</b>	8/>8
Volatile matter (%)	79 (77–80)		77 (76–79)		71 (47–77)	
Fixed C (%)	19 (18–20)		18 (17–19)		20 (17–47)	
Total S (%)	0.03 (0.03–0.04)	0.04/0.05/0.05, 0.05/0.05/0.05	<b>0.08 (0.06–0.10)</b>	0.05	0.10 (0.01–0.25)	0.20
Cl (%)	0.01	0.02/0.02/0.03, 0.03/0.05/0.1	<b>0.16 (0.01–0.33)</b>	0.08	<b>0.40 (0.16–0.6)</b>	0.10
F (ppm)	17 (15–23)		15		16 (15–36)	
C (%)	49 (49–50)		45 (42–48)		40 (32–46)	
H (%)	6.0 (5.8–6.1)		5.5 (5.0–5.9)		5.8 (5.3–6.5)	
N (%)	2.3 (0.6–5.4)	0.3/0.5/1.0, 0.3/0.3/0.6	0.4 (0.1–0.7)	0.5	0.8 (0.4–1.4)	2.0
O by difference (%)	40 (37–42)		44 (41–48)		44 (35–53)	
Gross calorific value (MJ.kg <sup>-1</sup> )	20.3 (19.8–20.6)		19.1 (18.7–19.5)		18.1 (17.5–19.1)	
<i>PTE contaminants</i>						
As (mg kg <sup>-1</sup> )	0.5	1, 2	0.5	1	0.5	1
B (mg kg <sup>-1</sup> )	5.7 (4.8–6.3)		3.4 (1.3–9.3)		6.9 (2.5–12)	
Cd (mg kg <sup>-1</sup> )	<b>0.62 (0.24–1.3)</b>	0.5, 1.0	0.14 (0–0.5)	0.5	0.10	0.5
Cr <sup>T</sup> (mg kg <sup>-1</sup> )	0.20 (0.14–0.26)	10, 15	1.1 (0.36–1.7)	50	2.6 (0.49–7.7)	50
Cu (mg kg <sup>-1</sup> )	6.9 (5.0–9.3)	10, 20	3.5 (1.7–6.5)	20	4.1 (1.7–11)	20
Pb (mg kg <sup>-1</sup> )	0.49 (0.29–0.73)	10, 20	0.62 (0.29–1.2)	10	2.2 (0.54–9.2)	10
Hg (mg kg <sup>-1</sup> )	0.02	0.1, 0.1	0.02	0.1	0.02	0.1
Ni (mg kg <sup>-1</sup> )	0.43 (0.29–0.6)	10, NL	1.1 (0.47–1.7)	10	2.3 (0.43–6.8)	10
Zn (mg kg <sup>-1</sup> )	195 (138–306)	100, 200	40 (22–99)	100	28 (12–62)	100
<i>Ash composition (wt %)</i>						
SiO <sub>2</sub>	2.6 (1.3–1.9)		62 (53–72)		67 (55–77)	
Al <sub>2</sub> O <sub>3</sub>	0.6 (0.5–0.9)		0.6 (0.3–1.3)		1.1 (0.2–2.9)	
Fe <sub>2</sub> O <sub>3</sub>	0.8 (0.5–1.2)		0.4 (0.2–1.3)		0.8 (0.3–1.9)	
TiO <sub>2</sub>	0.05 (0.03–0.07)		0.04 (0.02–0.07)		0.08 (0.02–0.18)	
Mn <sub>3</sub> O <sub>4</sub>	0.17 (0.08–0.34)		0.14 (0.05–0.28)		0.12 (0.05–0.28)	
CaO	32 (26–36)		6.3 (4.3–8.8)		7.7 (4.7–13)	
MgO	9.2 (6.2–12)		3.8 (3.3–4.8)		3.3 (2.5–4.6)	
Na <sub>2</sub> O	1.6 (0.7–2.5)		1.2 (0.6–2.1)		0.5 (0.2–1.0)	
K <sub>2</sub> O	30 (26–35)		15 (8–20)		12 (8–15)	
P <sub>2</sub> O <sub>5</sub>	21 (17–26)		7.9 (5.3–11)		5.8 (3.8–7.7)	
SO <sub>3</sub>	3.2 (2.4–5.1)		1.6 (1.0–2.6)		1.8 (0.9–3.7)	
<i>Ash fusion tests (reducing)<sup>c</sup></i>						
Initial deformation temperature °C	1200 ( <u>900</u> –1400)		1065 ( <u>950</u> –1100)		1214 (1000–1400)	
Softening temperature °C	1291 ( <u>980</u> –1480)		1282 (1090–1400)		1313 (1220–1400)	
Hemispherical temperature °C	1357 (1100–1480)		1332 (1240–1400)		1351 (1260–1400)	
Flow temperature °C	1400		1384 (1330–1430)		1381 (1310–1400)	

<sup>a</sup> Where multiple grades exist for a use these are separated by slashes.

