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ORIGINAL RESEARCH

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How much heat can we grow in our cities? Modelling UK urban biofuel production potential

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Abstract

Biofuel provides a globally significant opportunity to reduce fossil fuel dependence; however, its sustainability can only be meaningfully explored for individual cases. It depends on multiple considerations including: life cycle greenhouse gas emissions, air quality impacts, food versus fuel trade-offs, biodiversity impacts of land use change and socio-economic impacts of energy transitions. One solution that may address many of these issues is local production of biofuel on non-agricultural land. Urban areas drive global change, for example, they are responsible for 70% of global energy use, but are largely ignored in their resource production potential; however, underused urban greenspaces could be utilized for biofuel production near the point of consumption. This could avoid food versus fuel land conflicts in agricultural land and long-distance transport costs, provide ecosystem service benefits to urban dwellers and increase the sustainability and resilience of cities and towns. Here, we use a Geographic Information System to identify urban greenspaces suitable for biofuel production, using exclusion criteria, in 10 UK cities. We then model production potential of three different biofuels: *Miscanthus* grass, short rotation coppice (SRC) willow and SRC poplar, within the greenspaces identified and extrapolate up to a UK-scale. We demonstrate that approximately 10% of urban greenspace (3% of built-up land) is potentially suitable for biofuel production. We estimate the potential of this to meet energy demand through heat generation, electricity and combined heat and power (CHP) operations. Our findings show that, if fully utilized, urban biofuel production could meet nearly a fifth of demand for biomass in CHP systems in the United Kingdom's climate compatible energy scenarios by 2030, with potentially similar implications for other comparable countries and regions.

KEYWORDS

land-use, *Miscanthus*, poplar, resilience, short rotation coppice, sustainability, willow

1 | INTRODUCTION

There is an urgent need to shift global energy production away from fossil fuels towards renewable sources in order to reduce greenhouse gas (GHG) emissions (International Energy Agency, 2018). The specific location and use case of bioenergy are critical to whether biomass fuel switching delivers a net sustainability gain. Criticisms of biomass as a sustainable energy source relate to its life cycle emissions (Caputo et al., 2014; Thornley, Gilbert, Shackley, & Hammond, 2015), local air quality impacts (Bikkina et al., 2019), past economic and policy failures (Adams & Lindegaard, 2016; Parra-López et al., 2017), potential land conflict with food production (Aylott, Casella, Farrall, & Taylor, 2010; Hastings et al., 2014; Wang et al., 2014) and poorly designed policies leading to perverse incentives (Fajardy & Mac Dowell, 2017; Millward-Hopkins & Purnell, 2019).

One approach that ameliorates many of these concerns is to produce biofuel within urban areas, close to where it is to be used. Use of urban land in this way potentially presents a 'win-win-win' scenario by reducing food versus fuel conflicts on high quality agricultural land (Raman et al., 2015), providing a source of fuel close to centres of demand for energy (Renewable Fuels Agency, 2008), and increasing the sustainability and resilience of cities and towns (Norton, Evans, & Warren, 2016). The latter is increasingly important as the global urban population is growing, currently 55% and reaching 68% by 2050 (United Nations, 2018). Consequently, urban areas are drivers of global change and mechanisms to improve their sustainability and resilience are vital, as recognized in UN Sustainable Development Goal 11: Sustainable Cities and Communities. At present, cities account for 37%–49% of global GHG emissions and urban infrastructure for 70% of global energy use (Kekana & ISOCARP, 2019).

Urban biofuel cultivation that supplies local combined heat and power (CHP) systems, if carefully managed to minimize life cycle GHG emissions (comprised of both management/harvesting operations and fuel transport costs between source and destination locations; Bauen et al., 2010; Fajardy & Mac Dowell, 2017; Yang et al., 2017), could be used to reduce city-wide CO_2 emissions. Use of urban greenspace for biofuel production could also deliver additional ecosystem services to urban residents (McHugh, Edmondson, Gaston, Leake, & O'Sullivan, 2015) such as flood protection (O'Sullivan, Holt, Warren, & Evans, 2017), pollution mitigation (Sugiura, Tyrrel, Seymour, & Burgess, 2008) and soil carbon sequestration (Cunniff et al., 2015; Matthews, Grogan, & Matthews, 2002). Although representing poorer and more homogeneous habitat than fully natural or semi-natural habitats, biofuel plantations are also likely to support greater floral, invertebrate and avian biodiversity than arable cropland or mown grassland (Rowe, Street, & Taylor, 2009; Sage, Cunningham, & Boatman, 2006).

Urban greenspaces are recognized to provide vital ecosystem services (Grafius, Corstanje, Siriwardena, Plummer, & Harris, 2017; McDonnell & MacGregor-Fors, 2016); however, their ability to support provisioning services is poorly understood and research thus far has focussed on urban agricultural food production (CoDyre, Fraser, & Landman, 2015; Martellozzo et al., 2014). Here, we explore the potential suitability of greenspaces in 10 diverse cities across the United Kingdom to support biofuel production using a Geographic Information System (GIS)-based analysis. We focus on short rotation coppice production (SRC), the planting and regular harvesting of fast-growing tree species and *Miscanthus* grass. Relative to fossil fuels, SRC and *Miscanthus* biofuel represent a predictable, carbon-neutral energy source if managed sustainably (Hastings et al., 2014; Wang et al., 2014; Yang et al., 2017). As such, it is recognized as an important component of renewable energy production (European Commission, 2014; Foxon, 2013), and continues to form part of many national and transnational environmental policies and agreements (Alexander, Moran, Rounsevell, Hillier, & Smith, 2014; Matthews et al., 2002; McHugh et al., 2015; Upham & Speakman, 2007). The objective of this research was to estimate the potential of urban biofuel production at a national scale; whereas previous research has focused on rural environments where food versus fuel conflicts will be stronger (Aylott et al., 2010; Hastings et al., 2014) or assessed urban production potential in a single city (McHugh et al., 2015).

In this study, we estimate how much urban greenspace can support biomass production for CHP in UK cities. In so doing we explore whether urban biomass production has a 'sustainable' end market. Areal results for each city were combined with published geographic location-specific yield data on common biofuel crops (SRC willow; SRC poplar and *Miscanthus* grass) to explore the production potential of each city and, by extrapolation, to urban areas across the entire country. Our research builds directly on that of McHugh et al. (2015), who estimated the production potential in Leicester, United Kingdom; whereas here we consider 10 representative urban areas across the United Kingdom and through this seek to extrapolate our findings to a nationwide estimate. Finally, we investigate the implications of these results in the context of heat and power demand, national sustainability targets and future energy scenarios (FES).

2 | MATERIALS AND METHODS

2.1 | Study area

The 10 study areas this research considered were: the cities of Leicester, Southampton, Nottingham, Newcastle upon Tyne, Bristol, Edinburgh, Swansea/Abertawe, Milton Keynes, Liverpool and Sheffield (Figure 1). Collectively, these urban areas cover a broad geographic range across the island of Great Britain, as well as representing a wide variety of urban landscape structures and histories in order to act as a representative sample of UK urban areas as a whole.

2.2 | Vegetation location using aerial imagery and normalized difference vegetation index

Landmap colour infrared (CIR) aerial imagery (Landmap; Bluesky, 2014) was acquired for all study areas, chosen for its spatial resolution and availability. Due to the nature of the data and acquisition, gaps existed in some areas, usually outer rural or semi-rural regions surrounding the urban areas. Imagery was captured for each study area on different dates, and in some cases, the imagery from individual cities was split over multiple dates (see Table S1). Normalized difference vegetation index (NDVI) was derived for each study area from the imagery using the Image Analysis functionality in ArcGIS (ESRI, 2013). NDVI acts as a commonly used and straightforward measure of relative vegetation density, health and abundance due to biophysical and reflectance properties of living leaves, and is calculated based on the difference in reflectance between visible red wavelengths and near infrared wavelengths:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{Red})}{(\mathrm{NIR} + \mathrm{Red})}.$$

Once calculated, a threshold NDVI value was selected for each study area to distinguish vegetated from non-vegetated areas. The differences in acquisition dates, and thus seasonality of vegetation, between study areas meant that the appropriate NDVI threshold (determined by visual comparison) value varied by study area. Appropriate threshold values were thus selected through visual analysis of the imagery in various land covers of each city (see Table S1). Note that imagery in Nottingham was split between the east and west halves of the city by date with vegetation differences significant enough to warrant separate NDVI thresholds.

2.3 | Vegetation correction using Ordnance Survey MasterMap

Thresholding of NDVI values was able to separate vegetation from non-vegetation to a large degree; however, image properties and artefacts caused some lingering issues. In Southampton and Edinburgh, slight offsets between image colour bands and seasonal effects due to image timing caused some false vegetation readings in paved or built-up areas. In Newcastle upon Tyne and Swansea, reflectance from shallow offshore areas falsely registered as vegetation. In Sheffield and Swansea, upland areas covered with very sparse vegetation registered as non-vegetated.

