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Evaluating the opportunity that could be provided by underutilised non-agricultural land as a source of bioenergy

by

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This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

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Abstract

Given concerns regarding food security and land use changes, both direct and indirect, resulting from bioenergy production on agricultural land, a better understanding of the alternative land resources that may exist is required. The potential of ‘marginal’ land for bioenergy provision has been the subject of increasing research efforts. However, the marginal land discourse is problematically framed. One of the main issues pertains to the ambiguity of the terminology which has led to uncertainty regarding the sustainability of land found. Moreover, it is unclear to what extent non-agricultural land resources have been fully included by marginal land studies and what potential role they could play in providing bioenergy without impacting on agricultural production.

An extended understanding of locality and distribution is especially important when assessing potential sites for bioenergy provision. With this in mind, a bottom-up GIS methodology was developed to assess the opportunity that may be provided by underutilised non-agricultural land. The methodology adapted categorisations of bioenergy potential used by Voivontas et al. (2001) and Slade et al. (2010) to focus on the non-agricultural landbank that is available in Scotland. Initially the theoretical landbank, the hypothetical maximum amount of land available, took the form of a spatial database of non-agricultural land. This involved the compilation of detailed datasets representing boundaries of brownfield, licensed landfills, historic landfill and abandoned mine land. This was followed by the application of a multicriteria evaluation which resulted in the technical landbank, the proportion of the theoretical landbank that could be more realistically considered for bioenergy provision based on a range of technical constraints. Further exploratory spatial data analysis was also undertaken to provide an insight into the distribution of clusters of this landbank and the relationship that may exist with heat demand.

This research led to the identification of 24,862 hectares of underutilised non-agricultural land in Scotland in the theoretical landbank. This is the first attempt to produce a detailed spatial database of brownfield land at a national scale and the first quantification of the area of both licensed and historic landfill sites in Scotland. The 17,404 hectares of technical landbank represents the first time an assessment of non-agricultural land has been undertaken at this level of detail with the consideration of technical constraints, providing a better understanding of the role this land resource could play for a range of purposes. The work presented in this thesis provides the foundation for further research regarding the potential energy crop yields on this land resource, and, therefore, the contribution it could make towards Scotland’s ambitious renewable heat targets.

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Chapter 1

Introduction

The industrial revolution heavily accelerated land use changes over the last 3 centuries (Goldewijk and Ramankutty, 2010). Cities and their surrounding areas become the sites of some of the dirtiest industry such as ship-building, coal mining, steel making, textile fabrications, cast iron factories and many other forms of manufacturing which produced contaminants that stay in the environment long after the industry has ceased (Maantay, 2013). The 1960s was a period of deindustrialisation which led to the closing of factories and abandonment of industry (Maantay, 2013). Even without contamination, post-industrial landscapes were formed with areas of land left derelict, underused and neglected (Kim, 2016). Land that is not currently considered developable is often ignored, left in limbo, unworthy of any planning or further consideration (Kim et al., 2018). The English landscape tradition has prioritised the value of rural areas or urban parks that are tame and humanised (Kamvasinou, 2011), often presuming that these post-industrial 'in-between' spaces are high risk wastelands. This has also led to a lack of official acknowledgement of these derelict land categories (Kamvasinou, 2011) and consequently an absence of a single comprehensive source of data regarding these types of site (Stejskal, 2005). This is in contrast to the effort made in the compilation of spatial data representing more 'valuable' land types such as ancient woodland, wetlands or land well suited for agriculture (Scotland Environment, 2017; SNH, 2017).

These abandoned vacant spaces are currently the subject of little public interest, limited policy intervention, and poor levels of investment (Kim, 2016). Nevertheless, numerous potential options exist that could enhance the usefulness of these under-appreciated sites (Kim et al., 2018), arguable providing a unique opportunity to 're-create' these spaces (Haase et al., 2014). Competing regeneration options have been suggested. It has been argued that these underutilised spaces could provide much needed land for housing developments (Sinnett et al., 2014), whilst conversely it has been put forward that they could contribute to green infrastructure (Mathey et al., 2015). This thesis will focus heavily on the role these underused resources could play as an alternative to agricultural land as a source of sustainable bioenergy provision. Bioenergy models drastically require access to detailed spatial databases (Van Der Horst, 2002), as the environmental impact of this resource is inherently site dependent. As Van Der Horst (2002) argues, greater spatial detail is required when considering the location of biomass crops as sensitively placed cropping can cover up 'eyesores', reduce risk of erosion whilst simultaneously providing habitat for species (Van Der Horst, 2002). However, alternative uses of a detailed spatial database of these underutilised non-agricultural land types are also discussed.

1.1 Bioenergy provision context

Global energy consumption is increasing annually by an average of 2% each year, with just over 80% of this originating from fossil fuels (Johansson et al., 2012). Emissions of anthropogenic greenhouse gases are the highest they have ever been in history causing unequivocal warming of the climate that is heavily impacting natural and human systems across the planet (IPCC, 2014). A low carbon energy system is increasingly seen as an essential part of the solution to this anthropogenic climate change (Howard et al., 2013). The necessity for change has been recognised by governments (DEFRA, 2003; REN21, 2017) and has impacted policy, driving research, development and rapid deployment of alternative, renewable energy technologies (Foster et al., 2017). Consequently, overall primary energy supply from renewables increased 30% between 2004 and 2013 (REN21, 2014).

Bioenergy is the largest renewable energy source globally, currently representing almost 80% of the energy mix (World Energy Council, 2016). However, the role of bioenergy has recently come under increased scrutiny with the carbon neutrality of this energy source being questioned and research even claiming that it may be more carbon positive than fossil fuels (Johnson, 2009). The predominant concerns with bioenergy are related to the land on which feedstocks can be grown. As Trainor et al. (2016) explain, renewables have a greater direct land use footprint per unit energy than extractive energy sources. This requirement for land creates land use conflicts, with conversion of heavily vegetated or forested land to agriculture deemed to create a carbon debt (Dale et al., 2010). Furthermore, it has been argued that utilising current crop land for bioenergy will not only threaten food security (Lovett et al., 2009), but the subsequent indirect land use change will exacerbate global warming in a similar manner to directly converting forest and grasslands (Searchinger et al., 2008). The challenge of finding suitable areas for growing bioenergy feedstocks whilst ensuring sustainable food production and environmental protection is known as the bioenergy land use dilemma (Lewis and Kelly, 2014), otherwise known as the food versus fuel debate (Tenenbaum, 2008; Valentine et al., 2012).

One potential solution that has emerged is the use of 'marginal' land for bioenergy production (Gallagher, 2008; Wiegmann et al., 2008). However, the definition of marginal land tends to be ambiguous and varies a great deal within the literature (Dale et al., 2010). What was once a piece of terminology inherently linked to the economics of production on land has seemingly become an umbrella term for various idle, abandoned, or degraded lands (Dale et al., 2010) and a panacea for the food versus fuel debate. The extent to which this term includes non-agricultural land types, and therefore fully fulfils the requirements of land that can be used sustainably without impacting food security, is unclear. Utilising non-agricultural land types for bioenergy provision comes with a unique set of benefits and challenges, but there has not yet been a detailed national assessment of the availability of this land resource. The UK provides an interesting backdrop for such an assessment as it has strong bioenergy aspirations coupled with great uncertainty regarding the biomass resource availability (Welfle et al., 2014). This study will use Scotland as a case study to assess the opportunity that may be provided by non-agricultural land for sustainable bioenergy provision at a whole-country scale.

It is necessary to outline that in this thesis bioenergy provision refers to the potential to grow biomass, more specifically second-generation energy crops, and therefore does not include other types of bioenergy such as landfill gas or anaerobic digestion. Second-generation energy crops put less pressure of food commodities than first generation biofuels and therefore are more sustainable (Naik et al, 2010), and thus it is this type of bioenergy which is considered when investigating the opportunity provided by underutilised non-agricultural land in Scotland.

1.2 Scottish context

Scotland (Figure 1.1) has responded to current climate change concerns by setting ambitious renewable energy targets (Scottish Government, 2016a), including ensuring 30% energy for heat, electricity and transport are supplied by renewables by 2020 - rising to 50% by 2050 (Scottish Government, 2016a). Progress has been made towards these targets, in 2015 17.8% of total Scottish energy consumption was sourced from renewables - more than double the level in 2009 (Scottish Government, 2017b). Whilst good advancement is being made towards the target for electricity from renewables by 2020, 57.7% in 2015 towards a goal of 100%, the country is still lagging behind its non-electrical heat target of 11% from renewable sources (Scottish Government, 2016a). In 2016 it has been estimated 4.8 - 5.0% of non-electrical heat demand was met by renewables, a decrease from 5.4% in 2015 (Flynn et al., 2017). Biomass plays a vital role in progression towards the heat demand target, and currently provides 90% of renewable heat in Scotland (Scottish Government, 2017b). Unsurprisingly this, along with similar trends in the rest of the UK, has resulted in the nation being the largest importer of wood pellets in the world (Phillips and Wilson, 2015), with 66% of solid biomass imported (DECC, 2015). If reliance on these imports is to be lessened more land is required for growing dedicated energy crops. Meanwhile, planting of dedicated energy crops on UK agricultural land has been slow. For example, DEFRA statistics show only 7057 hectares of Miscanthus and 2962 hectares of short rotation coppice planted in England and Wales in 2016 (DEFRA,

2017) - equivalent figures for Scotland are not available. Dedicated energy crops, or second generation lignocellulosic feedstocks, can be grown on land not suitable for most food crops and, when appropriately managed, can enhance environmental conditions (Dale et al., 2011). This brings into question the availability of non-agricultural land that can be mobilised for growing such feedstocks without impacting on food security.

Encouragingly, Scotland compiles an inventory of vacant and derelict land, or brownfield land, annually from local authority returns (Scottish Government, 2014). In 2013, the total amount of vacant and derelict land reported in this survey was 11,114 hectares. Meanwhile, Scotland's Zero Waste Plan has set a target of 5% waste to landfill by 2025, meaning that an estimated 4 out of 5 current landfills may close (Scottish Government, 2010). Against this context, and during a period that Scottish Government are developing its new Bioenergy Action Plan (Scottish Government, 2017b), it appears to be an appropriate time to assess the availability of additional underutilised non-agricultural land types. Evans (2009), as part of a pilot project conducted in the North East of England, suggests that closed landfill, previous mine land and mineral workings could also provide opportunity for biomass production. As Bardos (2009) outlines, whilst in theory there exists information on these land resources, such as the vacant and derelict land survey, the quality of such information is variable. To be able to make any conclusions regarding the opportunity non-agricultural land could provide a detailed assessment of the quantity and distribution of such a landbank is required.

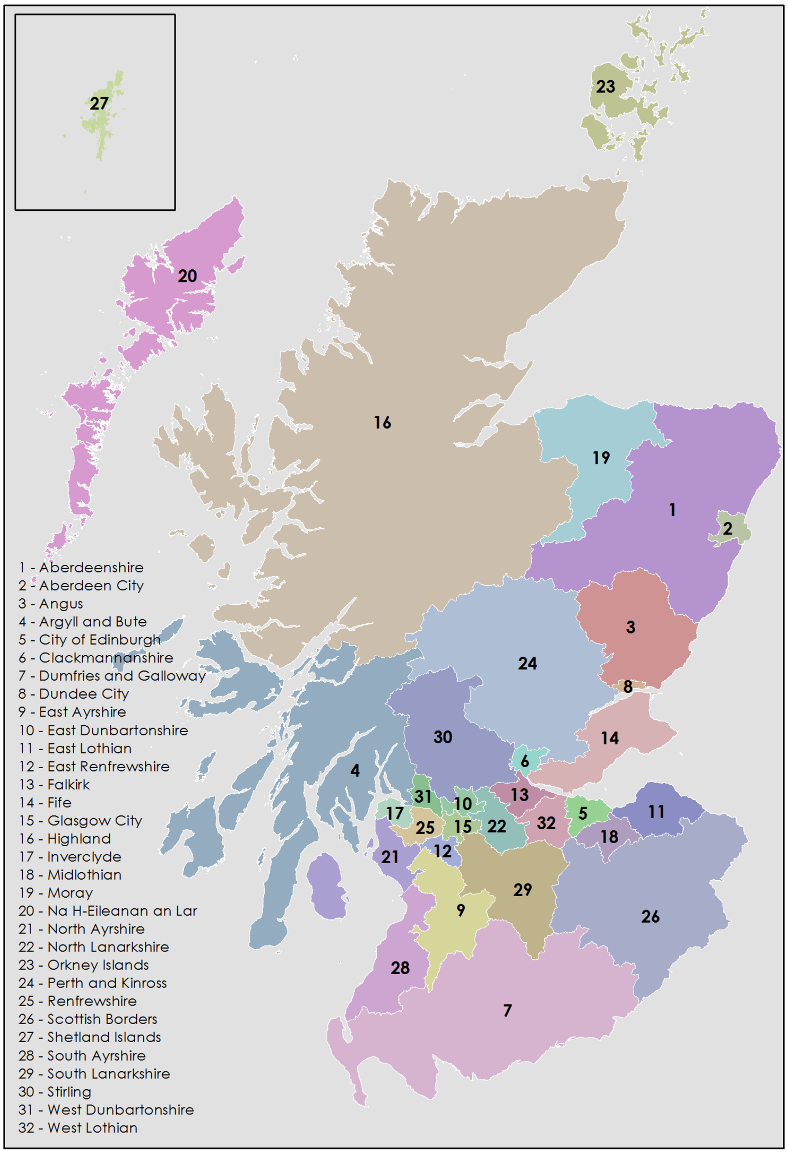


Figure 1.1: Map of Scotland with the 32 local authorities labelled numerically - utilising the Ordnance Survey boundary-line dataset (EDINA, 2017)

Scotland has also developed heat demand mapping which allows users to identify opportunities for decentralised energy projects (Scottish Government, 2017b). The mapping tool can be used to assess who needs heat and help to understand the local relationship between local supply and demand (DECC, 2013). The ability to identify potential areas of supply in close proximity to demand can help reduce vulnerabilities associated with transportation distances and grid connection (Saha and Eckelman, 2018). It is hoped that providing a comparison of the distribution of underutilised non-agricultural land types with areas of heat demand will add to a better understanding of the complex ‘energyscape’ (Howard et al., 2013) in Scotland. It is important to note that the methodologies adapted and applied in this thesis have been shaped within this Scottish contect and therefore would only by applicable in the context of developed countries. The use and valueing of underutilised non-agricultural land may be drastically different within developing countries, this is discussed in more detail in section 2.4.

1.3 Structure of the thesis

The aim of this thesis is to further an understanding of the opportunity that may be provided by underutilised non-agricultural land as a source of sustainable bioenergy. As part of the justification for conducting such research, a literature review will be undertaken to understand the degree to which this land type has been included in other attempts to seek an alternative to agricultural land, namely marginal land studies. Furthermore, this literature review will highlight land resources that could be included in a landbank representing underutilised non-agricultural land - the use of this terminology is discussed in box 1.1.

A GIS based methodology was developed to ascertain the non-agricultural landbank in Scotland, and further an understanding of the distribution of this land resource. The methodology adapted Voivontas et al. (2001) and Slade et al.’s (2010) categorisations of bioenergy potential. In doing so the research attempts to quantify both the maximum amount of land available, and the proportion of this land that may be available for bioenergy production once a range of constraints are applied. Finally, significant clusters of this land resource will be identified and compared with the Scottish Government’s heat demand map via exploratory spatial data analysis.

The literature review that follows, in chapter 2, will introduce bioenergy, describe its current contribution to a growing renewable energy market and discuss the criticism that this source of energy has begun to receive. The most prominent solution to rising criticism of using agricultural land for bioenergy production, the marginal land discourse, is then summarised including a discussion of the shortfalls of this approach. This discussion leads into an evaluation of the literature, which attempts to understand the extent to which non-agricultural land types have been included in marginal land studies. Further research that investigates the potential role that non-agricultural land types could play in supplying renewable energy technologies are then highlighted, and the unique benefits and challenges of using these land types are outlined.