<sup>b</sup> Identified values exceed industrial limits (bold) or commercial/residential limits only (bold italic).

<sup>c</sup> Values are underlined where below 1000 °C.



**Fig. 5 – Comparison of (a) Zn and Cu content and (b) Zn and Cd content of SRC, MC and RCG harvested from five brownfield sites. Limits for commercial/residential/industrial use of RCG/MC pellets [52] shown as solid (blue) line, industrial use of wood pellets [51] by dashed (red) line and commercial/residential use by (blue) dotted line where different from RCG/MC limits for Cu (see Table 4). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)**

predict melting behaviour of ash [56]. It can be seen that the energy grasses plot in the corner defined by  $\text{SiO}_2$  contents of 65–85%. Compositions in this area will have first melts at 720 °C at the eutectic point close to the composition  $\text{K}_2\text{O} \cdot 4\text{SiO}_2$  ( $\text{SiO}_2 = 72\%$ ). However, for the extreme case of RCG ash with >85%  $\text{SiO}_2$ , the final melting temperatures could be above 1400 °C, indicating a highly extended melting interval. It follows from this that at typical operational temperatures (<1000 °C) only a small proportion of the ash may have melted, which is then consistent with the lack of flow observed during the ash fusion tests (Table 4).

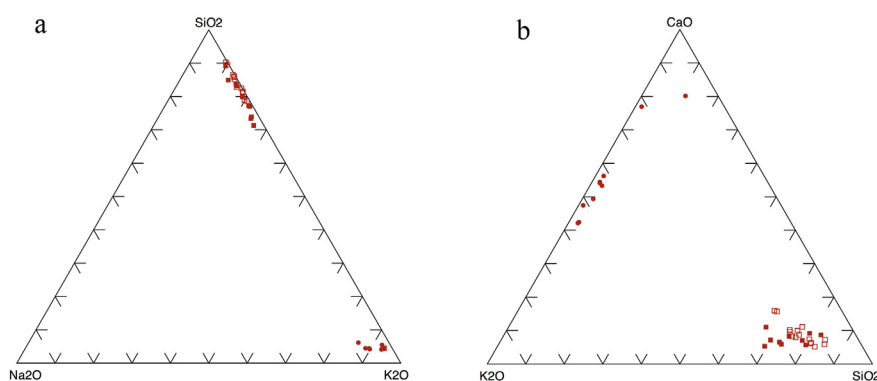
Harvesting and sampling of energy crops was not optimized for obtaining biomass with a high dry matter content. However, determination of moisture content after mowing, or from sub-sampling of baled RCG, indicates that moisture contents of c.30% are readily achievable (Table 5). Gross calorific values of RCG are approximately 17.5–18.2  $\text{MJ kg}^{-1}$  on a dry basis, reducing to net calorific values of 7.4–14.1  $\text{MJ kg}^{-1}$  for material as received when the combined effects of water and hydrogen content are included. For the average mechanical yield, water content at harvest, gross and net calorific values, this corresponds to a hypothetical gross energy yield of 97  $\text{GJ ha}^{-1} \text{a}^{-1}$  and a corresponding practical net energy

yield of 84  $\text{GJ ha}^{-1} \text{a}^{-1}$ . While the fuel parameters may differ slightly for MC or SRC, most notably the higher  $\text{H}_2\text{O}$  content of SRC at harvest, the overwhelming factor determining the energy yields from these crops would be the lower biomass yields, which were <1% of that of RCG over the first three years at these sites.

## 4. Discussion

### 4.1. Non-agricultural land types and challenges for bioenergy production

Provided that a suitably productive energy crop species can be identified, then a variety of non-agricultural land types could hypothetically be made available for sustainable biomass production, although each presents specific challenges for cultivation. These include marginal lands [14,16,23,31] (such as brownfields, previously developed or contaminated land, and other land types affected by diffuse contamination), abandoned agricultural land [25,57,58], degraded land [59,60], or capped landfills used for waste disposal [61,25].