In order to correct for these issues, Ordnance Survey MasterMap data (Ordnance Survey (GB), 2017) were used to identify known areas of buildings, structures and water and exclude these from consideration as vegetated surfaces. Polygon features identified either primarily or secondarily as buildings or structures, or primarily as water, were used to remove pixels from the NDVI vegetation layer. This was done on the expectation that the MasterMap data would depict these features reliably and help correct for uncertainties in areas known to be unvegetated, whereas NDVI thresholding is subject to uncertainty due to variations in seasonality, atmospheric properties and sensor characteristics.

2.4 | Calculation of urban areas suitable for biofuel production

Based on research described in McHugh et al. (2015) and adapted from Aylott et al. (2010), multiple exclusion criteria were applied in GIS to remove areas from analysis that were deemed unsuitable for biofuel production and operation due to legality, desirability or public usage rights. These include various protected lands (e.g. Sites of Special Scientific Interest—SSSI, national and local nature reserves and World Heritage Sites), common land (land with shared usage rights), public rights of way (land with public access rights), recipients of other government schemes such as countryside stewardship agreements (which encourage environmental improvements to rural lands) or areas otherwise set aside for uses incompatible with biofuel cultivation (Natural England, 2013; see Table S2). Current government guidance and grants for SRC and other biofuel operations in the United Kingdom focus on agricultural lands, but our research assumes that this guidance could be readily adapted for use in urban settings.

Lands listed under the Agricultural Land Classification (ALC) system as Grades 1–3 arable land were also excluded, as these represent lands with high-quality agricultural potential, in order to avoid conflicts between biofuel plantations and arable land that could be better utilized in food crop production. The remaining grades (4, 5, non-agricultural and urban) were theorized to be only marginally less efficient for biofuel production given recent findings about urban soil quality, compaction and carbon content being similar to or more favourable than agricultural lands (Edmondson, Davies, Gaston, & Leake, 2014; Edmondson, Davies, McCormack, Gaston, & Leake, 2011), while less desirable for food crop cultivation. Although the food/fuel conflict may seem an unnecessary consideration in urban areas at present, growing concerns over global food security and interest in urban agriculture supported the exclusion of high-grade land that may be better used for food production, even in urban areas (Edmondson et al., 2019). Subsequent refinement of spatial layers did not further consider ALC grade, as regional/climatic differences were found by Aylott et al. (2010) to explain a greater degree of variation in SRC yield across the United Kingdom than

ALC grade/soil quality, and were thus treated as a higher priority. Aylott et al. (2010) considered both region and ALC grade in England-wide estimates of SRC potential, finding a mean variation in yield of 2.9 oven dry tonnes (ODT) ha^{-1} year^{-1} across geographic regions, compared with a mean yield variation of 1.2 ODT ha^{-1} year^{-1} across ALC grades. Given this finding, we chose to use figures from Hastings et al. (2014) for yield estimations (discussed below) for their more complete regional coverage (inclusive of Scotland and Wales rather than only England), more recent figures and inclusion of multiple crop types. Although we did not explicitly consider climate impacts on crop yields, these data nonetheless enabled a representative coverage across Great Britain and region-specific yield figures, which were assumed to correlate with any noteworthy climatic effects.

Selection by attribute query was used to isolate the key exclusion features in each data set, which were then removed from the analysis area. The raster vegetation layer was clipped to those areas deemed suitable for biofuel plantation placement. Some areas initially intended for exclusion were not removed from analysis due to unavailability of appropriate spatial data on those areas (see Table S3), but their impact on our urban study sites was assumed to be minimal. Any existing woodlands and trees not already excluded under the above criteria were identified using Environment Agency LIDAR. All features with a height greater than 2 m were removed from analysis.

The resulting raster data sets, having been created from NDVI vegetation thresholding and the exclusion of local and national designated lands, private gardens and trees, were converted to vector. Enclosed holes in potential SRC area polygons smaller than 100 m^2 were removed as these appeared to be small artefacts from NDVI calculation and were assumed in reality to be valid areas belonging to their surrounding sites. Buffers were calculated to restrict potential biofuel sites to be greater than 10 m from urban residential private gardens (rural lands outside of built-up urban areas, even if privately owned, were still available for analysis if not excluded based on other criteria). A 3 m buffer around the edge of all potential sites was removed to allow vehicle access before production potential was calculated. Finally, the area of all resulting green patches was calculated, and patches smaller than 0.5 ha in size were removed to ensure that sites under consideration would be of an adequate size to make operations practical (McHugh et al., 2015).

Once calculated, the area potentially suitable for biofuel production in each study city was compared to each city's total administrative boundary and total built-up extent (i.e. developed urban landscape but still containing small greenspaces potentially suitable for biofuel cultivation; ONS, 2011; Rowland et al., 2017). This enabled comparisons between the study cities and provided a consistent basis from which to extrapolate mean biofuel potential to urban administrative and built-up areas across the entire United Kingdom, correcting for variation in the shape and urban makeup of administrative boundaries, with the caveat that urban landscape structure is highly variable and direct comparisons are difficult (e.g. these suitability proportions were not normally distributed in our analysis). Similarly, the total area of urban greenspace within each city's administrative boundary was calculated based on the NDVI thresholding described previously, and compared to total biofuel-suitable area to produce the proportion of greenspace in each city that may be suitable for biofuel production.

We conducted a validation process where 500 of the resulting study sites were randomly selected (stratified to 50 from each study city, representing 18.7% of the total 2,680 sites) and each of these compared with high-resolution Google Earth imagery to assess the accuracy of our exclusion process. This validation process found an agreement rate with the sites our analysis had deemed potentially suitable for biofuel production of 78%. The discrepancies were driven by two factors: (a) urban development between acquisition of the CIR imagery used in our analysis and the more current 2018 Google Earth imagery, and (b) some schools and private sports fields being incorrectly classified in the OS MasterMap data we used. Additionally, some airport grassland areas were included as potential sites (clearly unsuitable, although our exclusion process had not explicitly ruled them out—nevertheless, these spaces account for a relatively small area in only some of our study cities; see Table S4 for validation rates and information by city). Despite the discrepancies, the research here is not intended to represent an exhaustive multi-criteria site suitability analysis, but rather the consideration of a maximal edge case where we look to exclude obviously unsuitable areas while still allowing for the conversion of spaces such as mown grass in parks. Unconvertible areas such as cemeteries and airport grasslands fall within what we consider to be the allowable margin of error in our results.

2.5 | Calculation of potential biofuel yield

Calculations of total available biofuel-compatible land area within each urban area were combined with figures on the potential mean yield per area in ODT per hectare per year in each region. We considered willow (*Salix* spp.) and poplar (*Populus* spp.) trees as well as *Miscanthus* grass—three of the most commonly used biofuel crops in the United Kingdom. Yield figures were taken from modelled results in Hastings et al. (2014), specific to each region of Great Britain to account for climatic differences expected to affect yield (see Table S5). This enabled the estimation of the total potential biofuel yield per study city.

These yield estimates were then combined with information on per-building heating demand and the number of dwellings present in each study city to calculate a broad estimate of each city's residential heating demand, and the proportion of it that could potentially be met by locally urban-grown biofuels. Figures from Forest Research United Kingdom (Forest Research, 2017) were used after McHugh et al. (2015) to define typical heating demands of urban structures (e.g. residential homes, district heating schemes and municipal buildings). According to these data, a typical domestic house/dwelling requires an average of 3.99 ODT of wood chips per year, a district heating scheme requires an average of 119 ODT/year and a municipal building requires an average of 203 ODT/year. Note that these values are reported by Forest Research as tonnes of wood chips with 30% moisture content/year (5.7 tonnes/year for a typical domestic house, 170 for a typical district heating scheme and 290 for a municipal building); McHugh et al. converted these to ODT/year and it is McHugh's converted figures that we use here.

3 | RESULTS

3.1 | Potential urban biofuel cultivation area

The 10 UK urban areas we studied were variable in their underlying urban structure, which translated to variations in the amount and location of greenspace potentially available for biofuel production (Table 1). Cities such as Leicester (Figure 2a), Southampton (Figure S1) and Nottingham (Figure S2) represent typical cases where urban built-up extent closely matches the urban administrative boundary, so potential biofuel sites generally represent underused greenspaces within the urban matrix (3% of Leicester's total administrative area was deemed potentially suitable, 2% for Southampton and 6% for Nottingham).

Other urban areas such as Swansea included rural lands that were outside of urban built-up areas but within the city's administrative jurisdiction, and thus may be suitable for biofuel production according to the criteria used here. In the case of Swansea, this produced high absolute and proportional values of greenspace land deemed suitable for biofuel production (Figure 2b; 8% of total administrative area), although uncertainties in the suitability of uplands for biofuel production may lead these figures to overestimate suitable land area. By contrast, in other locations, the impact of these extra-urban lands was tempered by conflicting exclusion criteria; much of the extra-urban land in Milton Keynes is ALC grade 1–3 and was thus excluded to avoid conflict with high-grade food production lands (Figure S6; 3% of administrative area deemed suitable), and much of Sheffield's extra-urban land is part of the Peak District National Park and was thus excluded due to the presence of protected and sensitive habitats (Figure S8; 2% of administrative area deemed suitable).