Box 1.1 What is 'underutilised' non-agricultural land for bioenergy and what is a landbank?

This research is seeking to find an alternative to agricultural land to sustainably grow bioenergy feedstocks. Agricultural land, according to the 1947 Agricultural Act, is land that is farmed for the purposed of trade or business (Parliament of the United Kingdom, 1947). The term 'underutilised' has been included to ensure that further land use conflicts are avoided, and this includes areas of high biodiversity or sites that are currently utilised for human activities e.g. recreational use or signs of development.

The non-agricultural land types that have previously been considered are highlighted in sections 2.5 and 2.6. Of these land types, those that are best suited to further investigate in the Scottish context are outlined in section 3.3. The methodology outlined in Chapter 3 has been developed so that utilised areas, such as mine land undergoing restoration to their original or planned use, are not included in the spatial database that is created.

The term landbank was originally used to refer to public or community-owned entities created to acquire and manage vacant, abandoned, tax delinquent or forclosed property (US Department of Housing and Urban Development, 2012; Zlevor, 2016). It has been cited as a potential means of vacant land regeneration, giving communities the capacity to acquire sites on an interim bases (Kim, 2016; Kim et al., 2018). Nicholson et al.'s (2012) also utilise the term landbank to refer to the area of agricultural land that has the capacity for recycling organic materials. The authors choose this terminology to aid the description of shifting availability or the exclusion of areas due to constraints (Nicholson et al., 2012). This thesis reuses the terminology to refer to areas of underutilised non-agricultural land that have the capacity to be regenerated, more specifically for bioenergy provision, and the value of the landbank subsequently changes according to the application of spatial constraints as described in more detail in section 3.1.2.

Having established previous attempts to depict the non-agricultural land resource, chapter 3 presents the GIS-based methodology used to create a detailed spatial database representing these land types. The justification of utilising GIS and framing of the approach with considerations arising from previous uses of GIS, is followed by an explanation of how categorisations of bioenergy resource potential were adapted from Voivontas et al. (2001) and Slade et al. (2010) for the purposes of identifying suitable landbanks. The research design and methods used to identify the theoretical and technical landbanks are then described, along with a thorough assessment of sources of uncertainty and error that may arise during the implementation of this research.

The results are presented in chapters 4 and 5. The theoretical landbank, the hypothetical maximum amount of underutilised non-agricultural land, is presented in chapter 4. This includes the spatial database and detailed findings for each included land type. The technical landbank is the proportion of the theoretical landbank that can be utilised once a range of technical constraints are applied, is presented in chapter 5. Chapter 6 contains a discussion of the various potential applications of this landbank. The results of exploratory spatial data analysis are describing providing an insight into the distribution of clusters of this land resource and the spatial relationship that may exist with heat demand, in addition to a summary of alternative exploratory analysis that could be undertaken with the spatial database.

Finally, chapter 7 will provide a summary of the key findings of this research and the main conclusions that can be drawn from the results. This chapter will also include recommendations for future practice, based on the development of the methodology, and future research, which will outline how the results presented here can provide the foundation for further work.

1.4 Research Aims and Objectives

The aim of this thesis is to further an understanding of the opportunity that may be provided by underutilised non-agricultural land, particularly as a potential source of sustainable bioenergy. The following research questions are explored:

- To what degree does the 'marginal' land discourse sufficiently identify a sustainable landbank for future renewable energy provision?

- How well understood is the contribution that non-agricultural land types could play as a source of sustainable bioenergy provision?
- What is the best way to identify the collective area and distribution of underutilised non-agricultural land in Scotland?
- What are the potential applications for a landbank representing underutilised non-agricultural land?

Whilst the first two of these research questions are tackled within the literature review, the third research question is approached via the development of a methodology and subsequent results. The research design used is described in more detail in section 3.2. The final research questions is covered via the exploratory spatial data analysis and discussion within chapter 6.

Chapter 2

A review of attempts to identify suitable land for sustainable bioenergy provision without impacting agricultural production

The aim of this thesis is to understand the opportunity that could be provided by underutilised non-agricultural land as a provider of sustainable bioenergy provision. This chapter will provide context to the problem via a review of previous attempts to identify a sustainable solution for the bioenergy land use dilemma. Additionally, it is hoped that the following research questions will be addressed:

- To what degree does the 'marginal' land discourse sufficiently identify a sustainable landbank for future renewable energy provision?
- How well understood is the contribution that non-agricultural land types could play as a source of sustainable bioenergy provision?

The chapter will begin with an introduction to bioenergy and the role it currently plays in terms of renewable energy provision in section 2.1. This is followed by a discussion of the criticism of bioenergy and doubts over the sustainability of this renewable energy source and the associated importance of identifying suitable land if bioenergy is to continue to thrive. Section 2.3 will introduce the marginal land discourse that has arisen as a potential solution to identifying land resources that could be used to provide sustainable bioenergy. However, the problematic nature of this discourse will then be outlined along with an attempt to understand the degree to which non-agricultural land types are considered by marginal land studies. Finally, a review of suitable non-agricultural land types that could be considered in this research will be undertaken and the advantages and disadvantages of using these land types, as discussed in previous studies, will be highlighted in section 2.7. As explained in chapter 1, this research aims to further an understanding of the role that underutilised non-agricultural land could play in addressing the bioenergy land use dilemma (Lewis and Kelly, 2014) and therefore this literature review will focus on this application of these land types. However, there are several alternative uses of this landbank, and arguably therefore a range of additional benefits of quantifying it which are discussed in more detail in section 2.7.3.

2.1 The role of bioenergy

The importance of renewable energy in mitigating human induced climate change has long been established (Sims, 2004). Considering the need to cut greenhouse gas emissions from fossil fuel burning, ambitious targets have been set with the UK legally bound to achieving an 80% cut in carbon emissions by 2050 (Parliament of the United Kingdom, 2008). Having a broad energy mix is most likely to be the best method to achieve energy and climate change targets (Welfle et al., 2014). Bioenergy has been championed as a major contributor to this mix as a substitute to fossil fuels that can serve as a sink to capture and store atmospheric carbon (Dale et al., 2011). Furthermore, bioenergy has been identified as a potential solution which could not only help mitigate climate change and provide energy security but also promote rural development (Gallagher, 2008). Biomass can be readily substituted for fossil fuels, with the ability to utilise pre-existing power generation and distribution infrastructure (World Energy Council, 2016), and is a versatile source of renewable energy, capable of providing both electricity and heat (Wicke, 2011). Demands for low carbon energy has seen global biomass production increase dramatically in recent years (Schueler et al., 2016) and in 2016 bioenergy accounted for 72% of renewable energy sources used in the UK (DBEIS, 2017). This demand is set to continue increasing as it is predicted bioenergy could supply up to a third of global primary energy supply by 2050 (Bauen et al., 2009).

2.2 Bioenergy production - the need for more land

As outlined in the presentation of the Scottish context in section 1.1, good progress has been made towards some renewable energy targets - with Scotland achieving 57.7% of electricity demand from renewable sources in 2015 (Scottish Government, 2016a). However, in some areas, such as heat demand, we are still some way short of the ambitious 2020 objectives. More biomass will be needed to achieve ambitious renewable energy and climate stabilization targets (Schueler et al., 2016) but production and consumption must be sustainable if bioenergy is to be successful (Dale et al., 2011). The sustainability of bioenergy is heavily associated with the requirement for land, as an increasing demand for biomass inevitably leads to an increased demand for land on which energy crops can be grown (Andersson-Sköld et al., 2015). The large spatial footprint of bioenergy (Howard et al., 2013) therefore becomes problematic and it has become a priority to find locations where biomass can be grown sustainably.

Sustainable biomass is that which delivers lifecycle greenhouse gas emission savings (DECC, 2013) and an important aspect of this is ensuring it is not grown on land with high carbon stock or biodiversity value (DECC, 2013). The carbon debt controversy arises when discussing the conversion of land types with high carbon stock to agriculture for growing energy crops (Dale et al., 2010). As Fargione et al. (2008) explain, the conversion of rainforests, peatlands, savannas, or grasslands to produce crop-based biofuels can create a 'biofuel carbon debt'. The amount of carbon dioxide released during this conversion of land type has been quantified as 17 to 420 times greater than that saved in annual greenhouse gas reductions created by the displacement of fossil fuels (Fargione et al., 2008). Any large-scale land conversion of land for bioenergy crops will also have implications on global food security and existing ecosystem services (Lovett et al., 2009).

There are further concerns relating to the use of existing agricultural land for bioenergy production, as the use of fertile land currently in use for food crops leads to the clearing of carbon rich or biodiverse land elsewhere in the world to meet displaced demand for food crops (Tilman et al., 2009). This indirect land use change impact of bioenergy production can lead to biodiversity loss, rising food prices (Tilman et al., 2009), and additional greenhouse gas emissions which lead to doubts about the climate benefits of bioenergy as a source of renewable energy (Gallagher, 2008). It has been claimed that boosting biofuel crops without proper oversight could increase world hunger and food poverty (Boddiger, 2007). Bioenergy production on agricultural land causes energy markets to be placed in competition with food markets resulting in higher agricultural prices therefore having a considerable impact on land use and food security (Vasile et al., 2016). Moreover, Searchinger et al. (2008) warn that indirect land use change associated with increased corn-based ethanol demand could potentially lead to a doubling of greenhouse gas emissions in the next 30 years (Searchinger et al., 2008). The credibility of such claims has been labelled an over-simplification, with counter claims arguing that carbon emissions associated with indirect land use change are far too complicated to be portrayed in pre-existing models and that the motivation for people clearing land cannot be so easily quantified (Dale et al., 2010, 2011). However, the beneficial impacts of biomass crops, such as the carbon negative impact of carbon sequestration in soil and root biomass, have been overshadowed once the effects of land use change both direct and indirect begin to be considered (Gopalakrishnan et al., 2009).

The challenge of identifying a suitable amount of land whilst also ensuring sustainable food production and environmental protection is known as the bioenergy land use dilemma (Lewis and Kelly, 2014). As outlined above, land use decisions relating to biomass production can have significant effects on carbon sequestration, native plant diversity, food production, greenhouse gas emissions, water, and air quality (Dale et al., 2011). It has been argued that a requirement for sustainable biomass production is not only the avoidance of carbon rich areas but avoidance of agricultural land that would otherwise be used for food production (Gallagher, 2008). The consideration of land types that are not used for food provision would not only strengthen food security (Lovett et al., 2009) but has also become imperative to enhance the greenhouse gas emission savings that bioenergy could provide (Dale et al., 2011). For these reasons studies have emerged highlighting the need to further an understanding of the role idle, abandoned, or degraded land types could play in bioenergy provision (Gallagher, 2008; Wiegmann et al., 2008) and these land categories have since become associated with the term 'marginal' land.

2.3 Emergence of the'marginal' land discourse

According to Smit et al. (1991), the marginality of land 'relates fundamentally to the economic viability of land uses' and can be used to define areas in agriculture which have limited productive potential. The term 'marginal' land originally emerged from the field of agricultural economics in the 19th Century (Kang, Post, Nichols, Wang, West, Bandaru and Izaurralde, 2013), with Ricardo (1817) using the categorisation in his land rent theory, which became the foundation of marginal productivity theory. Marginal lands therefore became known as land at the 'margins of cultivation' (Peterson and Galbraith, 1932), at the margin of economic viability (Strijker, 2005), and 'where cost-effective production is not possible under given conditions' (Schroers, 2006). However, whilst land was originally deemed marginal purely from an economic perspective, the definition of marginal land broadened to include factors such as soil health and topography (Gopalakrishnan et al., 2009). Increasingly marginal land has become an 'umbrella term' to describe idle, barren, degraded, abandoned and underutilised lands (Dauber et al., 2012). This evolution of definitions can be identified via a comparison of schematic diagrams which attempt to visualise the role of marginal land in relation to other land types that may be available for bioenergy production (see Figure 2.1, Figure 2.2, Figure 2.3 and Figure 2.4).

Wiegmann et al. (2008) utilise a land economics based definition of marginal land, stating that land is marginal if cost effective production is not possible. The schematic diagram provided by the authors depicts marginal land as partially overlapping degraded and abandoned

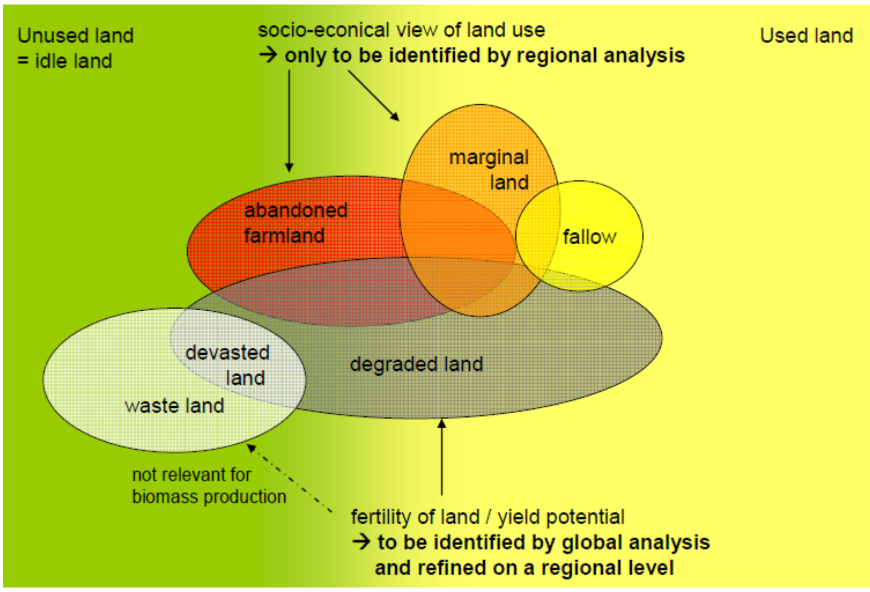


Figure 2.1: Schematic diagram showing interrelation of marginal land with other land types according to Wiegmann et al. (2008)

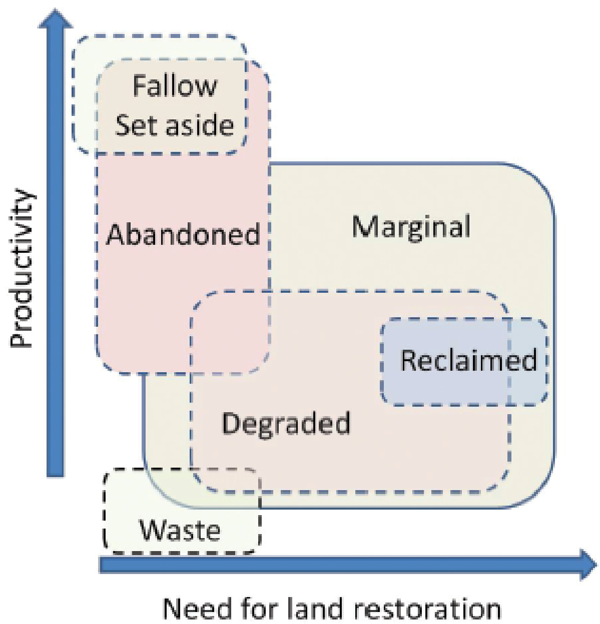


Figure 2.2: An alternative schematic diagram showing interrelation of marginal land with other land types according to Dauber et al. (2012)

land types, as well as fallow land (see Figure 2.1). In contrast Dauber et al.'s (2012) attempt (Figure 2.2) represents marginal land as significantly overlapping with abandoned land, fully encompassing degraded and reclaimed land types whilst separate from fallow and set aside lands. Blanco-Canqui (2016) present an illustration (Figure 2.3) that suggests potential marginal lands for growing dedicated energy crops could include an even wider range of land types from urban marginal soils to contaminated soils. Finally, and most recently, the EU funded project 'Sustainable Exploitation of Biomass for Bioenergy from Marginal Land' (SEEMLA, 2016) has adapted Dauber et al.'s (2012) figure to contextualise the condition of four pilot sites (SEEMLA, 2016). In the new figure (Figure 2.4) marginal land no longer fully encompasses degraded land but now includes brownfield sites with a higher ecological value. These studies, and their associated schematic diagrams, highlight the fluidity that is displayed when the notion of marginal land is conceived and the tendency for marginal land now to be understood as more of an umbrella term than the initial economic definition intended. Definitions of a selection of land categories that have been included by marginal land studies are provided in box 2.1