**Fig. 6 – Ternary diagrams (a)  $\text{K}_2\text{O}$ – $\text{SiO}_2$ – $\text{Na}_2\text{O}$  and (b)  $\text{K}_2\text{O}$ – $\text{CaO}$ – $\text{SiO}_2$  showing normalized ash compositions for SRC (circles), MC (solid squares) and RCG (open squares) harvested from five brownfield sites.**

Table 5 – Details of fuel characteristics of mechanically harvested and baled RCG.

Site	Harvest date	Baled yield (db) <sup>a</sup> ODT ha <sup>-1</sup>	Water content as mown (wb) <sup>b</sup> %	Gross CV (db) MJ kg <sup>-1</sup>	Ash content (db) %	H <sub>2</sub> O (ar) <sup>c</sup> %	Gross CV (ar) MJ kg <sup>-1</sup>	H % (db) %	Net CV MJ/kg (ar) <sup>d</sup> MJ kg <sup>-1</sup>	Gross energy yield (db) GJ ha <sup>-1</sup> a <sup>-1</sup>	Net energy yield (ar or wb) GJ ha <sup>-1</sup> a <sup>-1</sup>
Tees barrage	Mar-09	4.9	35.6	18.19	9.2	14.6	15.54	5.73	14.11	89	81
	Oct-09	4.9		17.92	12.3	48.8	9.174	5.47	7.370	88	71
Haverton hill	Mar-09	5.6	33.1	18.01	10.5	30.8	12.47	5.78	10.84	101	88
	Oct-09	5.6		17.79	11.1	31.2	12.24	5.31	10.68	100	87
Warden law	Mar-09	6.7		17.55	8.9	14.6	14.99	6.00	13.51	118	106
	Oct-09	5.9		17.78	9.5	37.7	11.07	5.54	9.399	105	89
Rainton bridge (ave)	Mar-09	5		17.94	11.4	24.4	13.56	5.69	12.02	102	90
	Oct-09	4.4		17.45	9.5	29.0	12.39	5.35	10.85	77	67
Spring (ave)		5.7		17.92	10.0	21.1	14.14	5.80	12.62	102	91
Ave autumn		5.2		17.73	10.6	36.7	11.22	5.42	9.57	92	79
Average all		5.5		17.829	10.3	28.9	12.68	5.61	11.10	97	85
Typical as mown		5.5	34.3	17.83	10.3	n/a	11.71	5.61	10.07	97	84

<sup>a</sup> Dry biomass (db) calculated from wet yield and water content (as mown).

<sup>b</sup> Wet biomass (wb) after cutting, average of two samples per site.

<sup>c</sup> As received (ar) by laboratory (after storage as bales).

<sup>d</sup> See (Van Loo and Koppejan 2008) for calculation method.

Worldwide definitions of “brownfield” land vary subtly [62], indicative of perhaps only previous development for non-agricultural purposes in the UK [63], but with an implied presumption of contamination in the US [64] – the commonality between these definitions is that immediate reuse is currently prevented pending some degree of investigation, contamination testing or subsequent possible remedial action. In the context of the present study any damage or soil contaminants from previous industrial use of brownfield land might limit growth through phytotoxicity or render food crops unsuitable for consumption from elevated Zn, Cu, Pb, As or Cd contents [65].

Definitions of marginal land also vary [66], including land unsuitable for food production, ambiguously defined lower quality land, and economically marginal land, from which it follows that lower biomass yields may be expected than on other agricultural land. Productivity and energy yield will be reduced on abandoned agricultural land [57].

On former landfilled waste disposal sites the generation of landfill gas, leachate, geotechnical instability and potential contamination would prevent future redevelopment without prohibitively expensive mitigation measures [67], so the sites are often simply enclosed to prevent access and then remain unused, presenting an opportunity for possible biomass production. However, shallow soil depth, compaction and low water holding capacity and poor nutritional status are all likely [61] which, unless addressed by soil amendment, will limit growth of energy crops such as willow coppice [68,69]. Low productivity after establishment was found for both willow and Miscanthus in the present study, even after surface soil amendment, illustrating the lack of water retention and availability in the relatively shallow soil profiles created on capped or compacted sites. For example, to grow trees successfully on capped landfills or similarly “disturbed” former mineral extraction sites typically requires a minimum of 1–1.5 m of placed soils during restoration [19,61,70]. Many older landfill sites or industrial brownfields will by necessity have much thinner soil horizons [21]. With the resultant initial investment in remedial site preparation by soil importation or amendment required for tree planting, this is unlikely to be a cost effective approach to widespread biomass provision.