FIGURE 1 Urban study areas (administrative boundaries) in the United Kingdom

3.2 | Urban biofuel production potential

Total potential biofuel production in each city was calculated based on region-specific yield estimates for each crop combined with the suitable area in that city (Figure 3). In all cases except Bristol, SRC poplar generated the highest predicted yields, whereas in Bristol, *Miscanthus* grass was predicted to be the most productive crop. Swansea showed the greatest total production potential of the study cities (three times that of Edinburgh, the next highest) in terms of total ODT/year, or six times that of Milton Keynes when compared on a per-dwelling basis. However, in per-hectare comparisons, Swansea (1.13 ODT ha^{-1} $year^{-1}$) was similar to Liverpool (0.93 ODT ha^{-1} $year^{-1}$), with Edinburgh (0.62 ODT ha^{-1} $year^{-1}$) and Nottingham (0.61 ODT ha^{-1} $year^{-1}$) considerably higher than the remaining six urban areas. Collectively, the results highlight the importance that urban form can have on biofuel production potential. Although not explicitly studied here, this can include considerations such as urban history, built-up versus

TABLE 1 Total potential biofuel production area in each study site, compared proportionally to total administrative area, total built-up land and total urban greenspace in that site. Proportions of suitable total administrative areas, built-up lands and urban greenspace were all not significantly different from normal distribution according to Shapiro–Wilk's test

Study site	Total biofuel-suitable area (ha)	Biofuel-suitable area in built-up land (ha)	Total administrative area (ha)	Total built-up land (ha)	Total urban greenspace (ha)	Proportion of total administrative area suitable for biofuel production (%)	Proportion of built-up land suitable for biofuel production (%)	Proportion of urban greenspace suitable for biofuel production (%)
Leicester	237.5	194.3	7,334.2	6,076.5	2,926.4	3.2	3.2	8.1
Southampton	88.6	71.5	5,638.5	4,578.6	2,181.2	1.6	1.6	4.1
Nottingham	462.9	322.1	7,461.4	6,427.7	3,621.3	6.2	5.0	12.8
Bristol	681.7	318.6	23,532.9	8,775.7	3,928.2	2.9	3.6	17.4
Edinburgh	1,304.9	278.1	27,300.4	10,520.2	13,609.1	4.8	2.6	9.6
Swansea	3,447.1	239.8	42,089.8	5,845.7	23,962.0	8.2	4.1	14.4
Newcastle	300.1	212.4	11,511.8	6,242.8	6,557.5	2.6	3.4	4.6
Milton Keynes	772.4	75.8	30,862.7	6,088.6	21,586.7	2.5	1.2	3.6
Liverpool	786.6	584.6	13,353.4	10,227.0	5,209.8	5.9	5.7	15.1
Sheffield	827.6	278.7	36,793.0	12,299.2	8,482.6	2.6	2.3	9.8
Mean	890.9	257.6	20,587.8	7,708.2	9,206.5	4.0	3.3	9.9
SE	305.2	45.9	4,203.7	808.3	2,498.3	0.7	0.5	1.6

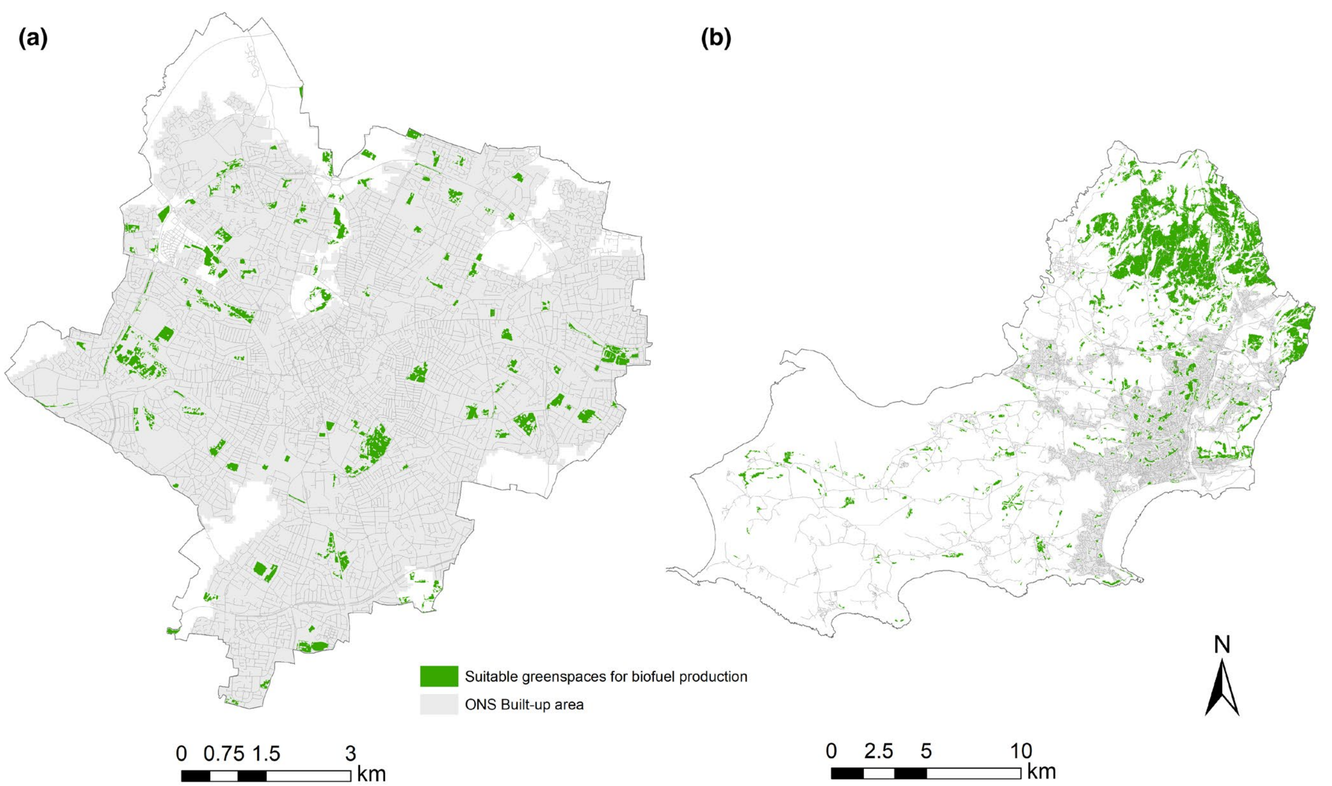

FIGURE 2 Suitable biofuel sites in (a) Leicester and (b) Swansea, United Kingdom. Outlines show extent of urban administrative area

administrative area, fragmentation of land parcels, road layout and relative proportions of different land covers.

In order to extrapolate areal suitability findings to the entire United Kingdom, the proportion of potential biofuel production land was calculated in each study city relative to the total administrative area and total built-up area contained within the administrative boundary of that city (Table 1). On average, 3.3 ± 0.5% *SE* of our study cities'

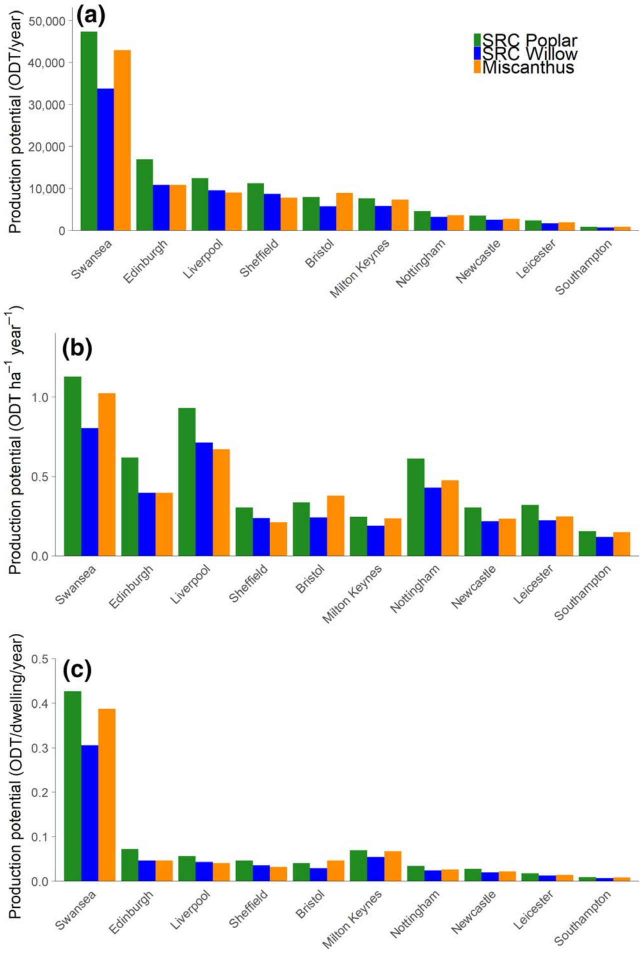

FIGURE 3 (a) Total, (b) per-hectare of total administrative area and (c) per-dwelling estimated biofuel production (ODT/year) by city based on suitable area and predicted yield for various biofuel crops (see Table S4). ODT, oven dry tonnes; SRC, short rotation coppice