Figure 2.3: Further land types that have been considered potential marginal land for growing dedicated energy crops according to Blanco-Canqui (2016)

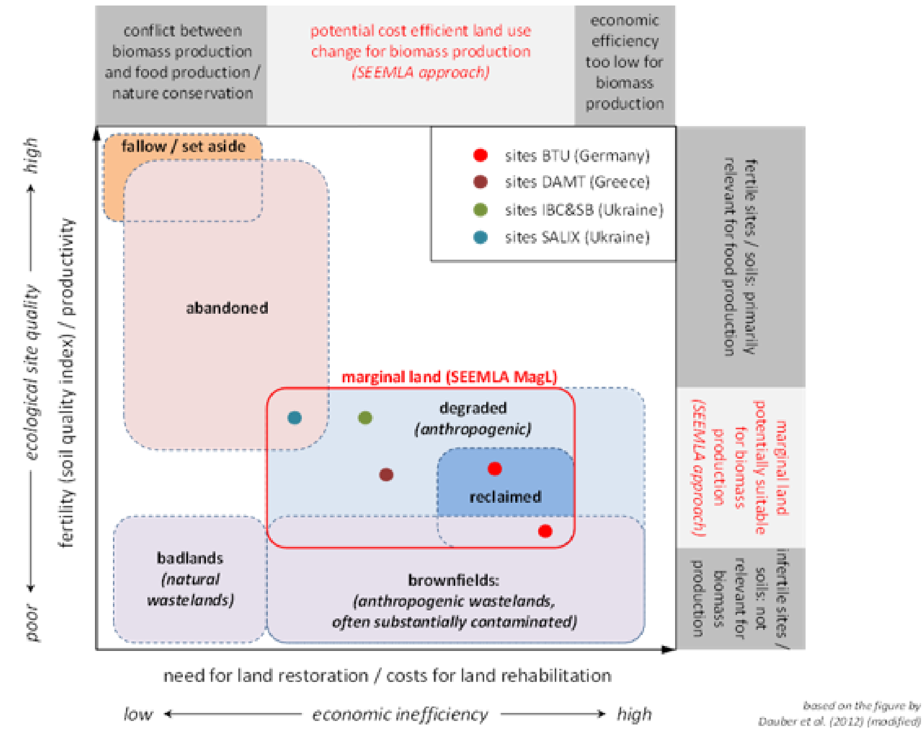


Figure 2.4: A more recent schematic diagram showing interrelation of marginal land with other land types used by SEEMLA (2016) to contextualise conditions of four pilot sites

Box 2.1 Definitions of land categories included by marginal land studies
The term marginal land has more recently become synonymous with a range of land types and categories. To add complication these sub-categories are also often defined differently amongst studies. To enable a better understanding definitions of some of the most common included land types are given below. Both Wiegmann et al. (2008) and Dauber et al. (2012) provide extensive summaries of includable land types and therefore these two studies were used as the primary source for definitions.

Idle land - The term idle land is related to the level of utilisation and therefore includes a range of land types that are considered unused; land that is considered to have shifted from intense use to no longer under anthropogenic use. This term encompasses abandoned farmland, devastated land and waste land. This term is often problematic because of the difficulty of establishing whether land has unconventional use to surrounding poputations, such as hunting or collection of medicinal plant. This is discussed further in section 2.4.

Abandoned land - Abandoned land refers to areas that were previously agricultural but have since been abandoned due to economic, political or environmental reasons. This term should be considered with caution due to the temporality of this land status, as discussed in more detail in 2.4.

Waste land - Waste land is considered to be naturally unfavourable for human use due to natural or biological conditions. This land is not considered suitable for bioenergy production.

Degraded land - Degradation is related to the level of productivity potential of the land and decline in natural land resources. This land category is usually identified via trend analysis which can highlight changes in net-primary productivity over time. Examples of degraged land types include abandoned farmland or post-mining land. These areas are considered to have reduced usefulness for agricultural productivity but could still harbour high levels of biodiversity.

Reclaimed land - This term related to land that was previously used for industrial purposes which is only considered usable once remediation has taken place.

Marginal land studies have also previously included temporary agricultural land categories such as fallow land, which is part of crop rotation, and set-aside land, which is politically motivated suspension of agriculture.

Regardless of the definition employed, the problematic nature of which is discussed in more detail in section 2.4, studies tend to reference a similar set of potential benefits of using marginal land for bioenergy provision. It is argued that because marginal land is largely unsuitable for agriculture it will avoid the negative effects of land use change, both direct and indirect, which is currently bringing the sustainability of bioenergy into disrepute (Wicke, 2011). Fargione et al. (2008) claim that biomass crops grown on abandoned or degraded lands ‘incur little or no carbon debt and can offer immediate and sustained greenhouse gas advantages’ (Fargione et al., 2008). In cases where marginal land has poor vegetation cover it has been suggested utilisation for energy crop purposed can increase the amount of sequestrated carbon in soil and root biomass (Mensah et al., 2003; Gopalakrishnan et al., 2009). Furthermore, it has been proposed that utilising these marginal lands can enhance their environmental condition (Dale et al., 2011) by improving soil fertility, reducing degradation, reducing wind and water erosion and providing biodiversity conservation (Tang et al., 2010; Wicke, 2011; Blanco-Canqui, 2016). Studies have also claimed that utilising marginal lands could bring additional societal benefits such as increased rural employment and improved scenery and infrastructure (Tang et al., 2010; Dale et al., 2011).

Considering these potential benefits marginal land is increasingly being discussed as a possible solution to the bioenergy land use dilemma. This is reflected in the number of studies that seek to understand the extent of marginal land resource that may be available for bioenergy crop production. As Lewis and Kelly (2014) point out, since 1993 there has been a large increase in the number of papers addressing terms such as marginal lands and biofuels in combination with methodological terminology including GIS and spatial. Such attempts have taken place at various scales, using a variety of models and data inputs (Lewis and Kelly, 2014). There are a number of studies that have attempted to identify the availability of marginal land at the global level (Campbell et al., 2008; Field et al., 2008; Cai et al., 2011; Nijsen et al., 2012). The earlier of these studies (Campbell et al., 2008; Field et al., 2008) compare past and current land cover using a global scale database to identify abandoned agricultural areas. Cai et al. (2011) attempted to apply land suitability indices based on soil productivity, topography, soil temperature regime and humidity. These indices were then combined with land cover mapping in an attempt to understand the current land use of areas deemed marginal based on the land suitability indices. As Lewis and Kelly (2014) argue, these global scale studies are challenged by the availability of up-to-date datasets at a suitable resolution. Similar obstacles exist for the growing number of studies seeking to identify the amount of marginal land at a national level or regional level. Numerous attempts have been made to identify marginal land nationally in developed countries such as the United States (Milbrandt et al., 2014) and Australia (Odeh et al., 2011), with several studies seeking to gain an understanding of the extent of this resource in China (Tang et al., 2010; Wu et al., 2010; Schweers et al., 2011; Zhuang et al., 2011; Lu et al., 2012; Liu et al., 2012, 2011; Wang and Shi, 2015) due to the countries' pressing need to avoid growing bioenergy crops on agricultural land (Lewis and Kelly, 2014). In the United Kingdom a number of studies have set out specifically to identify marginal land (Lovett et al., 2009; Turley et al., 2010). Additionally, there are a number of studies that have not explicitly mentioned marginal land but have similarly sought to identify land that can be used with a minimum impact on food production (Andersen et al., 2005; Haughton et al., 2009; Lovett et al., 2014). The approaches and findings of these attempts to identify marginal land in the UK are discussed in more detail in box 2.2.

Box 2.2 Attempts to identify marginal land for bioenergy production in the United Kingdom and Scotland

Several attempts have been made to identify the total amount of marginal land that could be available in the UK for growing dedicated energy crops. Each has taken a different approach in the consideration of avoiding prime agricultural land and this is reflected in the range of estimated land availability. Only two of these studies, Andersen et al. (2005) and Lovett et al. (2014), considers the availability of land in Scotland.

Andersen et al. (2005) - In an effort to determine Scotland's potential for biomass energy production this study applies several criteria relating to soil, land cover and climate. It identifies a total of 1.96 Mha of available land. Of this total, 208,100 ha is deemed to be marginally suited due to poorer conditions.

Haughton et al. (2009) - This study does not use the term marginal land. However, the authors have applied a combination of environmental and physical constraints as part of a Sustainability Appraisal Framework (SAF) approach in order to focus on 'environmentally-acceptable' locations. The study claims to have found 3.1 Mha of land in England suitable for planting. The study does not include Scotland.

Lovett et al. (2009) - Marginal land is defined as grade 3 and 4 agricultural land with a yield threshold of 9.9 odt ha^{-1} applied to align with the Biomass Strategy (DEFRA, 2007) target of 350,000 ha of perennial energy crops. The study identifies 362,859 ha of this 'more marginal' land. Scotland is also excluded from this study.

Turley et al. (2010) - This report, published by the UK Department for Energy and Climate Change, provides an assessment of marginal and idle land resource availability in England and Wales. The study combines agriculturally valuable land, such as fallow, set aside and grassland where stocked rates have declined, with non-agricultural idle land such as brownfields, urban spaces and hedgerows. The report concludes that there is approximately 4.34 Mha of land available.

Lovett et al. (2014) - This study also does not explicitly use the term marginal land but having identified 8.5 Mha of land in total the authors then overlay agricultural classification data to avoid areas important for agricultural production. The resulting layer of grade 4 and 5 agricultural land contains 1.40 Mha of land purportedly available for perennial energy crops in the UK. The only total given for Scotland in this study, 1.44 Mha, includes all agricultural land classifications and therefore cannot be considered marginal land.

At the regional level there have been studies conducted to understand the availability of marginal land in the United States (Gopalakrishnan et al., 2009, 2011; Kang, Post, Wang, Nichols, Bandaru and West, 2013; Gelfand et al., 2013; Saha and Eckelman, 2015; Stoof et al., 2015; Saha and Eckelman, 2018) and Italy (Fahd et al., 2012; Fiorese and Guariso, 2010; Tenerelli and Carver, 2012). Whilst there have been a wide range of studies investigating the availability of marginal land in developed countries, fewer studies have applied similar methods to identify the resource in developing countries. However, Milbrandt and Overend (2009) conducted a semi-global assessment of the provision of marginal land in Asian-Pacific Economic Cooperation countries which included developing countries of South-East Asia. Additionally, studies have also been conducted investigating the availability of marginal land in Sub-Saharan Africa (Wicke et al., 2011) and India (Sudha and Ravindranath, 1999; Edrisi and Abhilash, 2016). Research regarding the role that marginal land could play in providing land for bioenergy production is therefore abundant and varied yet the emergence and enthusiasm of research output regarding this land resource has brought the term under greater scrutiny.

2.4 Problems with the 'marginal' land discourse

Whilst some studies have strongly reinforced marginal land as a potential solution to the bioenergy land use dilemma (Fargione et al., 2008; Wicke, 2011), a number of researchers have underlined key issues and related assumptions (Shortall, 2013) with the term that brings into question its role as a sustainable option for bioenergy production or hampers attempts to identify the land resource.

The most pronounced problem with marginal land is related to the variation and ambiguity in its definition. The definition varies widely according to country, local conditions or the organisation studying the issue (Dale et al., 2010). Often the classification schemes used to identify marginal land (such as fig 2.1, fig 2.2 and fig 2.4) include several land class that are not on an equal hierarchical level and yet they can intersect or resemble sub-classes of higher categories (Dauber et al., 2012) leading to various interpretations as to what land types can be classed as marginal. As Wicke (2011) explains, the vagueness of the classification of this land type leads to practical difficulties in identifying marginal land. This, coupled with dissimilarities in model and datasets applied (Lewis and Kelly, 2014), has led to a wide range of estimates regarding the availability of land for growing dedicated energy crops (Glithero et al., 2015). In the UK, for example, the extent of marginal land resource estimates range from 362,859 ha (Lovett et al., 2009) to 3.1 Mha (Haughton et al., 2009). Furthermore, Glithero et al. (2015) consider these estimates to be high given the amount farmers would be willing to uptake energy crops and the context of current dedicated energy crop growth in England. The various ways in which the term has been approached makes comparisons of studies difficult (Gallagher, 2008) and therefore the appropriateness of the land resources identified are brought into question. Wicke (2011) argues that the ambiguity of the definition must be removed by the establishment of a clear criteria and methodology for identifying land that is sustainable for bioenergy production. At present this is lacking in the marginal land discourse which leads to questions regarding the certainty of identified land being a sustainable solution to the bioenergy land use dilemma.

Shortall (2013) identifies three dominant definitions of the term marginal land and outlines the technical, normative, and political assumptions that are embedded within each of them. According to Shortall (2013), the first two definitions - that marginal land represents either 'land unsuitable for food production' or 'ambiguous lower quality land' share the same assumptions. Both descriptions assume that there is enough of these land types, that production is possible on them, and that they can be targeted (Shortall, 2013). However, such assumptions are particularly problematic when the definition still contains a degree of ambiguity and could still represent several different land types from the most degraded agricultural land to brownfield land. The third definition, that marginal land is 'economically marginal land' has a different set of assumptions and related problems. Shortall (2013) explains that it is assumed that using economically marginal land for bioenergy production is possible in a sustainable way without competing with food production. However, the author continues by explaining that using land types such as grade 3 or 4 agricultural land would in fact still lead to the displacement of some food production (Shortall, 2013). Kang, Post, Nichols, Wang, West, Bandaru and Izaurralde (2013) argue that marginal land already plays an important role for agriculture, arguing that it was the primary factor behind a 25% increase in global wheat production in 1997. It is the temporality of the economic based definition that is particularly challenging when trying to gain an understanding of the role marginal land could play in providing sustainable bioenergy. Shortall (2013) explains that what is considered marginal for one crop under one set of economic conditions may not be marginal for another crop in other conditions, proposing that what is at the economic margin of production at one point in time may be considered not marginal as prices of harvesting, transport or production fluctuate. Dauber et al. (2012) touch on a similar theme by arguing that using land that is temporarily idle could still be contributing to indirect land use change if that land could have come into use for agriculture at a later date. Evidentially, there is a lack of clarity with regards to the type of land that is being referred to in many studies and, as Shortall (2013) concludes, depending on the definition employed marginal land could be arguably either unfeasible, due to poor quality land, or unsustainable, due to a continuation of detrimental land use change.

Regardless of the definition employed there are additional problems that have been discussed in the literature in relation to marginal land and the role it could play for sustainable bioenergy production. At the forefront of these issues is the condition of land types being included as marginal land. The 'law of marginality' as described by Lal (2009) states that marginal soils will produce marginal yields. Gelfand et al. (2013) also highlight the problematic nature of identifying land with low fertility. The impact of selecting marginal land is quantified by Fischer et al. (2010) who claim that yields are up to three times greater on suitable soils. Dauber et al. (2012) add that often land is deemed marginal because of a lower yield potential based on a lack of precipitation, therefore utilising such land could result in a large water footprint. In addition to the issue of land quality, it has been argued that marginal land is poorly located (Gelfand et al., 2013) and that the long distances needed to reach them could mean the loss of carbon dioxide neutrality (Dauber et al., 2012). These highlighted problems lead to doubts over the sustainability of marginal land for bioenergy crop production and because of the umbrella nature of the terminology used often several, vastly different, land types are considered to share the same limitations.