In urban or peri-urban areas other similar vacant, derelict, underutilized or neglected land parcels may exist, collectively referred to as “DUN” land [71]. These include the curtilage of operational industrial sites, surplus public open space, and land around utilities or infrastructure.

In the context of energy crop production these various non-agricultural land types described above share a range of potential agronomic challenges, including physical, chemical and biological factors: Phytotoxicity, remaining structures or ground obstacles, thin soils, physical compaction, consequently poor natural drainage, water infiltration, retention, or aeration, characteristically low organic matter content and limited nutrients, competition from weeds, pests and uncontrolled grazing. The land itself may be “made ground” with anthropogenic soil, highly variable topsoil and subsoil that are either thin, stony, heavy clays or simply non-existent. This could provide an opportunity for recycling soil-forming materials [14] if these are locally available. Otherwise, many common crops are either not viable or their productivity is

severely limited, at best giving yields comparable to low grade or marginal agricultural land. This is illustrated by the poor growth, establishment and survival rates of the two conventional energy crops, SRC and MC, achieved in our field trials [17]. Hence the successful cultivation of non-agricultural land for energy crops with a viable productivity requires the development of a specific methodology and the identification of the most appropriate species for the likely challenging soil conditions.

#### 4.2. Perennial rhizomatous grasses as alternatives to woody energy crops on non-agricultural land

As an alternative to forestry or coppice, three perennial rhizomatous grasses (PRGs) are commonly used for energy crop production [42], namely elephant grass (*Miscanthus x giganteus*), SG (*Panicum virgatum*) and RCG (*Phalaris arundinacea*). Compared to woody energy crops these grasses offer reduced lead time to production (typically 2–3 years), annual harvesting regimes thereafter, lower water content at harvest (20–30% compared to 50–60%). According to the literature perennials offer better productivity, net calorific values and ecological benefits than annual crops [42], with lower environmental impacts [59], lower carbon debt and greater greenhouse gas reductions [11], especially when grown on degraded or abandoned agricultural land [57]. Environmental benefits of the continuous annual cropping regime of PRGs include reduced tillage, soil degradation and carbon loss, higher radiation capture and root density, better soil stabilization, improved run-off quality and wildlife habitat [72]. While the C<sub>4</sub> grasses like MC and SG should provide higher yields in Southern and Central Europe, C<sub>3</sub> grasses like RCG may outperform these in northern Europe [42]. The usual commercial variety of MC is a sterile hybrid and must be planted as the rhizome or micro-propagated plant [73], so for non-agricultural land the higher planting and site preparation costs could provide the same economic disincentives for MC as for forestry, whereas SG and RCG can be grown directly from seed more cheaply.

RCG is native to Eurasia and North America with a wide climatic range across W Europe [74]. It is one of the highest yielding cool-season grasses [45]. It is a marginal wetland plant that tolerates waterlogging in poorly drained, heavy, compacted soils, together with drought [42], such as in well-drained, light or artificial soils. This is coupled with early season growth, rapid vegetative spread, high stem elongation potential, wide physiological tolerance, high architectural plasticity and longevity [75]. Mulching out of competing seeds, reduced grazing due to high alkaloid content, tolerance of phytotoxic metals and few known diseases are all attributes reported in the literature [45,42]. As a result this perennial would appear to be highly suited to establishment on non-agricultural land and the expected soil conditions. This is illustrated by considering the growth conditions of naturally established colonies (Fig. 7): At this freshwater lake RCG has naturally colonized and stabilized sandy gravels in a high-energy beach environment prone to periodic changes in water level, producing regular inundation and desiccation during both the winter and the summer growth period. This example provides a natural analogue for the free-draining



**Fig. 7 – Wild RCG (*Phalaris arundinacea*) colonizing sandy gravel above and below a fluctuating water line, Ullswater, English Lake District. Photo B. Kwa.**

anthropogenic mineral soils found on brownfield sites and the extremes of drought and flooding that could result from compaction and lack of drainage. Against this must be set the potential for invasive spread of non-native genotypes, such as in USA, where RCG is also a native species, but agricultural varieties locally outcompete other native plant species [75].