built-up area and 4.0 ± 0.7% *SE* of their administrative area were potentially suitable for supporting biofuel cultivation. Proportional calculations of biofuel potential relative to total available greenspace show that a mean of 9.9 ± 1.6% *SE* of the greenspace in UK urban areas may be suitable for consideration for biofuel production. Given that Great Britain contains a total of 1.64 million ha of built-up land (ONS, 2011 for England/Wales; Rowland et al., 2017 urban/suburban land cover for Scotland), our average figure of 3.3% for built-up area suitability potential suggests that a mean of 53,800 ha (±7,400 ha *SE*, and a mean potentially as low as 42,000 ha based on the 78% accuracy rating found in our mapping validation) of this land may be suitable for biofuel production. By applying yield estimates for the most productive crops in each region from Hastings et al. (2014), this represents a maximum nationwide biofuel production potential in urban built-up lands of 624,800 ODT/year. Although not explored here, reconsideration of legal and social frameworks defining some current exclusion criteria, such as high agricultural land grade and woodland grant schemes, could expand these figures further (Natural England, 2013).

These yield estimates represent a maximal potential biofuel supply, which were next considered in the context of heating demand. Figures from Forest Research UK (2017) were used after McHugh et al. (2015) to predict the heating potential of the most productive locally sourced biofuel crop in each city (Table 2). Additionally, comparing the recorded number of dwellings in each city (for England sites: Ministry of Housing, Communities, & Local Government, 2016; Swansea: StatsWales, 2016; Edinburgh: National Records of Scotland, 2017) to the estimated number of dwellings that could be heated this way enabled the calculation of the proportion of urban domestic heating demand that could potentially be met in each case. When expanded to the total built-up area of Great Britain, the maximal potential yield represents the ability to heat 156,591 dwellings, 5,250 district heating schemes or 3,078 municipal buildings. The Forest Research figures do not account for details such as transmission losses of heat and only report figures based on generalized approximate sizes of dwellings/schemes/buildings used for their calculations, but this still provides us with a broad national estimate of heating potential.

3.3 | Potential of urban biofuel to meet national sustainability targets

The factors contributing to estimates of each city's heating demand, and the potential of indigenous biofuel to meet it, account for a considerable degree of variation between cities; but they suggest that, on average, locally sourced urban biofuel is capable of meeting 2% of a city's residential heating demand (Table 2). Swansea stands out by being able to supply an order of magnitude more heat from local biofuel production than other study cities, due to a combination of its extensive biofuel-suitable extra-urban land and relatively modest demand by number of dwellings. Most other cities fall between zero and two percent, perhaps reflecting the more realistic or common case. However, the estimation of total potential to meet demand underplays the role urban biomass can have in achieving climate change targets. It is unlikely, for example, that the retrofit of biomass heating to average urban dwellings will be a realistic proposition due the range of end-user problems that can occur, concerns about pellet supply and pricing and maintenance requirements (Thomson & Liddell, 2015). Additionally, there are several technologies competing to become the low carbon option of choice for UK households to move space heating requirements away from natural gas combi boilers (which currently dominate provision in the United Kingdom), including air source heat pumps and hydrogen boilers with associated gas network retrofit (Hanna, Parrish, & Gross, 2016). As such, the most

TABLE 2 Estimated annual heating potential of locally sourced urban biofuel based on the most productive crop at each site (Table S4) and expected heating demand (3.99 ODT/year per house/dwelling, 119 ODT/year per district heating scheme and 203 ODT/year per municipal building, Forest Research, 2017; McHugh et al., 2015), number of residential dwellings present in each study site (England: Ministry of Housing, Communities, & Local Government, 2016; Swansea: StatsWales, 2016; Edinburgh: National Records of Scotland, 2017) and the estimated proportion of each site's annual heating demand that could be met under maximum biofuel cultivation within that urban area. Formulae at the bottom of the table show how results were calculated using our estimated urban output divided by demand figures from Forest Research, United Kingdom

Study site	Max. potential domestic heating (houses/dwellings)	Max. potential district heating (schemes)	Max. potential municipal heating (buildings)	Number of dwellings (houses/dwellings)	Percent of residential demand potentially met by local urban biofuel (%)
Leicester	588	19	11	132,170	0.44
Southampton	217	7	4	104,660	0.21
Nottingham	1,146	38	22	134,850	0.85
Bristol	2,238	75	43	195,340	1.15
Edinburgh	4,232	141	83	232,885	1.82
Swansea	11,879	398	233	110,892	10.71
Newcastle	870	29	17	124,690	0.70
Milton Keynes	1,893	63	37	108,740	1.74
Liverpool	3,112	104	61	220,520	1.41
Sheffield	2,800	93	55	242,280	1.16
Mean	2,897.5	96.7	56.6	160,702.7	2.02
SE	1,073.1	36.0	21.1	17,557.7	0.98
Formula	(max. ODT/year)/(3.99)	(max. ODT/year)/(119)	(max. ODT/year)/(203)		(max. potential domestic heating)/(number of dwellings)

likely destination for urban biomass is as a primary or mixed fuel for CHP generators feeding urban heat networks. Heat networks with CHP are seen as a critical pillar in UK energy system decarbonization, and are substantially present in those scenarios which meet the United Kingdom's climate change commitments (National Grid, 2018). With the potential yield data developed here, we can estimate the extent to which indigenous urban biomass can satisfy the fuel demand for these networks, thus ameliorating reliance on international supply chains and their associated emissions.

National Grid in its role as UK system operator produces annual FES, which in their most recent incarnation describes four potential energy system futures to 2050; two of which, ‘Community Renewables’ and ‘Two Degrees’, meet the United Kingdom's climate change commitments (National Grid, 2018). Both scenarios incorporate a rapid expansion of urban heat networks, and ‘Community Renewables’ predict up to 2 GW of installed decentralized biomass CHP capacity by 2040. National Grid does not compute the land area requirements for this, nor specify biomass sources such as SRC. However, using the Digest of UK Energy Statistics (DUKES) 2018 (BEIS, 2018) we can derive a ratio of installed electrical CHP capacity to heat output for both conventional CHP and Organic Rankine Cycle (ORC) installations. DUKES 2018 suggests that recent UK Government policy for distributed renewable heat has led to installation of a substantial number of ORC CHP engines, so our calculations here incorporate this technology (Table 3). From these calculations, we find that within the urban boundary of UK major cities (comprising 53,846 ha), we could grow up to 18% of the biomass fuel for CHP systems needed to meet the demands of a climate compatible energy scenario by 2030. As stated previously, the data underlying our analysis do not account for some relevant details such as heat loss in transmission which would lower the overall efficiency of operations; nevertheless, the work presented here displays the broad potential of urban biofuel production at a national scale, and producing them as near to the point of use as possible (i.e. within the same city) where they would then be used to produce heat and power for local consumers would seek to maximize efficiency across the life cycle.

4 | DISCUSSION

4.1 | Management considerations, co-benefits and trade-offs

The availability of greenspace for biofuel production in any given city, as a proportion of either its administrative or built-up area, reflects characteristics of urban form and landscape structure that also have implications for ecosystem service provision. Since biofuel suitability was restricted in part to

TABLE 3 Percentage of national biomass CHP fuel demand that can be met using biofuel grown within urban boundaries

What percentage of national biomass CHP demand can be grown within UK cities?[a]

Year	Biomass CHP electrical capacity (MW)[a]	Ratio of conventional CHP installed electrical (MW) capacity to heat output (MWh)[b]	Ratio of ORC CHP installed electrical (MW) capacity to heat output (MWh)[b]	Heat output of conventional biomass CHP (MWh) assuming 70% of FES value is conventional CHP	Heat output of ORC biomass CHP (MWh) assuming 30% of FES value ORC CHP	Land use requirement per MWh of conventional CHP assuming district heating conversion factors (ha)[c]	Land use requirement per MWh of ORC CHP using ORC conversion factors (ha)[c]	Percentage of national biomass CHP fuel demand that can be grown in the 53,846 ha of available urban land
2030	1,116.7	7.2	16.5	5,628,168	5,527,665	118,191.528	182,412.945	17.92
2040	1,850.2	7.2	16.5	9,325,008	9,158,490	195,825.168	302,230.17	10.81
2050	3,068.8	7.2	16.5	15,466,752	15,190,560	324,801.792	501,288.48	6.52