From a practical perspective, marginal land poses a challenge to identify. Dale et al. (2010)

discuss the difficulty in utilising satellite imagery to find marginal land. This is made even more difficult if the definition of the resource sought remains ambiguous. It is often assumed that land is idle (Wicke, 2011) yet it is problematic to assume this from land cover data or poor resolution satellite imagery alone. Some uses are particularly difficult to identify such as grazing or fuelwood collection (Dauber et al., 2012). As Dauber et al. (2012) explain, it is important to take into account the lands true existing use in contrast to a course land use classification. This requires any assessment to take into account the local context, and often means a top-down approach to identifying suitable land is not suitable. It is necessary to consider local perceptions and appreciations in relation to land use which is currenty overlooked by marginal land approaches. Van Der Horst and Vermeylen (2010) argues that targeting of 'marginal' land in developing countries can come at the expense of marginal communities. Land is valued differently according to the local context, and land that is assumed to be 'wasteland' by the wealthy may be vital for the 'day-to-day struggle for survival' for marginalised communities as they rely on this land for fuel, medicine, wild food or even building materials (Van Der Horst and Vermeylen, 2010).

Finally, Lewis and Kelly (2014) describe that hard to depict land uses can often not be captured via remote sensing which ultimately leads to them being left out of broad scale geospatial datasets. This is of particular concern when the often-wide reaching definition of marginal land is taken into consideration and could arguably lead to fears that some land types are being overlooked, a problem that is discussed further from a methodological point of view in section 3.1.1. Given the problems associated with marginal land, especially concerns that economically marginal or marginal agricultural land could be an unsustainable option, it is necessary to gain a better insight into the extent to which these studies have included the non-agricultural land resource in their considerations.

2.5 The extent to which 'marginal' land studies include non-agricultural land types

With the aim of understanding the role that non-agricultural land types are considered by previous research to contribute to the availability of marginal land, an evaluation of the literature was undertaken. An explanation of what is considered non-agricultural land for the purposes of this research is outlined in Box 1.1. The reasoning underpinning this analysis of the literature, centrally which studies and what land types were searched for and included, are outlined below.

Some publications stick strictly to an economic-based understanding of marginal land, which can lead to a focus on only marginal agricultural lands (Fiorese and Guariso, 2010; Odeh et al., 2011; Nilsson et al., 2015) or selection of lands only from an agricultural land classification dataset (Lovett et al., 2009; Swinton et al., 2011; Tenerelli and Carver, 2012). These studies do not make any attempt to include non-agricultural land types in their assessment of marginal land. Global scale studies deal with datasets at such a resolution that it is difficult to determine which land uses are being pinpointed by analysis (Lewis and Kelly, 2014). This is not intended to be a criticism of such global studies (Campbell et al., 2008; Field et al., 2008; Milbrandt and Overend, 2009; Cai et al., 2011; Nijsen et al., 2012). It is simply meant to highlight that it would not be possible to determine what proportion of the marginal land these studies identify is necessarily non-agricultural based on their use of global land cover datasets. Additionally, the identification of degraded land, a term associated with marginal land related to a loss of productivity potential (Stocking, 2001), has been attempted via a top-down assessment using the HYDE database (Schweers et al., 2011). This type of assessment, based on a historical global environment database, shares the limitation of producing an output from which it is challenging to distinguish identified land types, as well as further concerns that the degraded area identified may be in use or have a high biodiversity value (Dauber et al., 2012). Lastly, some studies seeking to identify marginal land based on land cover classification or physical and environmental characteristics fail to go into detail regarding the current use of lands identified (Gelfand et al., 2013; Kang, Post, Wang, Nichols, Bandaru and West, 2013).

These global scale studies, land degradation studies based on global datasets, and studies that fail to clarify the land use of identified areas were not considered any further in this assessment of non-agricultural lands inclusion in marginal land research. Furthermore, whilst abandoned agricultural land has been included as a marginal land type in some research (Kukk et al., 2010; Stoof et al., 2015), it was not considered to be a source of non-agricultural land in this review. As Dauber et al. (2012) explain, land types assumed to be idle could come into use for agriculture in the future, therefore causing indirect land use change. Finally, considering the requirement to find a sustainable alternative to agricultural land, land types with the potential to have a high carbon stock or biodiversity value, such as shrubland or grasslands, were also not included as a suitable non-agricultural land resource even if they were deemed to be marginal and not in use for food production. Turley et al. (2010), for instance, include hedgerows and low land bracken as an idle land resource but these were not included in the following calculations undertaken to establish the area of non-agricultural land identified by the study. This stipulation led to the exclusion of further studies who seemingly only identified these highly vegetated or bio-diverse land types (Wu et al., 2010; Liu et al., 2011).

After an evaluation of the marginal land literature 15 studies were found that explicitly include types of non-agricultural land and these are set out in Table 2.1. These studies were published between 2009 and 2018 and include seven studies conducted at a national scale, six at a regional scale and two at the local, or city, scale. The table includes information of the area targeted by the study, the interpretation of marginal land that is employed as well as outlining the reference to non-agricultural land types that is made. For each study, an attempt was made to calculate the contribution of non-agricultural land to the total amount of marginal land identified. Furthermore, the sum of non-agricultural land is shown as a proportion of the total study area investigated and any further comments pertaining to the studies' methodology were noted.

As is common in marginal land studies, and described in section 2.4, the definition of marginality applied by each of the selected studies was variable. Seven of the studies stipulated that marginal land must not be suitable for food-based agriculture (Gopalakrishnan et al., 2009; Liu et al., 2012; Lu et al., 2012; Saha and Eckelman, 2015; Wang and Shi, 2015; Niblick and Landis, 2016; Saha and Eckelman, 2018), with a further four studies specifically outlining marginal land as that which is not 'currently' available or not cost effective for agriculture, raising the issue of the temporal nature of marginality (Turley et al., 2010; Gopalakrishnan et al., 2011; Zhuang et al., 2011; Fahd et al., 2012). The different approaches taken often lead to plain contradictions. For instance, Gopalakrishnan et al. (2009) include conservation land as a source of marginal agricultural land which contrasts the definition outlined by Niblick and Landis (2016) that marginal land must not be 'otherwise fulling conservation purposes'.

Two of the studies, at the local or city scale, specified the inclusion of 'urban marginal lands' (Niblick et al., 2013; Saha and Eckelman, 2015). This approach led to the identification of various non-agricultural land types that may be found within the urban limits such as vacant lots, land surrounding developed lots and underutilised areas. In contrast to this and reflecting the fluidity of interpretations of marginal land types, Milbrandt et al. (2014) exclude all urban areas from their study.

Beyond the studies investigating urban marginal land there is a wide spectrum of non-agricultural land types that have been considered and included within the identified marginal landbanks. Most of the research conducted in China has included 'barren' and 'bare land', which seemingly includes shoal, bottomland, saline land, alkaline land (Zhuang et al., 2011; Liu et al., 2012; Lu et al., 2012) and, in one case, sand marsh and marsh land (Wang and Shi, 2015). It is unclear how appropriate these land types would be for dedicated energy crop production, as in addition to poor biophysical conditions these land types may lack suitable accessibility. One study seeking to identify the marginal land availability in China, conducted by Tang et al. (2010), does include several additional non-agricultural land types such as road side land, stream side land, house surroundings and land risers or boundaries. This inclusion of buffer strips along infrastructure such as roads, rivers, rail, or canal has been mirrored in several other studies (Gopalakrishnan et al., 2009, 2011; Turley et al., 2010; Milbrandt et al., 2014).

Amongst many of the studies the majority of non-agricultural land types included are areas impacted by previous human use, whether it be contaminated land (Gopalakrishnan et al., 2011), former mining land (Niblick et al., 2013; Edrisi and Abhilash, 2016), brownfield land (Gopalakrishnan et al., 2009; Turley et al., 2010; Gopalakrishnan et al., 2011; Fahd et al., 2012; Milbrandt et al., 2014; Niblick and Landis, 2016; Saha and Eckelman, 2018) or landfill and dumps (Niblick et al., 2013; Niblick and Landis, 2016; Saha and Eckelman, 2018). However, overall there is a stark lack of consistency as to which non-agricultural land types have been considered and therefore no standardisation in methodology applied in order to identify these land categories.

The absence of any degree of conformity to either a definition of marginal or agreement regarding the non-agricultural land categories that can be considered is reflected in the wide range of totals found for non-agricultural land areas. A comparison of the contribution of non-agricultural land types to the total amount of marginal land highlights the difference in approaches across the studies. The two local, or city, scale studies find a marginal landbank that is completely composed of non-agricultural land types - as is to be expected given the tendency for agricultural land types, marginal or otherwise, to be out-with city limits. In addition to these urban marginal land studies, one further study also included only non-agricultural land types in its assessment of available land (Niblick and Landis, 2016), yet the authors still presented their findings within the framing of understanding the role of marginal land. This mirrors Bardos (2009) who, despite not assessing the availability of the resources in detail and therefore not included here, suggests that brownfield, derelict and vacant and contaminated lands are marginal lands that could be considered for bioenergy provision. The remaining studies varied regarding contribution of non-agricultural land, with findings ranging from 0.17% to 75% of the total area identified being composed of these land types.

The discrepancies in findings amongst these studies is also present when the proportion of non-agricultural land found was calculated in relation to the total study area. The smaller scale, urban based studies (Niblick et al., 2013; Saha and Eckelman, 2015, 2018) found relatively higher proportions, ranging from 15% to 24% of total study area being composed of available non-agricultural land. Amongst the remainder of the studies the proportion of non-agricultural land varies between 0.005% and 5.8%. This is only the subset of marginal land assessment studies that mention of non-agricultural land, and yet amongst these studies both the definition of marginal land and the types of non-agricultural land types that have been included varies so widely and this is reflected in the landbank area identified. The disparity in these findings makes it difficult to conclude what role non-agricultural land could play with regards to bioenergy provision, and whether reliable enough evidence is made to promote or discount the potential opportunities this land type could bring.

In addition to uncertainty regarding the role non-agricultural land could play in providing sustainable bioenergy provision, further problems arise as a result of the mix of approaches taken to the inclusion of non-agricultural land types in marginal land provision assessments. In using the umbrella terminology, marginal land, the benefits of using non-agricultural land types are arguably being overlooked. Most prominent of these benefits is the security of knowing bioenergy production can take place with no competition with food production. Furthermore, the complexity and unique difficulties of using these non-agricultural land types need separate consideration if they are to be mobilised for bioenergy production. This aspect is seemingly disregarded when it is being considered as simply an additional marginal land resource. Finally, the identification of these land types within a marginal land framework could lead to the misapplication of methodologies that are not appropriate for identifying such land types. Examples of this can be seen within the studies identified, with either an assumption that a top-down methodology will suitably capture non-agricultural land types (Zhuang et al., 2011; Liu et al., 2012; Lu et al., 2012) or adapted methods applied which lack the detail, or consideration of uncertainty, to make realistic conclusions (Tang et al., 2010;

Niblick and Landis, 2016).

Table 2.1: Summary of the 15 'marginal' land studies identified that include non-agricultural land types

Scale	Year	Author	Where?	Marginal definition employed	Mention of non-agricultural land	Non-agricultural land area found (Mha)	Total area found (Mha)	Proportion of total land found that is non-agricultural (%)	Non-agricultural land as proportion of total land cover (%)	Comments
National	2010	Tang et al. (2010)	China	Land that may be used for growing energy crops such as wasteland and paddy fallowed in winter, plus land risers, land boundaries and land along highways/roads	Wasteland, land riser/boundary, stream side land, house surroundings, land along highways/roads	55.65	110	50.6	5.8	
	2010	Turley et al. (2010)	England and Wales	Land where cost effective agricultural production is not possible under a given set of conditions	Land resources with no current agricultural value: roadside verges; railway embankments; canal margins; brownfield land	0.6	4.34	13.76	3.96	
	2011	Zhuang et al. (2011)	China	Relatively poor natural condition but is able to grow energy plants, or land currently not used for agricultural production	Barren land (shoal/bottomland, saline and alkaline land, and bare land)	5.21	130.34	4	0.54	
	2012	Lu et al. (2012)	China	Land unsuitable for crop production, but ideal for growth of energy plants with high stress resistance	Unused land (including alkaline land, bare land and shoal/bottomland)	0.86	18.28	4.7	0.09	
	2014	Milbrandt et al. (2014)	United States	Lands with inherent disadvantages or lands that have been marginalized by natural and/or artificial forces	Abandoned mine lands; EPA sites including brownfield and superfund sites; rights-of-Ways including road, rail and transmission line buffers; barren land	21.18	86.48	24.49	2.15	Excludes all urban areas

Scale	Year	Author	Where?	Marginal definition employed	Mention of non-agricultural land	Non-agricultural land area found (Mha)	Total area found (Mha)	Proportion of total land found that is non-agricultural (%)	Non-agricultural land as proportion of total land cover (%)	Comments
National	2016	Edrisi and Abhilash (2016)	India	'potential marginal land' is defined as wastelands, all types of lands degraded by natural as well as anthropogenic activities, that meet a range of biophysical considerations	Mining/industrial wastelands	0.065	39.24	0.17	0.02	
	2016	Niblick and Landis (2016)	United States	Land unfit for food grade agriculture and not otherwise fulfilling conservation purposes or ecosystem services	Abandoned mine lands; brownfield land; closed landfill	2.82	2.82	100	0.29	
Regional	2009	Gopala-krishnan et al (2009)	Nebraska	Land not suitable for productive agriculture, which require inputs of water and nutrients to maintain productivity	River/riparian buffers; road buffers; brownfield sites	0.65	1.25	51.8	3.23	Brownfield deemed 'insignificant' and total includes conservation land
	2012	Gopala-krishnan et al (2011)	Nebraska	Land not capable of agroeconomic profitability based on land use, soil health and environmental degredation	Brownfield; riparian, road and impaired stream buffers; contaminated land	0.85	15.64	5.31	4.25	Lower range of estimates used for calculations
	2012	Fahd et al. (2012)	Campania	All non-cultivated areas where actual primary production is too low to allow competitive agriculture	highly polluted land suitable neither for food production nor for biodiversity development	0.045	0.2	22.5	3.31	

Scale	Year	Author	Where?	Marginal definition employed	Mention of non-agricultural land	Non-agricultural land area found (Mha)	Total area found (Mha)	Proportion of total land found that is non-agricultural (%)	Non-agricultural land as proportion of total land cover (%)	Comments
Regional	2012	Liu et al. (2012)	SW China	Land that has relatively poor natural condition but is able to grow energy plants, or land that is not currently in use for agriculture but is capable of growing certain plants	Barren land (shoal/bottomland, saline and alkaline land, and bare land)	0.007	0.92	0.77	0.005	
	2015	Wang and Shi (2015)	Guangdong Province	Land not suitable for growing field crops due to edaphic and/or climatic limitations, vulnerability to erosion, or other environmental risks, but might be usable for growing crops	Shoal/bottomland and unused land (sand marsh, marsh land, and bare land)	'very small proportion'	2.5	n/a	n/a	
	2018	Saha and Eckelman (2018)	MAPC region, Massachusetts	Lands that are not suitable for food based agriculture and have limited economic potential for fullfilling other ecosystem services	Residential and commerical underutilised areas; landfills; Junkyards	0.053-0.071	0.071	75	15	Not clear what proportion is abandoned cropland of final 25% therefore lower bound used for calculations
Local	2013	Niblick et al. (2013)	Pittsburgh, US	Urban marginal lands: lots with poor agricultural potential and unfit for residential purposes	Vacant lots; surrounds of developed lots; special land uses: strip mines, gullied land, gravel pits, quarries, coal dump, industrial dump	0.002	0.002	100	16.7	Not clear what proportion of 2400 ha belongs to specific land types
	2015	Saha and Eckelman (2015)	Boston	Urban marginal lands: land parcels that have limited economic value and are not suitable for agricultural purposes	Public/private lands; residential/commercial underutilised areas	0.003	0.003	100	24	Not clear how 'utilisation' is measured i.e. backyards included

2.6 Alternative attempts to consider the opportunities provided by non-agricultural land types

Whilst the previous section outlined the extent to which non-agricultural land types have been considered within marginal land resource assessment studies, there have been alternative attempts to understand the role these land types could play with regards to renewable energy provision. There are a variety of non-agricultural land types that could present opportunities for a renewable industry in need of more space (Howard et al., 2013; Spiess and De Sousa, 2016; Waite, 2017).