A further possible disadvantage of RCG is that it shows a lower N and energy use efficiency than MC, particularly for the higher N application rates needed to maximize production per unit area [76]. A positive consequence of this is that higher yields can be obtained without mineral fertilizers in water-logged organic soils where soil N levels are higher [77]. Conversely, yields on sandy low productivity soils may be low but responsive to N addition [78]. In our trials *in situ* incorporation of green waste compost to soils [38] was found to be a cost effective and environmentally benign means of achieving a viable seed bed and shallow, water retentive growth medium for RCG, as is illustrated by the uniform establishment and consistent productivity.

#### 4.3. Performance of RCG for biomass production on non-agricultural land

Of the three critical factors considered here to assess the potential of RCG as an energy crop grown on DUN land, the actual yields achievable on non-agricultural sites is fundamental, since it will determine both the economic viability and the overall energy balance of production. Agricultural yields for RCG as an energy crop of 7.5–9 odt ha<sup>-1</sup> are reported for Finland [42] for spring and autumn harvests respectively, ranging 6.5–7.5 odt ha<sup>-1</sup> with varying seasonal conditions in Lithuania [79], with perhaps higher yields achievable for conditions of optimum fertilization and good management [45]. This suggests that a figure of c.8 odt ha<sup>-1</sup> might reasonably be assumed as a benchmark for productive agricultural land in NE England. Yields below 4 odt ha<sup>-1</sup> were reported for marginal agricultural land in SE England to which up to 250 kg ha<sup>-1</sup> N had been applied

[78]. Against these our median yields of 6, 5 and 3 odt ha<sup>-1</sup> for the second, third and fourth/fifth years on brownfield sites compare favourably. Moreover, it should be born in mind that both MC and SRC effectively failed to establish productively on these same sites and particular ground conditions. RCG yields more than other cool-season grasses on heavy compacted soils because it is better able to tolerate the combination of poor drainage and drought [45]. Aerenchymatous tissues can supply oxygen to the root system allowing growth on waterlogged peat soils [80].

Establishment costs are also critical in determining whether biomass cropping will be economically viable. The average planting and plant material costs for RCG (seed, broadcasting, rolling) were £1029 ha<sup>-1</sup> compared to £2143–£4432 ha<sup>-1</sup> for SRC (cuttings, step-planting or hand-planting) and £2046–£2918 ha<sup>-1</sup> for MC (rhizomes, hand-planted or using modified potato planter). These costs (2007 prices, excluding Value Added Taxes) were for c. 0.25 ha plots on five geographically dispersed sites, so would be significantly improved upon through economies of scale for larger brownfield sites, but suggest that planting and planting stock costs for seeded grasses like RCG are at most 50% of those for MC or SRC. Land charges are estimated to be 18–23 % of the costs of farmland RCG production in the USA [45], so if use of vacant non-agricultural land could be secured free-of-charge in return for the associated aesthetic and environmental improvements, this improves viability further. Conversely, for brownfield land the site preparation costs will be considerably higher. For these trials the average costs of site preparation were £9446 ha<sup>-1</sup> (2007, excluding site fencing and VAT) of which 60% was the cost of purchasing and transporting the compost. Again these costs might be reduced considerably for larger sites, site clusters, or those nearby to composting facilities. For brownfield sites these might be offset against the likely costs of restoration for other non-productive uses, such as for green infrastructure or amenity use. Uncertainty over future economic performance has been a key barrier to investment in, and establishment of, long-term perennial crops by UK farmers on agricultural land [81,82]. With lower initial investment and annual cropping from the second season [79] RCG offers the potential for shorter payback periods and land commitment than for SRC or MC. Our trials indicated that actual harvested yields of 5–6 odt ha<sup>-1</sup> a<sup>-1</sup> at water contents of c. 30% were readily achievable using commonplace agricultural equipment, equivalent to a potential gross annual energy yield of 97 GJ ha<sup>-1</sup> a<sup>-1</sup>. This corresponds to a practical net energy yield of 84 GJ ha<sup>-1</sup>, which compares favourably to results for agricultural land of 101–123 GJ ha<sup>-1</sup> [79] (when recalculated for the same average water contents of 34.2%), for which an energy input of 8–19 GJ ha<sup>-1</sup> a<sup>-1</sup> was calculated.