Abbreviations: CHP, combined heat and power; ORC, Organic Rankine Cycle; SRC, short rotation coppice.
[a]National Grid Future Energy Scenarios 2018: Two Degrees Scenario FES 2018 Data Workbook Tab ES1.
[b]Digest of UK Energy Statistics 2018, Data set Tables 7.2–7.8.
[c]Forest Research 2017: https://www.forestresearch.gov.uk/tools-and-resources/biomass-energy-resources/reference-biomass/facts-figures/biomass-heating-of-buildings-of-different-sizes. District heat conversion factors = 0.021 ha/MWh SRC, ORC conversion factors = 0.033 ha/MWh SRC.

relatively large patches, low proportional suitability relative to the available greenspace in a given city may reflect higher degrees of greenspace fragmentation. Conversely, cities with a relatively high proportion of their greenspace suitable for biofuel production (e.g. Nottingham, Bristol, Swansea and Liverpool) possess more and larger greenspace patches with associated environmental benefits (Beninde, Veith, & Hochkirch, 2015; Grafius, Corstanje, & Harris, 2018; Saunders, Hobbs, & Margules, 1991). If managed effectively, biofuel production operations may support peripheral ecosystem service benefits such as biodiversity (O'Sullivan et al., 2017; Rowe et al., 2009; Sage et al., 2006), mitigation of air and soil pollution (Rowe et al., 2009; Sugiura et al., 2008), mitigation of flood risk (O'Sullivan et al., 2017), sequestration of carbon in the soil (Matthews et al., 2002), noise suppression from major roads and railways and aesthetic benefits (Rowe et al., 2009). These benefits must be balanced against potential disservices such as negative aesthetics (Dockerty, Appleton, & Lovett, 2012), noise and access conflicts from maintenance and harvesting operations, perceived increase in crime risk (Chiesura, 2004; Dobbs, Escobedo, & Zipperer, 2011), and land conflict with any alternate preferred uses of a given site. Additional factors, such as albedo, may remain relatively unchanged in lands converting from mown grass to SRC (De Groote et al., 2015; Markvart & Castaner, 2003; Schmidt-Walter, Richter, Herbst, Schuldt, & Lamersdorf, 2014). The use of marginal lands for energy crop production may help to avoid land conflicts while providing ecosystem services and benefitting remediation efforts (Blanco-Canqui, 2016).

The most appropriate crop type will depend on local considerations; regional differences in climate will determine which crops will maximize production, but again this will be balanced against other considerations. For example, *Miscanthus* or an SRC crop may maximize raw fuel production but be deemed undesirable in some locations, whereas an alternate approach such as pollarding of trees (Read, 2006; Smith, Pearce, & Wolfe, 2012) or short rotation forestry operations may produce only 15%–25% as much oven dry weight of fuel material (Forest Research, 2018; based on Forest Research figures for expected yields from forestry residues after thinning operations, specific figures for pollarding yields were unavailable) but be deemed more aesthetically desirable in some frequently used public lands such as parks. In some cases, it may also be possible to include secondary sources of fuel from other operations, such as cuttings from tree pruning. One example in Ecuador found that lechero trees (*Euphorbia laurifolia* L.), although perhaps exhibiting faster growth rates than most urban UK trees, produced an average of 9.95 kg of wood and leaf pruning waste per tree (Velázquez-Martí, Gaibor-Cházvez, Niño-Ruiz, & Narbona-Sahuquillo, 2018).

There are also myriad economic and logistical factors involved in the consideration of biofuel production, particularly in urban areas with their probable smaller site areas compared to rural areas, which remain largely unexplored, but addressing such complexities can be increasingly aided with the use of modelling tools (Bauen et al., 2010; Foster, 1993). Although economies of scale suggest that only larger sites might prove economically viable (Fiala & Bacenetti, 2012), a component-based understanding of the relative costs incurred by fuel transport, travel and harvest method and timing may find alternative solutions (Pecenka & Hoffmann, 2015): for example, an operation structured around frequent harvesting of relatively small plots would enable the use of lower performance equipment and provide a more continuous fuel supply, all of which could prove optimal for urban biofuel production (Sims & Venturi, 2004). Finding an appropriate balance between production output, economic and logistical practicality, co-benefits, residential preferences, rural versus urban land value and other considerations must be studied further and addressed on a case-by-case basis by individual local interests when deciding whether and where to locate urban biofuel operations. However, having a clear and broad understanding of the production potential, as we explore here, will strengthen this decision-making process.

4.2 | Comparison with previous research

We have explored the potential of biofuels in UK urban areas at a deliberately broad scale, considering 10 different study areas in order to generate a nationally representative picture that spans many UK regions and urban landscape types. Few published studies exist that offer comparable results; however, McHugh et al. (2015) estimated urban biofuel potential for the city of Leicester, United Kingdom, albeit based on different SRC yield estimates found in Aylott et al. (2010). This research found 297 ha of potentially suitable land within the urban boundary when using comparable exclusion criteria to our study, capable of producing an average of 3,052 ODT of wood chip per year. Our analysis here, by comparison, estimated 238 ha producing 1,639 ODT/year for SRC willow or 2,347 ODT/year for SRC poplar. Based on heating demand figures from Forestry Research, United Kingdom (Forest Research, 2017; McHugh et al., 2015), for residential dwellings, district heating schemes and municipal buildings, McHugh et al. (2015) calculated that local urban SRC in Leicester could supply heat for 1,566 houses, 52 district heating schemes or 30 municipal buildings. Our research produced more modest results, finding that urban biofuel production in Leicester could potentially supply heating for 588 domestic houses, 19 district heating schemes or 11 municipal buildings. The differences between these findings may stem in part from methodological differences in suitability mapping, although the criteria were largely the same between studies; as such, the greatest portion of this difference is believed to originate from the different sources of predicted yield values, for which much uncertainty remains given the limited degree to which urban biofuel potential has been investigated thus far. Another consideration for future research is that climate change may alter the suitability and optimal selection of crops in different regions over time (Bellarby, Wattenbach, Tuck, Glendining, & Smith, 2010). Understanding the productivity of urban biofuel operations is in its infancy and data poor, so current uncertainties are large but will decrease with further research and real-world implementation.

4.3 | Local policy implications

In addition to national targets and scenarios, numerous local authorities in the United Kingdom express independent aspirations towards increasing urban resilience and sustainability through the greater uptake of locally sourced biofuels, often in concert with CHP systems and/or district heating schemes. These are commonly included in their policies and strategies for sustainable (or 'green') development, carbon emissions reduction and climate change mitigation. Although current situations and commitments are variable, some urban areas operate district heating and/or power schemes that are undergoing expansion and conversion to run on biomass fuel as part of green strategies (Leicester City Council, 2017; Minshull, Luke, Shiels, Phillips, & Leach, 2015; Newcastle City Council, 2010; Nottingham City Council, 2010; Sheffield City Council, 2005). Others without current schemes are considering them or conducting feasibility studies (Liverpool City Region Local Enterprise Partnership, ARUP, Climate Change Local Area Support Programme (CLASP), & Service, 2012; Southampton City Council, 2011; Swansea City Council, 2016; The City of Edinburgh Council, 2015). Multiple authorities have specifically identified the potential sustainability benefits of producing biofuels locally (Centre for Sustainable Energy, 2012; Liverpool City Region Local Enterprise Partnership et al., 2012; Minshull et al., 2015; Newcastle City Council, 2010), or at least the costs of importing them externally (Nottingham City Council, 2010), and in Southampton, a proposed 100 MW biomass plant was rejected largely over concerns about the import of biofuel and the associated whole-system detriment to residents and the environment (Vinson, 2011). These examples strengthen the case for greater consideration of urban production of biofuels and their associated use in local district heating and/or energy production schemes, as such operations could support many stated aspirations of local authority strategies while avoiding the identified environmental and cost disadvantages of importing biofuel from distant or foreign suppliers.

4.4 | Research and policy in the United Kingdom and beyond

The United Kingdom has recently committed to a goal of net zero carbon emissions by 2050 (Prime Minister's Office, Clark, & May, 2019), as one of many countries around the world seeking to reduce its GHG emissions through an increased focus on renewable energy, and with fast-growing biofuel resources in particular as one way to work towards this goal. Research in the Northeast United States, for example, modelled the potential yield of different energy crops for that region, finding short rotation willow to be the most favourable albeit dependent on various market conditions and incentives (Brandt et al., 2018). Research in China has explored the balances and trade-offs between bioenergy crops, food crops and local water table depletion with a goal of informing governmental policy on the optimal management of these resources (Yang, Chen, Pacenka, Steenhuis, & Sui, 2019). Biofuel research in Germany alternately has explored GHG abatement in the transportation sector given its wide-ranging impact, finding that a prioritized focus on land passenger transport is key (Millinger, Meisel, & Thrän, 2019). In all such cases, production of biofuel crops in urban spaces could potentially contribute.