Brownfield land has received a lot of attention regarding potential redevelopment opportunities (Oliver et al., 2005). The definition of brownfield land varies globally, with a tendency in the United States to focus on the presence of contamination (Oliver et al., 2005). For the purposes of this research, and with the aim of distinguishing it from other non-agricultural land resources that may be contaminated, the definition provided by Alker et al. (2000) was deemed most appropriate. According to this definition brownfield land is 'any land or premises which has previously been used or developed and it not currently fully in use, although it may be partially occupied or utilised. It may also be vacant, derelict, or contaminated' (Alker et al., 2000). Brownfield lands are often considered eyesores or even potential health hazards (Adelaja et al., 2010). The difficulty of redeveloping these sites partnered with the increased requirement for renewable sources of energy have resulted in them being considered for renewable energy provision (Adelaja et al., 2010). In terms of biomass production, brownfield land has been discussed as a potentially usable land resource in the North East of England (Evans, 2009) as part of an EU-funded scoping document of available non-agricultural land types. The practicality of utilising this land type for bioenergy production has been touched upon by several further studies. Lord (2015) describes the use of compost to establish energy crops on brownfield land and following this five 1 hectare brownfield sites in North East England were harvested for 3 to 5 years. Furthermore, Smith et al. (2013) compared the yield of bioenergy crops on a remediated site in the United States with a historically cropped agricultural site and found there to be little difference in yields, arguing that brownfield land has the potential to produce suitable quality feedstock. Beyond bioenergy, brownfield land has been assessed in terms of the role it could play in providing other renewable energies. Adelaja et al. (2010) investigated the wind and solar potential on brownfield sites in Michigan, concluding that utilisation of this resource could provide 43% of Michigan's residential electricity consumption. Similarly, the potential for brownfield redevelopment for solar energy purposes has also been investigated in Czech Republic (Klusáček et al., 2014). In the UK context, Donaldson and Lord (2018) have provided an assessment of the brownfield land availability in Glasgow City, arguing that these sites could be reused for ground source heating to help alleviate fuel poverty in the city. This collection of studies highlights the opportunity that brownfield land could play in the provision of renewable energy from non-agricultural sources.

Research regarding brownfield land in the United States for renewable energy provision is often undertaken alongside the consideration of other contaminated land types. Foremost of these attempts is the Environmental Protection Agency's 'RE-Powering America's Land' initiative, which sought to better understand the role formerly contaminated lands, landfills, and mine lands could play for renewable energy development (EPA, 2016). This initiative includes brownfields as well as superfund sites, sites contaminated by hazardous waste and identified by the EPA for clean-up, as contaminated lands. Mosey et al. (2007) investigated these 'limbo lands' on behalf of the EPA, creating a screening process to identify sites with a high potential for renewable energy technologies. More recently, Waite (2017) also undertook research regarding the potential for renewable energy installations on 81,000 sites associated with federal clean-up programs in US.

Both Mosey et al. (2007) and Waite (2017) in America, and Evans (2009) in the UK, have included landfill as an option for siting of renewable energy technologies. McKendry (2002) has discussed the potential for restored landfill sites to provide biomass which could supplement landfill gas fuelled power stations. Furthermore, Ettala (1988) studied tree plantations on six landfill sites in Finland, finding that short-rotation plantations can be established and the quality of the resulting biomass would allow it to be cultivated as a source of energy. The concept of using closed landfill for the provision of renewable energy has also been investigated in Hungary (Szabó et al., 2017), with the researchers declaring solar photovoltaic installations on former landfill sites a 'win-win'. According to their findings the establishment of solar PV systems can simultaneously avoid the environmental, economic and land value concerns of post landfill closure whilst providing renewable energy. Another land type also considered by the EPA Re-Powering America initiative is abandoned mine land. In reference to the EPA initiative, Buchsbaum (2015) discusses that abandoned mines and the area immediately surrounding them are not usually considered for reuse due to safety and environmental concerns, and yet there have been examples of them being utilised for cleaner sources of energy in countries such as Germany (Buchsbaum, 2015). The use of this type of land has been discussed elsewhere, with Rocio et al. (2013) reporting that abandoned mercury mine could be cropped and a Waste Resources Action Plan project identifying the potential for biofuel crop production on a former coal washing site in Kinglassie (WRAP, 2009). The latter of these studies conducted trials on a 5 hectare site to demonstrate that compost can be used to improve poor soil quality sufficiently to enable the establishment of crops (WRAP, 2009). Old mineral workings have also been considered in terms of their potential for siting bioenergy projects (Evans, 2009), with Dubuc (2007) identifying clusters of quarries to provide bioenergy for nearby power plant demand. An additional non-agricultural land type that was included in the assessment of marginal undertaken by Gopalakrishnan et al. (2009, 2011) was riparian buffers. These areas surrounding waterways have been investigated separately, with Fortier et al. (2016) assessing the potential to produce biomass on deforested farm streams in 3 watersheds. A final set of non-agricultural land types that have been considered for renewable energy technology establishment are unconventional urban sources (Arodudu et al., 2014). Arodudu et al. (2014) employed a GIS methodology to identify and estimate the bioenergy potential from green roofs and construction sites which the authors argue can be used in addition to domestic organic waste and leaf-fall collection from recreational parks.

The literature outlined above establishes a collection of non-agricultural land types that have been considered in relation to renewable energy technologies. A common theme and limitation raised across these studies is the quality of data and consequently poor methodologies employed. Oliver et al. (2005), for instance, outline the requirement for more data regarding brownfield in Europe to enable successful monitoring of flows in this resource. The presence of incomplete or missing data in existing databases representing these land types has also been highlighted (Klusáček et al., 2014). This requirement for more data potentially undermines the validity of these studies as a representation of the land resource that exists. Mosey et al. (2007) attempt to provide an insight into the provision of 'limbo lands', including landfill, superfund, abandoned mine land, brownfield and former industrial sites, and yet the analysis only utilises data from the national priority list of sites 'threatening releases of hazardous substances, pollutant or contaminants' (Mosey et al., 2007). Likewise, Waite (2017) is limited to the sites that had been screened by the EPA's intiative, and the author admits that only eleven states provided further data. Additionally, the studies that implement a GIS approach, such as Niblick and Landis (2016), have represented the land resource as points yet if any judgement is to be made about their suitability for siting renewable technology further detail would be required, this issue is outlined further in section 3.1.1. One such study striving to create a more detailed picture of the non-agricultural land resource, albeit without a consideration of the potential for renewables, is the investigation undertaken on behalf of the Northwest Development Agency (Northwest Development Agency, 2002). This pilot study implemented a bottom-up approach based on aerial imagery to identifying derelict, underused and neglected land (Northwest Development Agency, 2002). The authors then consulted local authorities regarding the identified sites and evaluated end-use suitability. Future attempts to identify the non-agricultural land resource for renewable energy provision could consider adopting elements of the methodology utilised by the Northwest Development Agency (2002) to gain a better picture of the degree to which these sites can be mobilised. The availability of complete databases underpin any investigation into the opportunity non-agricultural land could have in providing renewable energy. This is discussed further, alongside a consideration of which of these non-agricultural land types could be considered in Scotland, in section 3.3.

2.7 Benefits and challenges of using non-agricultural land types

A further justification for considering non-agricultural land distinctively from other marginal land is to allow the unique benefits and challenges of using this land resource to be addressed separately. The multitude of benefits and challenges of using these land types for bioenergy, and more broadly renewable energy development in general, have been raised within the literature. By focusing on the availability of these land types, the results provided in this thesis can be framed by the following advantages and challenges.

2.7.1 Benefits of using non-agricultural land types for renewable energy provision

Spiess and De Sousa (2016) summarise the advantages of siting renewable energy technology on brownfield land as 'triple bottom-line benefits', and this understanding can be extended across all the non-agricultural land types raised in section 2.6 with environmental, social and economic benefits evidenced in all cases. The most heavily discussed of this triad of benefits is the potential environmental impact of using these land types for bioenergy or other renewable technologies. Most relevant is the unique opportunity that using land types such as brownfield land could provide in producing carbon neutral biomass without impacting on food production (Lord et al., 2010). Additionally, it has been argued that implementation of bioenergy could bring a range of further environmental benefits such as ecological improvement (Lord et al., 2010), blight removal (Adelaja et al., 2010), and helping to rebuild the soil profile on land that is often of poor quality (Blanco-Canqui, 2016). Blanco-Canqui (2016) has even suggested that growing dedicated energy crops on reclaimed mine soils can have a higher potential to sequester soil carbon in the first 20-25 years following reclamation than on agricultural land. A further benefit adjoined to bioenergy production on contaminated lands is the role energy crops could play in remediating these sites (Lord et al., 2010; Andersson-Sköld et al., 2015). Phytoremediation is the use of plants to destroy, extract, stabilize or contain contaminants (Andersson-Sköld et al., 2015), and has been promoted as a cost effective in situ remediation option (Blanco-Canqui, 2016) that avoids the need for energy intensive process-based remediation or extraction (Lord et al., 2010). Phytoremediation has also been encouraged, despite being a slower form of remediation (Gomes, 2012), due to the additional environmental advantages of erosion control, reduced greenhouse gas emissions and waste generation, and increasing the biodiversity on sites (Andersson-Sköld et al., 2015), whilst simultaneously generating revenue from the biomass sold (Enell et al., 2016). Many contaminated sites currently have a negative asset value due to the looming costs of future remediation or maintenance (Lord et al., 2010) which could be side-stepped if the site is put into use for bioenergy provision. Alternatively, other sites are not contaminated enough to trigger industrial remediation options and therefore sit idle (Andersson-Sköld et al., 2015), which could also be avoided if these sites were considered as a source of bioenergy. In the case of landfills, phytocapping, the placing of a layer of soil material atop the landfill and growing of a dense layer of vegetation, has been deemed to enhance aesthetic qualities and introduce economic benefits if energy can be generated (Seshadri et al., 2016). Lamb et al. (2012) also describes how phytocapping can mitigate the environmental impact of leachate generation and GHG emissions. Finally, a further set of unique environmental benefits have been highlighted if renewable energy technologies target the urban non-agricultural land resource - including the role that biomass could play in urban flood prevention, reducing the urban heat island effect (Arodudu et al., 2014) and generating ecosystem services (Blanco-Canqui, 2016).

In addition to these environmental benefits it has also been argued that there are economic benefits to be gained from using non-agricultural land for bioenergy provision (Paulson et al., 2003). One such economic benefit, which can be extended to other land-based renewables, is that using these non-agricultural land types may be cost effective as sites already have road connections, and often also have fencing and are connected to the grid (Spiess and De Sousa, 2016; Szabó et al., 2017). Furthermore, Donaldson and Lord (2018) argue that brownfield land can provide low cost energy to target fuel poverty identifying a tendency for these sites to be in close proximity to social housing. It has also been claimed that targeting brownfield land for bioenergy can lead to the creation of jobs and investments in often run-down post-industrial landscapes (Adelaja et al., 2010; Spiess and De Sousa, 2016).

The economic benefits of utilising these non-agricultural land types are linked to positive social impacts. Using sites for bioenergy provision, for instance, has been linked to community redevelopment benefits (Adelaja et al., 2010; Lord et al., 2010) and aesthetic improvement (Paulson et al., 2003). Bambra et al. (2014) have called for brownfield land to be considered an element of environmental deprivation, highlighting the link between brownfield land and spatial inequalities in health including morbidity. This research concludes that people living in wards with a higher proportion of brownfield land are significantly more likely to suffer from poorer health than those living in wards with a smaller proportion (Bambra et al., 2014). The paper continues by not only linking contaminated brownfield with potential risks to physical health via the 'source-pathway-receptor' model, but also arguing that brownfield land is an 'untherapeutic landscape' (Bambra et al., 2014) and a marker of long term industrial decline and 'spoiled identity'(Bambra et al., 2014). The authors relate the state of brownfields with the notion of biophilia, arguing that humans prefer natural settings due to an inherent association with resources and protection (Curtis, 2010). From this perspective, the greening or remediation of brownfield or other non-agricultural land types could be considered to have wider societal benefits and could potentially be linked to an improvement in community health.

2.7.2 Challenges of using non-agricultural land types for renewable energy provision

The most prominent of issues regarding the use non-agricultural land types for renewable energy deployment, particularly bioenergy, is the quality of the land. Lord et al. (2010) outline several set-backs that may face attempts to grow biomass on these land resources including shallow soil depth, compaction and low water retention, limited nutrients, low organic matter and potential phytotoxicity (Lord, 2015). Additional issues arise due to competition on these sites from weeds and pests, and the existence of structural remains and made-ground (Lord, 2015). The quality of the land can have a direct impact on the ability to grow biomass on these sites and Blanco-Canqui (2016) concludes that a lower yield is to be expected on these land types compared with prime agricultural land. However, Spiess and De Sousa (2016) declare that despite technical and environmental, financial, regulatory, industrial, and social barriers, ultimately the challenges to establishing renewable technology on brownfield land only differ from other renewable energy developments in the case of contamination. Donaldson and Lord (2018) reiterate this aspect, underlining the fact that the costs associated with remediation need to be considered if non-agricultural land types are to be utilised for renewable energy technologies.

Besides these challenges associated with the quality of the land resource, there are further complications that need to be considered due to the high proportion of these land types within, or close to, urban areas (Saha and Eckelman, 2018). The urban setting can lead to access and logistical problems as well as potential developers being faced with high land prices and labour costs (Saha and Eckelman, 2018). The siting of renewable energy technologies can also lead to neighbourhood concerns (Saha and Eckelman, 2018) and an element of NIMBYism (Spiess and De Sousa, 2016). A further barrier to deployment of renewables in urban areas, according to Saha and Eckelman (2018), is the competition for use of the land with other economic activities. The competition for use of these sites is not unique to urban areas though and it is necessary to discuss the alternative uses that could be vying to utilise non-agricultural areas.

2.7.3 Alternative uses of non-agricultural landbank

There is a wide spectrum of potential end uses for non-agricultural land resources that are currently left idle or underutilised. Current work has focused on the alternative benefits, other than via development, for urban brownfield land (Morrison, 2015), and this is the non-agricultural land resource with the greatest competition for use given the barriers to using land types such as closed landfill and abandoned mine land. However, many of these alternative benefits could play a role in shaping the competion for all the non-agricultural land resources highlighted in section 2.6. Of these competing alternative benefits, the role of these land types in ecological restoration is most heavily argued (Plieninger and Gaertner, 2011; Macadam and Bairner, 2012; Morrison, 2015). There has been an increased awareness of the importance of previously developed land for wildlife (Macadam and Bairner, 2012) and biodiversity conservation (Plieninger and Gaertner, 2011). Macadam and Bairner (2012) argue that brownfield sites can support many rare, scarce and UK Biodiversity Action Plan priority species. Similarly, Plieninger and Gaertner (2011) have suggested that degraded lands may support biodiversity levels similar or above managed landscapes and are therefore an untapped resource for conservation (Plieninger and Gaertner, 2011). Plieninger and Gaertner (2011) continue by arguing that use of these lands for bioenergy may generate difficult trade-offs with ecosystem functions and conservation of biodiversity, even claiming that energy crops exhibit 'traits of invasive weeds' (Plieninger and Gaertner, 2011). It has been suggested that these non-agricultural land types, such as brownfield land, would be better utilised as a source of greenspace including wildflower meadows (Prentis and Norton, 1992) or forestry (Doick and Hutchings, 2007). Mathey et al. (2015) has proposed that brownfield land in urban settings would be ideal for greenspace provision with the additional benefits of microclimate regulation and new recreational space development. Contrary to these greenspace ambitions, it has also been suggested that brownfield land could play an important role in housing provision (CPRE, 2016). A report produced by the Campaign to Protect Rural England, concluded that up to 1.1 Million homes could be built in England on brownfield land, with enough land to meet 5-year house land supply targets (CPRE, 2016).