Estimates of the purely economic value of this energy yield and break even point are complicated by a number of site-specific variables, including size and economies of scale, harvest timing, method and water content, distance to point of use, energy conversion choice and efficiency. However, an initial assessment based on the scenario of local dedicated biomass combustion and electrical generation (Narec, Blyth UK, unpublished report D4.3 for BioReGen Project, 2010) [34] suggested that the equivalent monetary value of the associated remediation,

biodiversity and ecosystem service benefits would need to be considered to ensure short-term economic viability.

#### 4.4. Market flexibility and suitability for use of RCG produced from non-agricultural land

Two further issues were proposed at the outset of this study as being critical to the viability of using brownfield land for biomass production, namely the potential for fuel contamination and the related issue of suitability for use for a recognized market. The potential for direct or indirect uptake from brownfield soil leads to a presumption or perception of cross contamination: For pellet feedstocks for example “Where any operator in the fuel supply chain has reason to suspect serious contamination of land (e.g. coal slag heaps) or if planting has been used specifically for the sequestration of chemicals or growing biomass is fertilised by sewage sludge (originating from waste water treatment or chemical process), fuel analysis should be carried out to identify chemical impurities such as halogenated organic compounds or heavy metals” [52]. Our results have confirmed that on brownfield sites these effects are most pronounced in SRC and MC rather than RCG [15]. Although RCG contains lower levels of heavy metal such as Zn and Cd, it would fall below the standard required for commercial or residential pellets due to Cl and possibly S content, which might be expected to rise on made ground comprising certain types of industrial wastes. The effects of alkali content on ash melting temperature were not found to be significant in our fusion tests. However, Paulrud et al. [56] observed worse results in fluidized bed agglomeration tests, and with a high ash content and the potential for acid generation described above it is likely that use of brownfield fuel for combustion would still be restricted to industrial scale facilities with appropriate air pollution controls.

In addition to the options of spring or autumn harvesting of dry, senescent RCG for biomass combustion [83,84], RCG might also be used to supply other developing renewable energy markets, giving operational flexibility and economic surety to producers. These could include second generation bioethanol production [85,86], pyrolysis [87] or biomass carbon capture and storage [88]. RCG might be used as a feedstock for anaerobic digestion [89,90], for methane or hydrogen [91] with summer harvesting of vegetative growth and the possibility to increase biomass or energy yield through multiple harvesting [92,80] or energy storage as silage [93] adding further flexibility and certainty of use. In Northern European latitudes where maize cannot be cultivated [94], RCG may be a suitable alternative feedstock for anaerobic digestion, especially when grown on marginal land. For maritime European climates, such as Scotland, these alternatives to combustion offer the distinct advantage that harvesting of a dry standing crop is not a prerequisite for storage or an adequate net calorific value and energy yield.

## 5. Conclusions

1. RCG can be readily established from seed at relatively low cost and grown productively on derelict underutilized neglected (DUN) land, including brownfield sites, capped landfills and other similar artificial soil profiles following

limited ground preparation and low intensity cultivation, such as *in situ* incorporation of 500 t ha<sup>-1</sup> green waste compost.

2. The biomass productivity of RCG out-performs that of conventional energy crops on non-agricultural land (in NE England), including the C<sub>4</sub> perennial rhizomatous grasses such as SG or MC, or woody species such as SRC.
3. RCG biomass grown on contaminated land shows limited contaminant uptake when compared to MC or SRC, especially for the uptake of Zn and Cd. Although the biomass is rich in K and low in Ca, additional Si and ash content offset this, improving fuel quality for combustion. The biomass is suitable for use for commercial and industrial scale combustion, with the added advantage of alternative energy uses, such as conversion via anaerobic digestion to biogas or to bioethanol for transport fuels.
4. The combination of rapid establishment, low initial cost and annual harvesting means that temporary cropping of non-agricultural land with RCG is a technically viable proposition: Economic viability is dependent on consideration of the associated natural capital and eco-system service gains, synergies or trade-offs resulting from its use as part of the “energyscape” [95].
5. In addition to the land types considered here, by analogy, RCG is also a promising candidate for establishment on low productivity marginal agricultural land. Since derelict underutilized land is unused and marginal agricultural land is uneconomic for agriculture, use of these land banks for growing energy crops would have less impact on food production in the context of the food-fuel-water “nexus” allowing sustainable bioenergy energy provision services approaching 100 GJ ha<sup>-1</sup> a<sup>-1</sup>.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.biombioe.2015.04.015>.

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