From a policy standpoint, nations have historically acted in accordance with their own unique situations, such as the United States' focus on the economics of maize corn-based ethanol (Dutta, 2019), and France and Germany's adoption of biofuel policies in response to agricultural surpluses in the early 20th century and later the 1970s oil crisis. In many cases, national policy remains driven more by economic self-interest and energy security than global environmental concerns (Oliveira, McKay, & Plank, 2017); however, multinational agreements may offer a more holistic perspective that better recognizes the advantages of small-scale urban biofuel operations. Examples of such agreements include the European Commission's 2030 Climate & Energy Framework (European Commission, 2014), which sets a binding target for European nations of generating at least 27% of their total energy from renewable sources by 2030, and the Conference of the Parties (COP 21) Paris Agreement of the United Nations Framework Convention on Climate Change, in which 174 countries have set a goal of limiting global average warming due to anthropogenic GHG emissions to 'well below 2°C' compared to pre-industrial levels (United Nations Framework Convention on Climate Change (UNFCCC), 2016). Such international agreements commonly account for local differences in resources and feasibility by not dictating explicitly how the signatory nations achieve these goals, and in many cases, fast-growing biofuel crops for local consumption in heat and/or power generation may represent a valuable resource; being relatively straightforward to implement at local levels, but potentially scaling up to have noteworthy regional and global impacts on GHG reduction.

5 | CONCLUSIONS

Our findings demonstrate that a typical UK urban area holds a great deal of largely unconsidered potential to provision its residents with sustainable biofuel for electrical power and/or heat generation. Optimal decisions pertaining to biofuel species used, type of energy produced, supply chain details and location of operations must be determined on a case-by-case basis. The estimates calculated here represent a maximal edge case which is unlikely to be desirable in practice; however, more land could become classified as suitable if some restriction criteria were loosened. Such decisions will necessarily address conflicting preferences and values from local residents and users, consider entire supply chains and life cycles of operations (Strohbach, Arnold, & Haase, 2012) and balance trade-offs and synergies between different ecosystem services and disservices that may be provided by biofuel operations beyond their primary goal of fuel production. However, the potential is clear and compelling, and modelling tools are increasingly becoming available to address the inherent challenges (Tallis et al., 2013). Urban areas in the United Kingdom have the capability to supply a significant proportion of their own energy demand using low-carbon or carbon-neutral methods, produced near the point of demand to avoid costs incurred in long-distance fuel transport, and without land conflict with rural food crop production. The advantages of such practices are in line with the expressed goals of numerous local authorities as well as national policies and international agreements. Overall, our findings suggest that urban biofuel production can make a significant contribution to the volume of biomass called for in local, national and potentially international sustainability scenarios. Furthermore, the largely unconsidered nature of this renewable fuel source makes this potential contribution particularly striking. Future research should seek to further investigate the feasibility of such operations at various scales and in different locations, as well as according to different criteria that were not explicitly studied here. A more exact consideration of the effects of site fragmentation and size on economies of scale, trade-offs between urban and rural lands that consider potential land value as well as transport costs and the impacts of local climate on biofuel crop yields are perhaps the most vital issues for immediate consideration, particularly in the context of a sensitivity analysis capable of comparing the relative importance of these factors.

We have shown that ca. 3% of the built-up area of a typical UK city, 4% of its total administrative area and nearly 10% of its total urban greenspace are potentially suitable for biofuel production. Scaled up, this urban biofuel potential may be capable of meeting approximately 18% of the United

Kingdom's biomass CHP heating fuel demand in a climate compatible scenario by 2030 as outlined by the National Grid's Future Energy Scenarios. Urban biofuel operations face multiple challenges that must be addressed at local scales and on a case-by-case basis in order to ensure they are viable and sustainable, but if such challenges can be met urban biofuel production may represent an opportunity to make cities and energy systems more sustainable and resilient while providing numerous peripheral benefits to urban residents and nature.

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AUTHOR CONTRIBUTIONS

DRG, JLE and NM devised the initial research design. GIS suitability analysis was carried out by DRG. SH interpreted results with respect to published energy scenarios and targets. All authors contributed to the writing and editing of the manuscript.

DATA AVAILABILITY STATEMENT

Sources for data used in this research are cited in the manuscript. New data generated by this research that support its findings are available from the corresponding author upon request.

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REFERENCES

Adams, P. W. R., & Lindegaard, K. (2016). A critical appraisal of the effectiveness of UK perennial energy crops policy since 1990. *Renewable and Sustainable Energy Reviews*, *55*, 188–202. https://doi.org/10.1016/j.rser.2015.10.126

Alexander, P., Moran, D., Rounsevell, M. D. A., Hillier, J., & Smith, P. (2014). Cost and potential of carbon abatement from the UK perennial energy crop market. *GCB Bioenergy*, *6*(2), 156–168. https://doi.org/10.1111/gcbb.12148

Aylott, M. J., Casella, E., Farrall, K., & Taylor, G. (2010). Estimating the supply of biomass from short rotation coppice in England, given social, economic and environmental constraints to land availability. *Biofuels*, *1*(5), 719–727. https://doi.org/10.4155/bfs.10.30

Bauen, A. W., Dunnett, A. J., Richter, G. M., Dailey, A. G., Aylott, M., Casella, E., & Taylor, G. (2010). Modelling supply and demand of bioenergy from short rotation coppice and Miscanthus in the UK. *Bioresource Technology*, *101*(21), 8132–8143. https://doi.org/10.1016/j.biortech.2010.05.002

BEIS. (2018). Digest of United Kingdom Energy Statistics (DUKES). In *UK National Statistics*. Retrieved from https://www.gov.uk/government/statistics/digest-of-uk-energy-statistics-dukes-2018-main-report

Bellarby, J., Wattenbach, M., Tuck, G., Glendining, M. J., & Smith, P. (2010). The potential distribution of bioenergy crops in the UK under present and future climate. *Biomass and Bioenergy*, *34*(12), 1935–1945. https://doi.org/10.1016/j.biombioe.2010.08.009

Beninde, J., Veith, M., & Hochkirch, A. (2015). Biodiversity in cities needs space: A meta-analysis of factors determining intra-urban biodiversity variation. *Ecology Letters*, *18*(6), 581–592. https://doi.org/10.1111/ele.12427

Bikkina, S., Andersson, A., Kirillova, E. N., Holmstrand, H., Tiwari, S., Srivastava, A. K., … Gustafsson, Ö. (2019). Air quality in megacity Delhi affected by countryside biomass burning. *Nature Sustainability*, *2*(3), 200–205. https://doi.org/10.1038/s41893-019-0219-0

Blanco-Canqui, H. (2016). Growing dedicated energy crops on marginal lands and ecosystem services. *Soil Science Society of America Journal*, *80*(4), 845. https://doi.org/10.2136/sssaj2016.03.0080

Brandt, C., Volk, T., Richard, T., Davis, M., Shedden, M., Langholtz, M., & Eaton, L. (2018). Economic comparative advantage of willow biomass in the Northeast USA. *Biofuels, Bioproducts and Biorefining*, *13*(1), 74–85. https://doi.org/10.1002/bbb.1939

Caputo, J., Balogh, S. B., Volk, T. A., Johnson, L., Puettmann, M., Lippke, B., & Oneil, E. (2014). Incorporating uncertainty into a life cycle assessment (LCA) model of short rotation willow biomass (Salix spp.) crops. *BioEnergy Research*, *7*(1), 48–59. https://doi.org/10.1007/s12155-013-9347-y

Centre for Sustainable Energy. (2012). *Milton Keynes energy mapping project – summary report*. Bristol, UK: Centre for Sustainable Energy.

Chiesura, A. (2004). The role of urban parks for the sustainable city. *Landscape and Urban Planning*, *68*(1), 129–138. https://doi.org/10.1016/j.landurbplan.2003.08.003

CoDyre, M., Fraser, E. D. G. G., & Landman, K. (2015). How does your garden grow? An empirical evaluation of the costs and potential of urban gardening. *Urban Forestry and Urban Greening*, *14*(1), 72–79. https://doi.org/10.1016/j.ufug.2014.11.001

Cunniff, J., Purdy, S. J., Barraclough, T. J. P., Castle, M., Maddison, A. L., Jones, L. E., … Karp, A. (2015). High yielding biomass genotypes of willow (Salix spp.) show differences in below ground biomass allocation. *Biomass and Bioenergy*, *80*, 114–127. https://doi.org/10.1016/j.biombioe.2015.04.020

De Groote, T., Zona, D., Broeckx, L. S., Verlinden, M. S., Luyssaert, S., Bellassen, V., … Janssens, I. A. (2015). ORCHIDEE-SRC v1.0: An extension of the land surface model ORCHIDEE for simulating short rotation coppice poplar plantations. *Geoscientific Model Development*, *8*(5), 1461–1471. https://doi.org/10.5194/gmd-8-1461-2015

Dobbs, C., Escobedo, F. J., & Zipperer, W. C. (2011). A framework for developing urban forest ecosystem services and goods indicators. *Landscape and Urban Planning*, *99*(3–4), 196–206. https://doi.org/10.1016/j.landurbplan.2010.11.004

Dockerty, T., Appleton, K., & Lovett, A. (2012). Public opinion on energy crops in the landscape: Considerations for the expansion of renewable energy from biomass. *Journal of Environmental Planning* *and Management*, *55*(9), 1134–1158. https://doi.org/10.1080/09640568.2011.636966