There is therefore a multitude of competing uses for these non-agricultural land types. However, whilst these could be considered a barrier for the implementation of bioenergy developments, or other renewable technologies on the land, it also highlights the requirement for detailed, usable information on this land resource. Such information could be applied to ensure that the future decision making regarding the best use of these land types is well informed.

This chapter has outlined the requirement to identify alternative land resources to help solve the bioenergy land use dilemma. The current discourse is dominated by discussion regarding the role that marginal land could play in this capacity. However, the problematic nature of this ambiguously defined land category has been described alongside efforts to try and understand the degree to which these marginal land studies have included non-agricultural land resources. By highlighting the available non-agricultural land types, and associated benefits and challenges of using these areas, it is hoped that the requirement for a more detailed assessment of the opportunity this land resource can play in providing sustainable bioenergy without impacting on agricultural production has become evident.

Chapter 3

Methodology

The main aim of this thesis, as outlined in Chapter 1, is to further an understanding of the opportunity that could be provided by underutilised non-agricultural land as a source of sustainable bioenergy. To fully understand the role this land type could offer it is necessary to quantify the area of resource and provide an insight into its distribution. A methodology has been developed to quantify the resource at a national scale, using Scotland as a case study. Having identified the landbank, further exploratory data analysis techniques were employed to highlight key clusters of this land resource. In outlining the methodology, this chapter will seek to explore the following research questions:

- What is the best way to identify the collective area and distribution of underutilised non-agricultural land in Scotland?
- How can we highlight significant clusters of underutilised non-agricultural land for bioenergy provision?

The methodological choices made are best framed by previous research, therefore this chapter will begin by briefly summarising the rise of GIS-based methods in section 3.1. Some of the weaknesses or challenges faced by past research are highlighted in section 3.1.1, justifying the methodological choices made in this thesis. This is followed by a discussion of the differing 'levels' of bioenergy potential, in section 3.1.2, and an explanation of how these are represented as landbanks to be investigated within the scope of this thesis. The research design and structure of the remainder of this chapter are outlined in section 3.2. Additionally, a thorough evaluation uncertainty and error is undertaken in sections 3.2.1, 3.3.1, 3.4.7 and 3.6.3.

3.1 Shaping a Geographical Information Systems (GIS) approach

Biomass requires a large area of land per unit of energy produced (Blaschke et al., 2013), therefore the provision of biomass is inextricably linked to the provision of land area. An extended understanding of locality and distribution is important when assessing potential sites for bioenergy provision. The sustainability of bioenergy is heavily impacted by geographic nuances (Calvert, 2011) such as distance from point of use, and potentially overlooked small sites could be deemed usable if located within close proximity to clusters of other identified areas (Lam et al., 2010). To appropriately understand the spatial relationships of, and between, sites a geographical information systems (GIS) approach was deemed most suitable. A GIS combines geographical features with tabular data to store, analyse and display real-world geospatial problems (Dempsey, 2017). A GIS incorporates hardware, software, data and human decision making to allow us to answer questions regarding spatial location and pattern (Heywood et al., 2011). The role of a GIS is often to simplify an enormously complex world, and ultimately the selection of data, construction of models and specification of spatial methods heavily influences the manner in which the real world is represented (Jacquez et al., 2000).

Initially GIS was not without its critics, with worries it would lead to a generation of 'button pushers' who lack an understanding of the geographic principles that are required to solve everyday problems (Kenzer, 1992). This led to GIS being labelled a reductionist epistemology, with concerns it often over simplifies complex problems (Wheatley, 2000; Longley et al., 2005). Despite these initial criticisms GIS is now a well-established field of research which requires an understanding of basic and fundamental geographical concepts in order to appropriately apply the computational tools available. The ability of GIS to manipulate large amounts of geographic data makes it an ideal means for suitable site selection however it is also important to understand instances when human decision making, consideration of literature and the opinion of key stakeholders are required. This chapter will highlight these instances alongside a detailed explanation of the methods that were applied.

3.1.1 Considerations arising from previous applications of GIS and Bioenergy potential studies

As Calvert (2011) summarises, geomatic techniques are increasingly important in providing relevant and robust information when assessing bioenergy resource availability. GIS has already been well used as a tool to analyse the spatial features of available land and to deal with the dispersed geographical distribution of biomass potential (Voivontas et al., 2001). There have been numerous studies utilising GIS to identify bioenergy potential on all available land at both a regional (Beccali et al., 2009; Fiorese and Guariso, 2010; Tenerelli and Carver, 2012; Kang, Post, Nichols, Wang, West, Bandaru and Izaurralde, 2013) and national (Cole et al., 1996; Andersen et al., 2005) scale.

As outlined in the literature review, in section 2.3 and section 2.5, GIS has continued to be a pivotal tool in attempting to distinguish and quantify marginal land at a global (Campbell et al., 2008; Field et al., 2008; Cai et al., 2011; Nijsen et al., 2012), national (Lovett et al., 2009; Tang et al., 2010; Turley et al., 2010; Wu et al., 2010; Odeh et al., 2011; Schweers et al., 2011; Zhuang et al., 2011; Lu et al., 2012; Liu et al., 2012, 2011; Milbrandt et al., 2014; Wang and Shi, 2015) and regional (Gopalakrishnan et al., 2009; Fahd et al., 2012; Kang, Post, Wang, Nichols, Bandaru and West, 2013; Gelfand et al., 2013; Saha and Eckelman, 2015, 2018; Stoof et al., 2015) scale. Lewis and Kelly (2014) provide a thorough review of the use of GIS to map marginal land as a proxy for bioenergy crop potential and have found a great degree of inconsistency across the studies. Whilst the primary source of these differences, which is discussed in more detail in section 2.4, is the lack of a shared working definition of marginal land (Lewis and Kelly, 2014), the lack of consistency in mapped results can also be linked to methodological differences including model framework, data, scale and treatment of uncertainty (Lewis and Kelly, 2014).

Despite the dissimilarities outlined by Lewis and Kelly (2014) most of the studies take a top-down raster-based approach when identifying suitable land. This primarily involves selecting a category of land within a land cover or capability dataset. Unfortunately, these datasets are often not available at a particularly fine scale and the accuracy is difficult to determine. As Lewis and Kelly's (2014) review shows, the resolution of input land cover datasets used by studies vary from 30 m to 1 km^2. Lewis and Kelly (2014) also highlight that studies then combine multiple raster datasets with differing resolutions and lineages. This ultimately adds to uncertainty regarding the accuracy of the resultant dataset. Furthermore, it is difficult to target a specific land type if there is not a corresponding category within the land cover dataset. This can lead to large uncertainty when attempting to identify land types with different attributes using low resolution raster datasets. This is also further complicated by the presumed existance of 'mixels' in the raster layer - a raster cell whose area is divided among more than one class (Longley et al., 2005). Whilst raster data can be very useful when conducting analysis of datasets (See box 3.1) it is not necessarily the best foundation on which to create a spatial database representing a difficult to define land type. The top-down raster based application of GIS would not be suitable in attempting to identify underutilised non-agricultural land and therefore an alternative bottom-up site specific method has been developed for the identification of land. At this stage the accuracy of the dataset is paramount, to get a true impression of the land resource. At a later stage, during analysis, a raster based approach will be adopted but it is acknowledged that this will significantly impact the level of uncertainty in the resultant output (see section 3.6.3).

Box 3.1 Data models explained - Raster vs. Vector

There are two fundamental data models used to represent features within a GIS: vector and raster models (see also Figure 3.1). Each model has its advantages and disadvantages depending on the application desired. Whilst Berry's (1993) often used quote 'raster is faster, but vector is corrector' is somewhat of a simplification, especially given recent advances is computer processing power, it does give an indication to scenarios in which either model may be better suited.

Raster: It often helps to think of raster data as being arranged in a grid, with rows and columns of uniformly sized and shaped cells (Johnson and Wilson, 2003). The raster model treats the world as a continuous surface and thus every cell has an assigned value, including 'null' values. The simplicity of the data structure means analysing raster datasets is often quick and easy to perform, particularly overlay processes. However, the use of cells often means familiar features may be rendered unrecognisably and there may even be a loss of information.

Vector: The vector data model uses discrete point, line and polygon features, with corresponding x and y location coordinates, to represent the world's features. Point features are represented in the database by a single co-ordinate, line features are represented by a set of connected vertices each with a co-ordinate. Polygon features are created when a set of vertices are joined and closed, with the first and last point having the same coordinate. In a vector data model each object has topological information which describes its spatial relationship with surrounding objects (Johnson and Wilson, 2003). A vector data structure provides a good representation of phenomenology (Geospatial Innovation Facility, 2015) this is because it is not constrained by a grid size or shape. On the other hand, storing continuous datasets such as elevation or rainfall would require a degree of generalization and would quickly become processing intensive. Furthermore, the combination of several vector maps through overlay would create a number of geometric difficulties (Geospatial Innovation Facility, 2015).

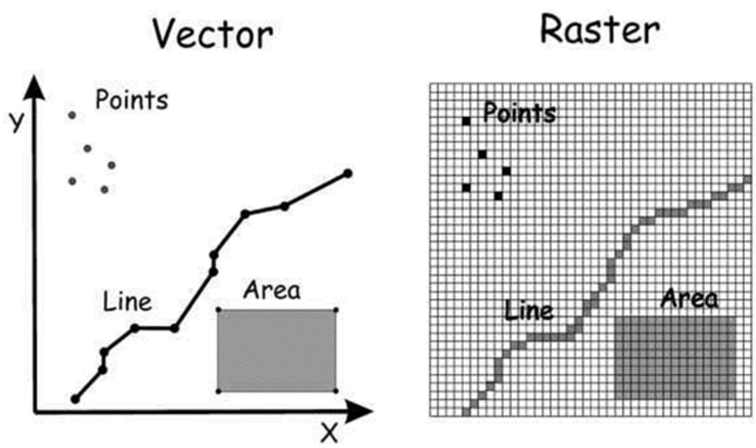


Figure 3.1: Simplified distinction between Raster and Vector data models (Geospatial Innovation Facility, 2015)

A site-specific bottom-up approach would require the creation or adaption of a database or inventory of appropriate sites. Two recent attempts to evaluate the renewable potential of brownfield land have used pre-existing databases of sites as the starting point for their research (Adelaja et al., 2010; Niblick and Landis, 2016). Such databases provide a sound basis for investigating the role of specific land types however the information contained within such databases is potentially limited. Adelaja et al. (2010) utilise a list of sites from the Mississippi Department of Environmental Quality, however not all the sites have information on size therefore they are forced to estimate some sizes using a random, stratified sample. Niblick and Landis (2016) join two US Environmental Protection Agency databases to get site areas but subsequently were forced to remove sites with an area given as null or zero - an indication of the level of completeness of the database they are relying on. Both studies represent sites as points. The areas of the sites are merely attached as an attribute, the accuracy of which they are unable to elaborate upon in detail. The depiction of sites using only points provides further disadvantages. The lack of boundary information leading to large uncertainty, or even complete non-understanding, regarding the extent of each site. Ultimately this make it impossible to make a judgement based on characteristics within the sites' bounds.

A GIS approach can enable the production of a spatial database that allows each site to be represented in greater detail than a point with attached attribute data. A more detailed approach has already been taken in some attempts to find biomass sources that do not conflict with agriculture or ecologically valuable areas. For instance, the sources of biomass in urban areas such as green roofs, parks and construction areas can be best captured using a combination of satellite imagery and vector mapping (Arodudu et al., 2014). A similar approach has been utilised by the Northwest Development Agency in their survey of derelict, underused and neglected land in the North-West of England (Northwest Development Agency, 2002), using digital aerial images to interpret sites. A comparable methodology combining multiple mapping sources would be required to capture non-agricultural land parcels that could potentially be used for bioenergy provision.

Whilst there have been many studies utilising GIS to identify bioenergy potential of agricultural land or whole areas, few studies have outlined a framework for identifying the potential of non-agricultural land. Amongst those that have made a concerted effort to investigate the significance of these land types, namely Niblick and Landis (2016), there are still a number of methodological flaws which were considered when designing this research. Before outlining the research design, it is necessary to detail the landbanks that are considered in this thesis.

3.1.2 Framing an understanding of the potential availability of land in terms of landbanks

Often studies of bioenergy resource potential take a multi-level approach, with each progressive level narrowing down the availability of resources according to a stricter set of boundary conditions (Slade et al., 2010). One of the first studies to adopt this structuring of methodology was Voivontas et al. (2001) who presented a GIS decision support system with four-levels of analysis of power production from agricultural residues - identifying the theoretical, available, technological and economically exploitable biomass potential. Whilst these categories have been adapted and used in numerous biomass potential studies (Field et al., 2008; Verkerk et al., 2011), other new types of 'potential' have also been defined including ultimate potential, implementational potential and sustainable potential (Slade et al., 2010; Vavrova et al., 2016). Whilst Voivontas et al's original levels of analysis were focused on the power production potential from agricultural residues, Slade et al. (2010) have presented a more general set of hierarchical definitions that can be applied to biomass resource potential studies. Each level of potential ultimately involves a different calculation of a reducing biomass yield or possible energy production. For the purpose of this thesis the most suitable of Voivontas et al.'s (2001) and Slade et al.'s (2010) categories will be adopted, adapted and focused towards understanding the potential underutilised non-agricultural land resource that exists rather than the potential energy availability.

The theoretical potential is the total amount of biomass that could be grown before any restrictions are applied (Slade et al., 2010) - the hypothetical maximum yield of agricultural residues (Voivontas et al., 2001). This thesis will seek to identify the theoretical landbank, the total amount of underutilised non-agricultural land that can be identified before any technical constraints are applied. This stage will include the identification of includable, underutilised, land types followed by the quantification of the total area giving an indication of the opportunity that could be presented by these land type.

The technical potential has been described as the total amount of the theoretical potential that can be used once a range of ecological, technological, and topographic constraints are considered (Slade et al., 2010), this is also known as the available potential (Voivontas et al., 2001). This will be repurposed for this research as the technical landbank, the total proportion of the original theoretical landbank which can be used once a variety of constraints are applied. These two types of landbank provide the core structure for the investigation into the opportunity that could be provided by underutilised non-agricultural land.

3.2 Research design

The research design has been tailored, to adequately answer the research questions, with past methodological successes and weaknesses in mind. Suitable non-agricultural land types that could be included in this study have been identified as part of the literature review in sections 2.5 and 2.6. The land resources that can be included in the Scottish case study within this thesis are outlined in section 3.3. A GIS-based methodology was then developed that produces a representation of the theoretical landbank via a spatial database created using a bottom-up approach - explained in more detail in section 3.4. This database is a collection of polygons in vector format, providing as accurate representation of the land type concerned as possible. The technical potential landbank was then explored via a multi-criteria evaluation which allowed constraints to be applied to the initial theoretical landbank - as outlined in section 3.5. At this stage the data will be converted to raster format, enabling complex spatial analysis to be performed. The theoretical and technical landbanks were then investigated further via exploratory spatial data analysis techniques, described in more depth in section 3.6. These techniques were used to explore spatial clustering of sites and to compare the identified landbanks with other datasets. The combination of these elements provided the backbone of this thesis (Figure 3.2 and Figure 7.1).

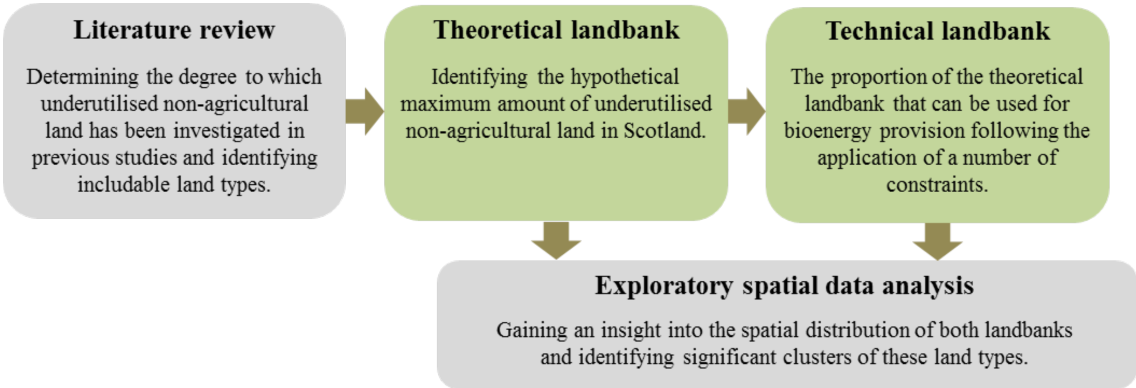


Figure 3.2: Core elements that form the backbone of the research design and their interrelationship.

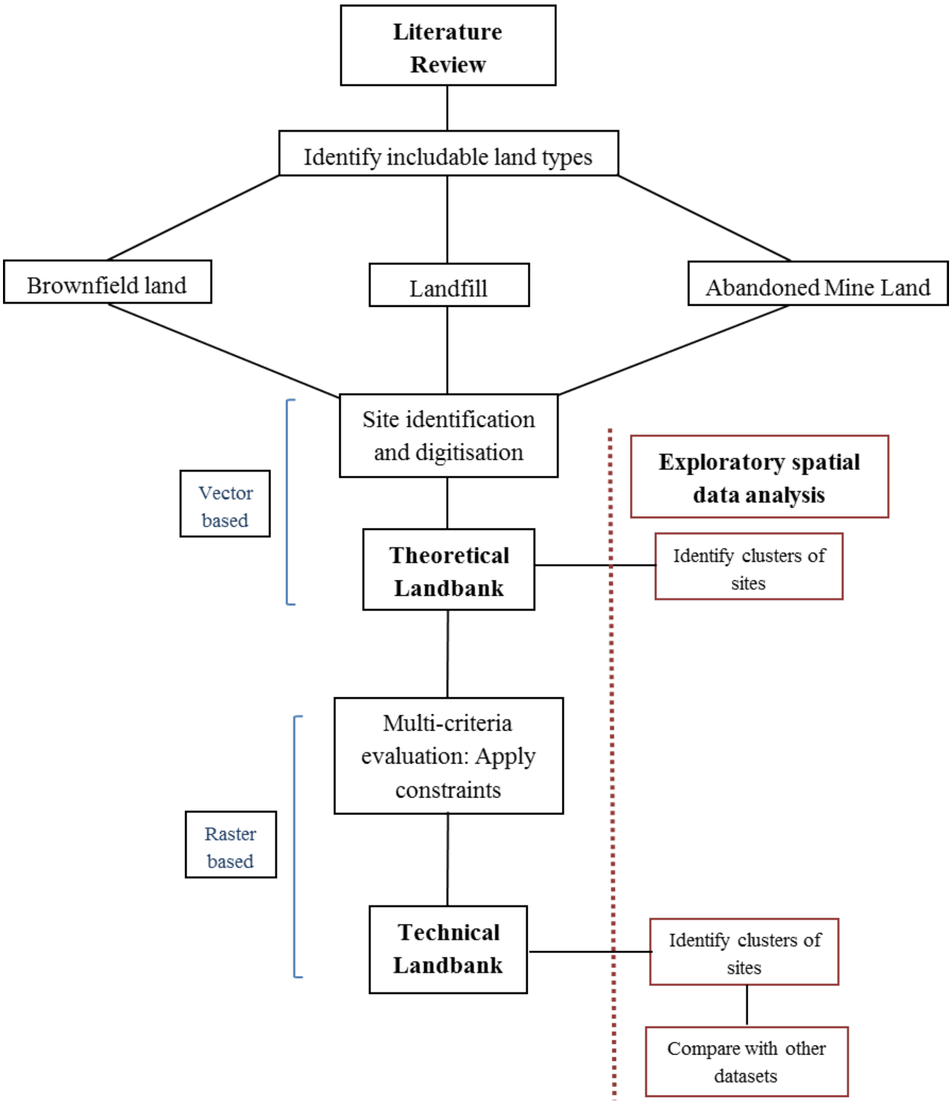


Figure 3.3: Simplified model of research design implemented, including the core land types investigated, techniques and data models used.

3.2.1 Uncertainty and error within the research design

The impossibility of depicting the complexity of the real world means that GIS is prone to uncertainty (Fisher, 1999). Uncertainty springs from the user's choices surrounding how real world feature are conceived, measured and represented, and how these representations are analysed (Longley et al., 2005). Longley et al. (2005) set out a conceptual view of uncertainty (see Figure 3.4), with three levels which provide a framework for evaluating the distortion or transformation that the representation of the real world undergoes when being stored or analysed within a GIS. These levels are used in this chapter to facilitate discussion regarding uncertainty, error and data quality issues that may arise within this research.

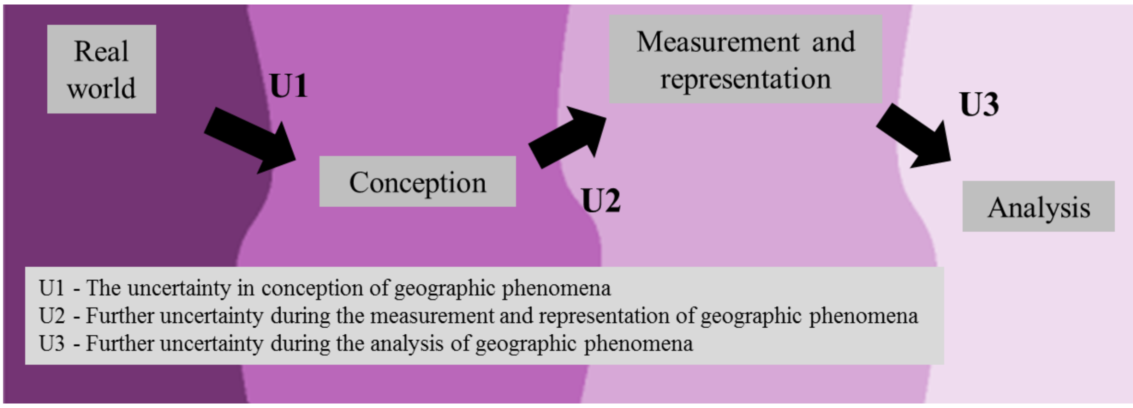


Figure 3.4: A conceptual view of uncertainty based on Longley et al. (2005)

U1 represents the uncertainty in the conception of geographic phenomena (Longley et al., 2005). Issues of vagueness and ambiguity can undermine any attempt to represent features within a GIS, and this is evident in previous attempts to map 'marginal' land as discussed in section 2.4. This is discussed in more detail in relation to the conception of underutilised non-agricultural land in part 3.3.1. U2 represents the further uncertainty that may creep in during the measurement and representation of geographic phenomena (Longley et al., 2005). This is discussed in section 3.4.7, as this relates to the creation of the theoretical landbank. Finally, U3 represents further uncertainty that may be taken on during the analysis of geographic phenomena (Longley et al., 2005). This is discussed in more detail in section 3.6.3, as it is relevant to the analysis that results in the technical landbank and the spatial exploratory techniques used to examine both landbanks.

3.3 Selection of suitable non-agricultural land types within the Scottish context

There were three considerations that impacted whether land types could be included as part of this research. Firstly, a judgement was made regarding the logistical suitability of any land types for bioenergy provision. A review of underutilised non-agricultural land types that have been considered in previous studies was undertaken in section 2.6, and any land types that were included in marginal land resource assessments were highlighted in section 2.5. The selection of land categories to be included in this study was undertaken based on their appropriateness within the Scottish context. For instance, whilst roadside and riparian buffers may have been deemed a suitable land for consideration in North America (Gopalakrishnan et al., 2009) this would not be the case in Scotland. This is due to Scotland having relatively fewer long straight sections of roads compared to the US. Any roads that do meet this criterion, such as motorways, would prove logistically difficult to harvest. A similar restriction would mean that river and stream buffers, as considered by Gopalakrishnan et al. (2009, 2011) and Tang et al. (2010), would not be available for use in Scotland. Similarly, Turley et al. (2010) include railway embankments and canal margins, once again reaching these remote areas for harvesting would not be realistically possible. The literature review did highlight key land types that would be more suitable for further investigation. In particular, Evans (2009) proposes several non-agricultural land categories on which biomass production could be undertaken such as closed landfill sites, restored colliery sites and restored opencast land. Secondly, as discussed in more detail in section 3.4, the creation of any spatial database relies on the availability of current data or inventories which can form the basis of further investigation. This was the most limiting factor regarding the inclusion of a land resource. Pre-existing information relating to locations of land types was required for any resource to be included in this research. Finally, the term 'underutilised' has been adopted as part of the requirement for inclusion of land, as discussed in box 1.1. This has been applied even at the theoretical landbank stage, in an attempt to avoid future land use conflicts. This is reflected not only in the selection of land types which typically lay vacant for long periods of time, but also within the digitisation methodology which employed aerial imagery as a tool to ensure included land was not in use.

Taking into account the above considerations of the appropriateness of land to the Scottish context, availability of data and requirement of the land to be underutilised, 3 classes of land were deemed most suitable for inclusion in this research: brownfield land (Adelaja et al., 2010; Niblick and Landis, 2016), closed and historic landfill (Mosey et al., 2007; Szabó et al., 2017), and abandoned mine land (Mosey et al., 2007; Niblick and Landis, 2016). Furthermore, Scotland's Zero Waste Plan's goal of reducing the total waste that goes to landfill to 5% by 2025 (Scottish Government, 2010) would lead to the closing of approximately four out of five currently authorised landfill sites therefore these have also been included. Whilst great care was taken in the selection of these land types, it is necessary to discuss the role that defining a land class such as underutilised non-agricultural land has in the introduction of uncertainty within the research.

3.3.1 Uncertainty in the conception of underutilised non-agricultural land

Error can be defined as a flaw in data, and within a GIS this is often understood to be an indicator of a difference between reality and the GIS representation. A common source of error is one which arises from the way in which we understand and model reality (Heywood et al., 2011), otherwise known as conceptual error. Uncertainty in the conception of a geographic phenomena can arise due to both vagueness and ambiguity. Vagueness becomes an issue when a label is not robust leading to uncertainty in both boundary position and attributes (Longley et al., 2005). The definition of underutilised non-agricultural land was not considered to be vague but it is arguably susceptible to issues resulting from ambiguity. Ambiguity arises due to spaces or entities being conceived differently by different people (Longley et al., 2005). Our ability to appropriately map an entity may be constrained by the classifications that are used by those collecting the data. This is particularly pertinent as this thesis seeks to avoid the pitfalls of ambiguity which have impeded the geographic investigation of 'marginal' land. The term underutilised non-agricultural land may be problematic as allocating land as underutilised is a subjective process. However, the uncertainty that may arise due to the ambiguity of the terminology has been largely avoided by targeting specific land types such as vacant and derelict land and landfill which are well defined. Nevertheless, whilst the four main land types have been chosen on the assumption they are lying largely dormant and could be put to better use, it is worth considering that this may not necessarily be the case.

The thesis involved compiling datasets from a range of different sources, therefore the way each land type may be conceived by each organisation or data provider is a source of uncertainty. This is most evident during the compilation of data on historic landfill, as outlined in section 3.4.3, local authorities had differing approaches towards what is includable with some also providing data on infilled land and quarries. An approach utilising fuzzy membership, which abandons the concept that things must belong to a certain class or not, could have been adopted (Nisar Ahamed et al., 2000). This approach, however, was not deemed be a suitable solution as the ambiguity is rooted within the definition of the land type itself and a fuzzy interpretation would not aid the compilation of an accurate dataset. Ultimately the decision of whether a particular dataset was included was made by one researcher and therefore the total amount of land identified depends on their conception of underutilised non-agricultural land. This was particularly noticeable when deciphering abandoned mine land from mine land on which restoration has taken place, as outlined in more detail in section 3.4.4. In clearly setting out the methodology applied, and the decision making process regarding the inclusion or not of a piece of land, it is hoped this source of uncertainty can be addressed.

3.4 Identification of the theoretical landbank

The theoretical landbank is the hypothetical maximum amount of underutilised non-agricultural land that could be available for bioenergy provision, before any boundary conditions are applied. As outlined previously, the theoretical landbank took the form of a spatial database of brownfield, authorised, closed and historic landfill, and some recently abandoned mine land. Databases are at the heart of any GIS, with most systems built upon a general purpose relational database (Worboys, 2003). Data must be captured in a form that the database can handle and input into the system (Worboys, 2003). An initial search for existing data representing each land type was undertaken, if data did not exist or was not of great enough detail then digitisation was required (Figure 3.5). Digitising is the means of converting spatial data into a digital dataset with a vector structure (Worboys, 2003). This involved the capturing of site boundaries as polygons to give greater detail, rather than merely representing locations as point entities.

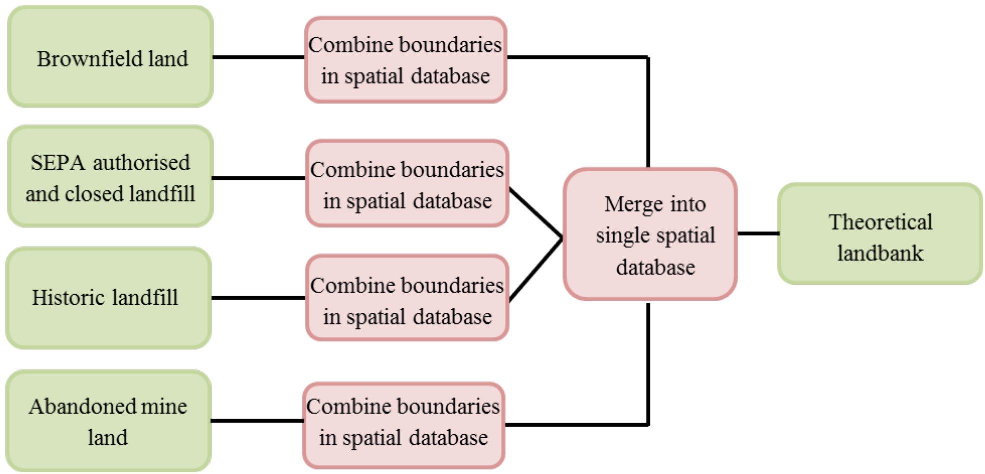


Figure 3.5: Overview of boundaries included in the spatial database representing the theoretical landbank

The digitisation methodology was tailored for each land type, depending largely on both the quantity and quality of pre-existing data and existence of secondary datasets which aided the capture of new sites. These datasets (see Table 3.1) included base-mapping and aerial imagery sources which provided guidance during the digitisation process. It was deemed most efficient to conduct the digitisation using ArcMap software, which has a full suite of editing tools to aid the capture of site boundaries. Furthermore, ArcGIS includes several useful base-map layers that can be loaded such as ESRI's World Imagery aerial imagery. The World Imagery basemap was used as the primary base-mapping layer for all of the digitisation due to a more satisfactory coverage, scale and usability. The basemap was easily integrated into the ArcGIS workflow, allowing boundaries to be drawn as a layer draped over the imagery. The World Imagery dataset is constantly updated by ESRI (ESRI, 2017b), provides satellite and aerial coverage of one meter or better resolution and is compiled using several reputable data sources such as Getmapping and DigitalGlobe. This often means it is the aerial imagery source with the least cloud coverage and it has the most up-to-date imagery that is freely available.