Dutta, A. (2019). Forecasting ethanol market volatility: New evidence from the corn implied volatility index. *Biofuels, Bioproducts and Biorefining*, *13*(1), 48–54. https://doi.org/10.1002/bbb.1931

Edmondson, J. L., Blevins, R. S., Cunningham, H., Dobson, M. C., Leake, J. R., & Grafius, D. R. (2019). Grow your own food security? Integrating science and citizen science to estimate the contribution of own growing to UK food production. *Plants, People, Planet*, *1*(2), 93–97. https://doi.org/10.1002/ppp3.20

Edmondson, J. L., Davies, Z. G., Gaston, K. J., & Leake, J. R. (2014). Urban cultivation in allotments maintains soil qualities adversely affected by conventional agriculture. *Journal of Applied Ecology*, *51*(4), 880–889. https://doi.org/10.1111/1365-2664.12254

Edmondson, J. L., Davies, Z. G., McCormack, S. A., Gaston, K. J., & Leake, J. R. (2011). Are soils in urban ecosystems compacted? A citywide analysis. *Biology Letters*, *7*(5), 771–774. https://doi.org/10.1098/rsbl.2011.0260

ESRI. (2013). *ArcGIS*. Redlands, CA: Environmental Systems Research Institute.

European Commission. (2014). *2030 climate & energy framework – conclusions*. Brussels, Belgium: European Commission. Retrieved from https://ec.europa.eu/clima/policies/strategies/2030_en#tab-0-1

Fajardy, M., & Mac Dowell, N. (2017). Can BECCS deliver sustainable and resource efficient negative emissions? *Energy & Environmental Science*, *10*(6), 1389–1426. https://doi.org/10.1039/C7EE00465F

Fiala, M., & Bacenetti, J. (2012). Economic, energetic and environmental impact in short rotation coppice harvesting operations. *Biomass and Bioenergy*, *42*, 107–113. https://doi.org/10.1016/j.biombioe.2011.07.004

Forest Research. (2017). Biomass heating of buildings of different sizes. Retrieved from https://www.forestresearch.gov.uk/tools-and-resources/biomass-energy-resources/reference-biomass/facts-figures/biomass-heating-of-buildings-of-different-sizes/

Forest Research. (2018). Potential yields of biofuels per ha p.a. Retrieved from https://www.forestresearch.gov.uk/tools-and-resources/biomass-energy-resources/reference-biomass/facts-figures/potential-yields-of-biofuels-per-ha-pa/

Foster, C. (1993). The carbon and energy budgets of energy crops. *Energy Conversion and Management*, *34*(9–11), 897–904. https://doi.org/10.1016/0196-8904(93)90034-8

Foxon, T. J. (2013). Transition pathways for a UK low carbon electricity future. *Energy Policy*, *52*, 10–24. https://doi.org/10.1016/j.enpol.2012.04.001

Grafius, D. R., Corstanje, R., & Harris, J. A. (2018). Linking ecosystem services, urban form and green space configuration using multivariate landscape metric analysis. *Landscape Ecology*, *33*(4), 557–573. https://doi.org/10.1007/s10980-018-0618-z

Grafius, D. R., Corstanje, R., Siriwardena, G. M., Plummer, K. E., & Harris, J. A. (2017). A bird's eye view: Using circuit theory to study urban landscape connectivity for birds. *Landscape Ecology*, *32*(9), 1771–1787. https://doi.org/10.1007/s10980-017-0548-1

Hanna, R., Parrish, B., & Gross, R. (2016). *Best practice in heat decarbonisation policy: A review of the international experience of policies to promote the uptake of low-carbon heat supply*. Retrieved from http://hdl.handle.net/10044/1/53614

Hastings, A., Tallis, M. J., Casella, E., Matthews, R. W., Henshall, P. A., Milner, S., … Taylor, G. (2014). The technical potential of Great Britain to produce ligno-cellulosic biomass for bioenergy in current and future climates. *Global Change Biology Bioenergy*, *6*(2), 108–122. https://doi.org/10.1111/gcbb.12103

International Energy Agency. (2018). *World energy outlook*. Retrieved from https://www.iea.org/weo/

Kekana, M., & ISOCARP. (2019). Proposal for an IPCC Special Report on Cities and Climate Change. Retrieved from https://www.isocarp.org/news/ipcc-special-report-cities-climate-change/

Landmap; Bluesky. (2014). *Colour Infrared (CIR) data for England and Wales*. Retrieved from http://catalogue.ceda.ac.uk/uuid/51c4273d47ef0130c422eafb2f99d4fe

Leicester City Council. (2017). *Leicester's Sustainability Action Plan*. Retrieved from https://www.leicester.gov.uk/media/181523/sustainability-action-plan-2016-2019-updated-2017.pdf

Liverpool City Region Local Enterprise Partnership, ARUP, Climate Change Local Area Support Programme (CLASP), & Service, M. E. A. (2012). *Liverpool City Region Sustainable Energy Action Plan 2012*. Liverpool, UK: Liverpool City Region Local Enterprise Partnership.

Markvart, T., & Castaner, L. (2003). *Practical handbook of photovoltaics: Fundamentals and applications* (1st ed., A. McEvoy, T. Markvart, & L. Castaner Eds.). Retrieved from https://www.elsevier.com/books/practical-handbook-of-photovoltaics/mcevoy/978-1-85617-390-2

Martellozzo, F., Landry, J.-S., Plouffe, D., Seufert, V., Rowhani, P., & Ramankutty, N. (2014). Urban agriculture: A global analysis of the space constraint to meet urban vegetable demand. *Environmental Research Letters*, *9*(6), 064025. https://doi.org/10.1088/1748-9326/9/6/064025

Matthews, R., Grogan, P., & Matthews, R. (2002). A modelling analysis of the potential for soil carbon sequestration under short rotation coppice willow bioenergy plantations. *Soil Use and Management*, *18*(3), 175–183. https://doi.org/10.1079/Sum2002119

McDonnell, M. J., & MacGregor-Fors, I. (2016). The ecological future of cities. *Science*, *352*(6288), 936–938. https://doi.org/10.1126/science.aaf3630

McHugh, N., Edmondson, J. L., Gaston, K. J., Leake, J. R., & O'Sullivan, O. S. (2015). Modelling short rotation coppice and tree planting for urban carbon management – A citywide analysis. *Journal of Applied Ecology*, *52*(5), 1237–1245. https://doi.org/10.1111/1365-2664.12491

Millinger, M., Meisel, K., & Thrän, D. (2019). Greenhouse gas abatement optimal deployment of biofuels from crops in Germany. *Transportation Research Part D: Transport and Environment*, *69*, 265–275. https://doi.org/10.1016/j.trd.2019.02.005

Millward-Hopkins, J., & Purnell, P. (2019). Circulating blame in the circular economy: The case of wood-waste biofuels and coal ash. *Energy Policy*, *129*, 168–172. https://doi.org/10.1016/j.enpol.2019.02.019

Ministry of Housing, Communities and Local Government. (2016). Live tables on dwelling stock. Retrieved from https://www.gov.uk/government/statistical-data-sets/live-tables-on-dwelling-stock-including-vacants

Minshull, A., Luke, A., Shiels, S., Phillips, J., & Leach, M. (2015). *Our Resilient Future: A Framework for Climate and Energy Security*. Retrieved from https://www.bristol.gov.uk/documents/20182/33423/Our+Resilient+Future+A+Framework+for+-Climate+and+Energy+Security/2ee3fe3d-efa5-425a-b271-14dca33517e6

National Grid. (2018). *Future Energy Scenarios*. Retrieved from http://fes.nationalgrid.com/media/1363/fes-interactive-version-final.pdf

National Records of Scotland. (2017). *Estimates of Households and Dwellings in Scotland, 2016*. Retrieved from https://www.nrscotland.gov.uk/statistics-and-data/statistics/statistics-by-theme/households/household-estimates/2016

Natural England. (2013). *Energy crops scheme establishment grants handbook 3rd edition version 3.1*. Worcester, UK: Natural England.

Newcastle City Council. (2010). *Citywide Climate Change Strategy & Action Plan 2010–2020*. Retrieved from https://www.newcastle.gov.uk/environment-and-waste/climate-change-and-energy-saving/our-climate-change-commitment

Norton, B. A., Evans, K. L., & Warren, P. H. (2016). Urban biodiversity and landscape ecology: Patterns, processes and planning. *Current Landscape Ecology Reports*, *1*(4), 178–192. https://doi.org/10.1007/s40823-016-0018-5

Nottingham City Council. (2010). *Energy Strategy 2010–2020*. Retrieved from https://www.nottinghamcity.gov.uk/environmental-health-and-safer-housing/energy-services/

Oliveira, G. D. L. T., McKay, B., & Plank, C. (2017). How biofuel policies backfire: Misguided goals, inefficient mechanisms, and political-ecological blind spots. *Energy Policy*, *108*(March), 765–775. https://doi.org/10.1016/j.enpol.2017.03.036

ONS. (2011). *Built up area sub-divisions, December 2011 boundaries*. Retrieved from http://geoportal.statistics.gov.uk/datasets/built-up-area-sub-divisions-december-2011-boundaries

Ordnance Survey (GB). (2017). *OS MasterMap Topography Layer [FileGeoDatabase geospatial data]*. Retrieved from http://digimap.edina.ac.uk

O'Sullivan, O. S., Holt, A. R., Warren, P. H., & Evans, K. L. (2017). Optimising UK urban road verge contributions to biodiversity and ecosystem services with cost-effective management. *Journal of Environmental Management*, *191*, 162–171. https://doi.org/10.1016/j.jenvman.2016.12.062

Parra-López, C., Holley, M., Lindegaard, K., Sayadi, S., Esteban-López, G., Durán-Zuazo, V. H., … Rzewuski, W. (2017). Strengthening the development of the short rotation plantations bioenergy sector: Policy insights from six European countries. *Renewable Energy*, *114*, 781–793. https://doi.org/10.1016/j.renene.2017.07.098

Pecenka, R., & Hoffmann, T. (2015). Harvest technology for short rotation coppices and costs of harvest, transport and storage. *Agronomy Research*, *13*(2), 361–371.

Prime Minister's Office, Clark, G., & May, T. (2019). PM Theresa May: We will end UK contribution to climate change by 2050. Retrieved from https://www.gov.uk/government/news/pm-theresa-may-we-will-end-uk-contribution-to-climate-change-by-2050

Raman, S., Mohr, A., Helliwell, R., Ribeiro, B., Shortall, O., Smith, R., & Millar, K. (2015). Integrating social and value dimensions into sustainability assessment of lignocellulosic biofuels. *Biomass and Bioenergy*, *82*, 49–62. https://doi.org/10.1016/j.biombioe.2015.04.022

Read, H. (2006). *A brief review of pollards and pollarding in Europe*. Retrieved from http://static1.squarespace.com/static/5109cdf5e4b008f90f024aab/t/5341cfece4b02bd951e18b01/1396821996503/12acte_2_read.pdf

Renewable Fuels Agency. (2008). *The Gallagher Review of the indirect effects of biofuels production*. Retrieved from www.renewablefuelsagency.org

Rowe, R. L., Street, N. R., & Taylor, G. (2009). Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK. *Renewable and Sustainable Energy Reviews*, *13*(1), 271–290. https://doi.org/10.1016/j.rser.2007.07.008

Rowland, C. S., Morton, R. D., Carrasco, L., McShane, G., O'Neil, A. W., & Wood, C. M. (2017). *Land Cover Map 2015 (vector, GB)*. NERC Environmental Information Data Centre. Retrieved from https://catalogue.ceh.ac.uk/documents/6c6c9203-7333-4d96-88ab-78925e7a4e73

Sage, R., Cunningham, M., & Boatman, N. (2006). Birds in willow short rotation coppice compared to other arable crops in central England and a review of bird census data from energy crops in the UK. *Ibis*, *148*(suppl. 1), 184–197. https://doi.org/10.1111/j.1474-919X.2006.00522.x

Saunders, D. A., Hobbs, R. J., & Margules, C. R. (1991). Biological consequences of ecosystem fragmentation – A review. *Conservation Biology*, *5*(1), 18–32. https://doi.org/10.1111/j.1523-1739.1991.tb00384.x

Schmidt-Walter, P., Richter, F., Herbst, M., Schuldt, B., & Lamersdorf, N. P. (2014). Transpiration and water use strategies of a young and a full-grown short rotation coppice differing in canopy cover and leaf area. *Agricultural and Forest Meteorology*, *195–196*, 165–178. https://doi.org/10.1016/j.agrformet.2014.05.006

Sheffield City Council. (2005). *Green city strategy*. Sheffield, UK: Sheffield City Council.

Sims, R. E. H., & Venturi, P. (2004). All-year-round harvesting of short rotation coppice eucalyptus compared with the delivered costs of biomass from more conventional short season, harvesting systems. *Biomass and Bioenergy*, *26*(1), 27–37. https://doi.org/10.1016/S0961-9534(03)00081-3

Smith, J., Pearce, B. D., & Wolfe, M. S. (2012). A European perspective for developing modern multifunctional agroforestry systems for sustainable intensification. *Renewable Agriculture and Food Systems*, *27*(4), 323–332. https://doi.org/10.1017/S1742170511000597

Southampton City Council. (2011). *Southampton: Low carbon city 2011–2020. Part 2: The strategy*. Retrieved from http://www.southampton.gov.uk/policies/low-carbon-city-strategy.pdf

StatsWales. (2016). Dwelling stock estimates by local authority and tenure. Retrieved from https://statswales.gov.wales/Catalogue/Housing/Dwelling-Stock-Estimates/dwellingstockestimates-by-localauthority-tenure

Strohbach, M. W., Arnold, E., & Haase, D. (2012). The carbon footprint of urban green space – A life cycle approach. *Landscape and Urban Planning*, *104*(2), 220–229. https://doi.org/10.1016/j.landurbplan.2011.10.013

Sugiura, A., Tyrrel, S. F., Seymour, I., & Burgess, P. J. (2008). Water Renew systems: Wastewater polishing using renewable energy crops. *Water Science and Technology*, *57*(9), 1421–1428. https://doi.org/10.2166/wst.2008.240

Swansea City Council. (2016). *City & County of Swansea's energy strategy*. Swansea, UK: Swansea City Council.

Tallis, M. J., Casella, E., Henshall, P. A., Aylott, M. J., Randle, T. J., Morison, J. I. L., & Taylor, G. (2013). Development and evaluation of ForestGrowth-SRC a process-based model for short rotation coppice yield and spatial supply reveals poplar uses water more efficiently than willow. *GCB Bioenergy*, *5*(1), 53–66. https://doi.org/10.1111/j.1757-1707.2012.01191.x

The City of Edinburgh Council. (2015). *The power to change: Edinburgh's sustainable energy action plan 2015–2020*. Edinburgh, UK: The City of Edinburgh Council.

Thomson, H., & Liddell, C. (2015). The suitability of wood pellet heating for domestic households: A review of literature. *Renewable and Sustainable Energy Reviews*, *42*, 1362–1369. https://doi.org/10.1016/j.rser.2014.11.009

Thornley, P., Gilbert, P., Shackley, S., & Hammond, J. (2015). Maximizing the greenhouse gas reductions from biomass: The role of life cycle assessment. *Biomass and Bioenergy*, *81*, 35–43. https://doi.org/10.1016/j.biombioe.2015.05.002

United Nations. (2018). World urbanization prospects: The 2018 revision. In *Word Urbanization Prospects: The 2018 Revision*. Retrieved from https://population.un.org/wup/Publications/Files/WUP2018-KeyFacts.pdf

United Nations Framework Convention on Climate Change (UNFCCC). (2016). *Report of the Conference of the Parties on COP 21, FCCC/CP/2015/10* (Vol. 01192). Retrieved from https://unfccc.int/process-and-meetings/conferences/past-conferences/paris-climate-change-conference-november-2015/cop-21/cop-21-reports

Upham, P., & Speakman, D. (2007). Stakeholder opinion on constrained 2030 bioenergy scenarios for North West England. *Energy Policy*, *35*(11), 5549–5561. https://doi.org/10.1016/j.enpol.2007.05.026

Velázquez-Martí, B., Gaibor-Cházvez, J., Niño-Ruiz, Z., & Narbona-Sahuquillo, S. (2018). Complete characterization of pruning waste from the lechero tree (*Euphorbia laurifolia* L.) as raw material for biofuel. *Renewable Energy*, *129*, 629–637. https://doi.org/10.1016/j.renene.2018.06.050

Vinson, A. (2011). Southampton Lib Dems say no to Biomass Plant. Retrieved from https://greenlibdems.org.uk/en/article/2011/0479174/southampton-lib-dems-say-no-to-biomass-plant

Wang, S., Hastings, A., Wang, S., Sunnenberg, G., Tallis, M. J., Casella, E., … Smith, P. (2014). The potential for bioenergy crops to contribute to meeting GB heat and electricity demands. *GCB Bioenergy*, *6*(2), 136–141. https://doi.org/10.1111/gcbb.12123

Yang, X. L., Chen, Y. Q., Pacenka, S., Steenhuis, T. S., & Sui, P. (2019). Managing food and bioenergy crops with declining groundwater levels in the North China Plain. *Field Crops Research*, *234*(February), 1–14. https://doi.org/10.1016/j.fcr.2019.02.003

Yang, Y., Brammer, J. G., Wright, D. G., Scott, J. A., Serrano, C., & Bridgwater, A. V. (2017). Combined heat and power from the intermediate pyrolysis of biomass materials: Performance, economics and environmental impact. *Applied Energy*, *191*, 639–652. https://doi.org/10.1016/j.apenergy.2017.02.004

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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