Table 3.1: Secondary data sources used to aid the identification of the theoretical landbank

Dataset/base-mapping	Source	Details
Google Maps Imagery	Google (2017)	Used to verify boundary location if unclear on ESRI World Imagery. Imagery is taken from a variety of sources including Landsat satellite and DigitalGlobe. Date of imagery varies. In several cases Google streetview imagery taken from car-mounted camera, was used to check site conditions at ground level.
Bing Maps Imagery	Microsoft (2017)	Imagery taken from several different sources - often similar to ESRI World Imagery, but also checked if boundary unclear on either World Imagery or Google Maps. Date of imagery varies.
Canmore Mapping	Historic Scotland (RCAHMS, 2016)	The Canmore database contains over 320,000 records and 1.3 million catalogue entries for archaeological sites, buildings, industrial and maritime heritage. Includes some information on old quarries/landfills, and old industry locations - therefore helped verification of vacant and derelict and historic landfill boundaries.
Ordnance Survey Mapping	EDINA (2017)	The Digimap Ordnance Survey collection provided contemporary OS maps, including up-to-date 1:25,000 colour raster layer and 1:1000 OS MasterMap Topography layer. This was heavily used to help identify boundary location.
National Library Scotland Historic Mapping	National Library of Scotland Maps (2016)	High resolution zoomable historic maps from 1560 to 1961. Side-by-side viewer that allowed historic mapping to be viewed alongside contemporary mapping - very useful tool when trying to identify historic landfill boundaries.
Ordnance Survey historic Mapping	EDINA (2017)	Historic Digimap offered a range of historical OS mapping data products from 1843 to 1996. University of Strathclyde license (2015/16) allowed this resource to be used in identifying historic landfill boundaries.
Digital Globe Imagery	Digital Globe (2017)	High resolution earth imagery database that can be searched to find more up-to-date imagery which may not have yet been amalgamated into the ESRI World Imagery dataset. Date of imagery varies.

This amalgamation of datasets does make dating any given frame of imagery difficult, therefore the digitisation process involved a large amount of cross-checking against other imagery sources such as Bing Maps and Google Maps imagery. This helped to ensure the digitisation was taken from the most recent imagery possible, and provided a back-up should the World Imagery dataset contain areas with unsatisfactory cloud coverage or resolution. Whilst this methodology is based on the utilisation of ArcGIS software, the steps are transferable to other GIS environments, including open-source options such as QGIS.

3.4.1 Compiling a spatial database representing brownfield land

In the UK brownfield is used as a term to describe previously developed land (Oliver et al., 2005), and in Scotland brownfield land has been reported as vacant and derelict land (see box 3.2). The Scottish Government Communities Analysis Division manages data on vacant and derelict land and publishes this information annually in the Scottish Vacant and Derelict Land Survey (Scottish Government, 2014).

Box 3.2 Definitions of vacant and derelict land in Scotland according to the Scottish Vacant and Derelict Land Survey (Scottish Government, 2014)
Vacant land - Land which is unused for the purposes for which it is held and is viewed as an appropriate site for development

Derelict land - Land which has been so damaged by development, that it is incapable of development for beneficial use without rehabilitation, or land which is not being used for the purpose for which it is held or a use acceptable in the local plan.

This database was used to compile the brownfield component of the spatial database. The 2013 Scottish Vacant and Derelict Land Survey (Scottish Government, 2014) was used as it was the most recently published at the time this study commenced. Long term trends have shown little change in the amount of vacant and derelict land recorded by these annual surveys, however the limitation of basing this research on a survey which provides only a snapshot is discussed as a source of temporal uncertainty in section 3.4.6.

The information compiled in the survey has been sourced from each local authority and submitted annually, with the site register published online. This site register includes site addresses, and easting and northing grid reference alongside further information regarding previous use and development potential. The survey also includes contact details for individuals at each local authority who are involved in the recording or submission of the vacant and derelict land within their area. This list of local stakeholders was used as each local authority was contacted to see if they had more detailed GIS data containing site boundaries. In instances that the local authority had created boundaries with the aid of Ordnance Survey base-mapping an end-user license had to be signed in order to use the dataset (See Appendix A.1 for example). The One Scotland Mapping Agreement is a license between the Scottish Government and Ordnance Survey allowing public sector organisations to access and share OS digital mapping, and data created with the use of Ordnance Survey mapping.

In the instances that local authorities had shapefiles representing the vacant and derelict land these site boundaries were each checked at a scale of 1:3,000 or less, and could then be automatically added to a spatial database in ArcGIS, otherwise known as a file geodatabase (Figure 3.6). This scale was used as it allowed the identification of both gross errors and minor digitisation mistakes that could significantly impact the total area, whilst not being such a large scale that it heavily increased the time to assess each site. This scale was also used where digitisation of new sites was required, as it allowed significant irregular features such as pan-handles, thin protruding extensions on an otherwise regular shaped parcel of land, to be captured. This enabled the digitisation process to be undertaken quickly yet accurately for each site.

Having contacted all 33 councils, it became apparent that not all authorities would have GIS data therefore a digitisation methodology had to be adopted to capture the boundaries of additional sites (Table 3.2). Additionally, the survey reports sites in Loch Lomond and the Trossachs National Park separately despite it being a planning authority rather than a local authority. The National Park was also contacted regarding site information. Care was taken not to double count these sites if they were also recorded by the respective local authority

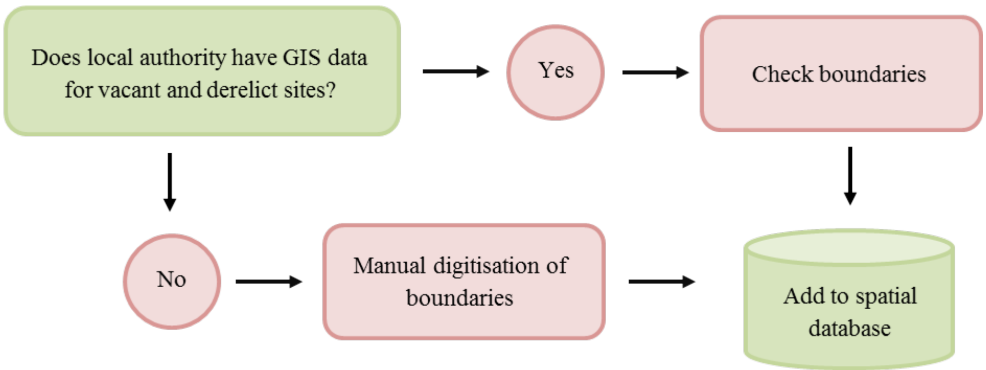
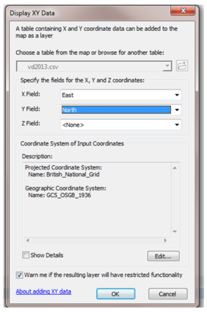
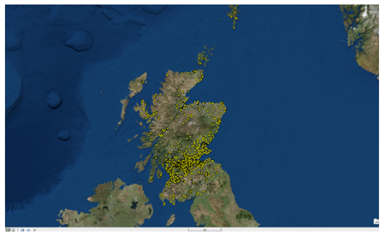
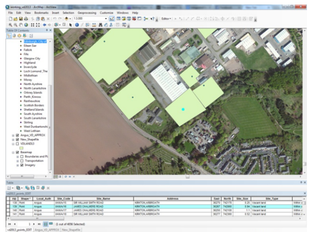
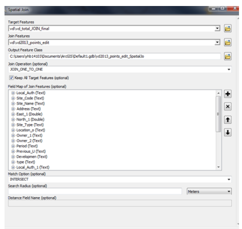


Figure 3.6: Decision making process when dealing with response for boundary data from local authority

they happen to fall in geographically. Once digitised these sites were appended to the local authority. The national park was not considered as a separate area when totals were reported at a later stage.

In total seven local authorities, plus Loch Lomond and the Trossachs national park, did not have GIS data representing sites. This meant that the boundaries of 294 sites needed to be captured - 7.2% of vacant and derelict sites reported in the survey. This involved several steps (Table 3.2) carried out within the ArcMap software environment, using the size reported in the Scottish Vacant and Derelict land survey as a guide. ArcMap was used as it is a powerful tool not only for creating but also managing spatial data - boundaries can be created in the form of polygons within a shapefile and these shapefiles can be stored within a geodatabase. World Imagery satellite imagery was used as the basemapping layer and was the primary reference for the boundary location, but Ordnance Survey Mapping (EDINA, 2017), Royal Commission on the Ancient and Historical Monuments of Scotland (RCAHMS, 2016) mapping, Bing Maps Imagery (Microsoft, 2017) and Google Maps Imagery (Google, 2017) were also useful aids if a boundary was unclear. Every effort was made to ensure a consistent methodology was used when drawing site boundaries, despite these efforts there are several ways in which error can be introduced even if the best practice is followed, as outlined in section 3.4.6. All of the GIS data received from local authorities was joined with the newly digitised sites in one geodatabase representing brownfield land in Scotland.

Table 3.2: Step-by-step boundary digitisation methodology utilising ArcGIS

No.	Procedure	Example
Step 1	Display vacant and derelict land sites as points mapped using the Easting and Northing co-ordinates in the Scottish Vacant and Derelict Land Survey. The survey must be saved as a .csv then added as layer in ArcGIS. The points were displayed using the OSGB 1936/British National Grid projected coordinate system and projected in Traverse Mercator.	
Step 2	Overlap points onto of World Imagery basemap in ArcGIS. The World Imagery (WGS84) needs to be re-projected so that it aligns with the British National Grid based datasets. This is done by changing the data-frame properties.	
Step 3	Draw polygon using satellite imagery as a guide. The ArcGIS Calculate Geometry function can be used to calculate area of drawn polygon. If the boundary is not immediately obvious, or the first digitised effort in not within 0.1ha of the size reported in the survey, other mapping sources (see table 3.1) are used to help locate the boundary location.	
Step 4	The polygons representing boundaries can be spatially joined to the original projected point - adding all the attributes from the point (and therefore the survey) to the newly drawn polygon. NB: The have_their_centre_in function was selected as the match option for the spatial join.	
Step 5	Add boundaries to geodatabase representing underutilised non-agricultural land.	

3.4.2 Compiling a spatial database representing SEPA authorised and closed landfill

Landfill sites that reach capacity are covered with a cap such as clay and then restored using various materials including soil, this land is intended to be reused for agricultural purposes, amenity uses or nature conservation (SEPA, 2016). However, the land may not always go back into use and often these sites are left dormant until suitable end uses can be found. The introduction of Waste Management Licensing Regulation in 1994 (SEPA, 2009) and the formation of the Scottish Environmental Protection Agency (SEPA) led to SEPA becoming responsible for waste site licensing in Scotland. All currently authorised sites holding a Waste Management Licence (WML) or a Pollution Prevention Control (PPC) permit, along with closed sites since 1996, are recorded in the 'Landfill sites and capacities in Scotland' report (SEPA, 2012). However, this reports the operating capacity of the landfill in terms of tonnes rather than area. SEPA were contacted and confirmed that they do not have more detailed GIS data representing the landfill boundaries which could have been integrated into the spatial database. This meant that the boundaries for both the authorised and closed landfills had to be digitised manually, this was done using the 2012 capacity reports database as it was the most recently published. The capacities report contains information on the landfill operator and license conditions alongside site address and grid reference. The lack of pre-existing information on site area means that extra care needs to be taken during the digitisation process, with secondary mapping sources such as ordnance survey mapping playing a greater role in identifying boundary locations. Furthermore, whilst SEPA maps published online (Figure 3.7) suggest the underpinning database is complete this was not the case. The databases contained instances of duplicated or missing data entries. Some sites did not have accurate co-ordinate information or had undergone significant change of use. Each of these needed to be checked in detail to ensure the correct location and boundary was identified. Incorrect grid references in the database were corrected (see Appendix A.2) and sites that could not be included were also noted (see Appendix A.3).

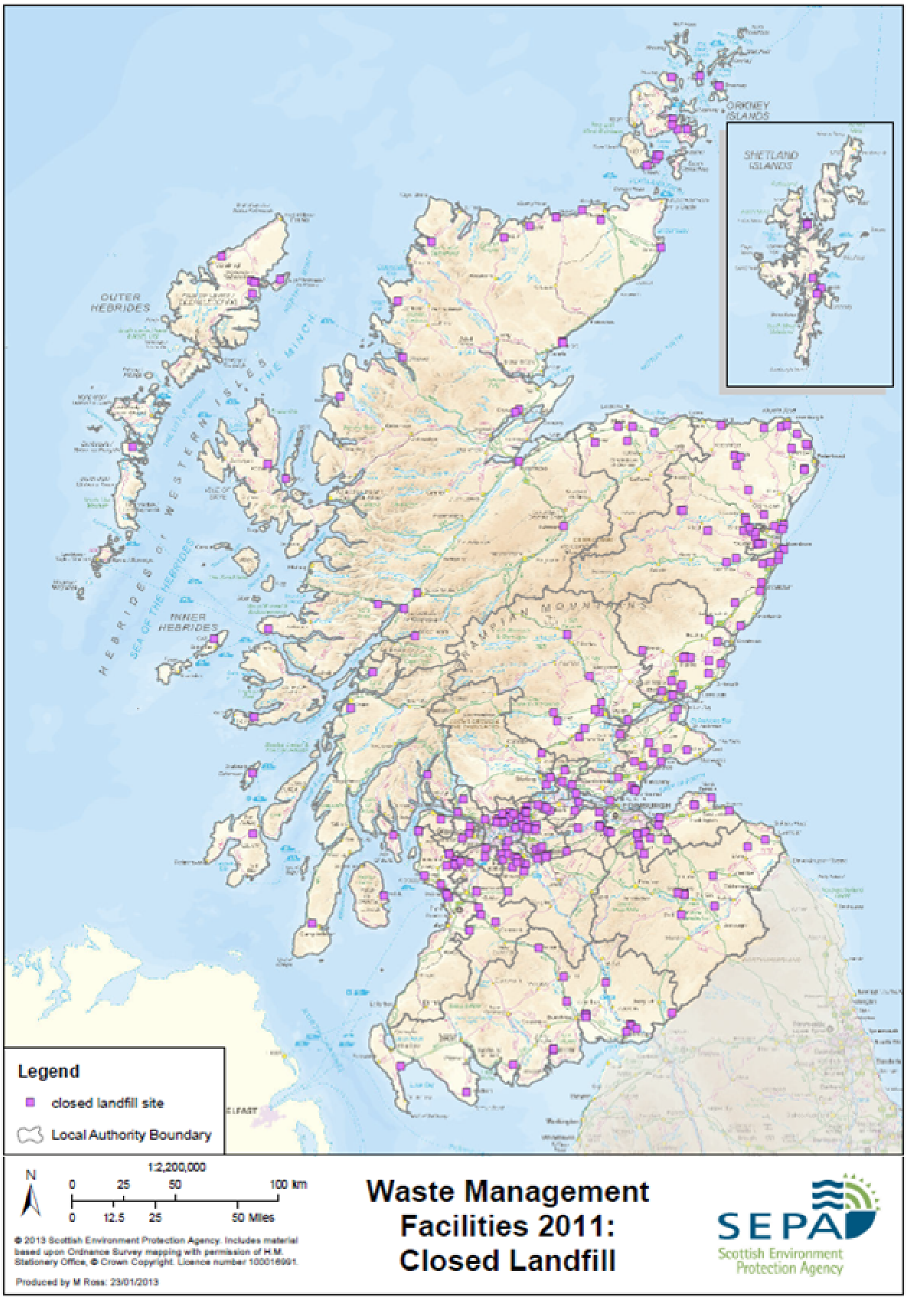


Figure 3.7: Map of Waste Management Facilities in Scotland provided on SEPA website in 2013 (SEPA, 2013)

Figure 3.8: Example of site boundary in Renfrewshire that was deemed unsuitable for inclusion due to undrainable water and therefore coded 'UO'

The process for digitising these sites followed similar steps to that used to capture brownfield sites (Table 3.2) once again utilising the ArcMap software. The authorised and closed landfill sites were displayed using the co-ordinates in the capacity report database. These points were then overlaid on top of ESRI's World Imagery and polygons were drawn representing landfill boundaries. Whilst the process is almost identical to that used for capturing brownfield land, during the digitisation process closed landfill sites that were deemed unsuitable due to a significant change of usage were recorded. The reason for exclusion was noted and using a coding scheme (see Table 3.3) the detail was added to the polygons attribute data. Unsuitable sites, such as those that have become established woodland or sites that consisted of undrainable water (see fig 3.8), could therefore be excluded when combined to create the larger database representing underutilised non-agricultural land.

The boundaries for authorised and closed sites were digitised as two separate polygon shapefiles and then merged into one file geodatabase. The polygons were spatially joined to the point data therefore appending any additional information from the capacity report.

Table 3.3: Coding of excludable land types explained

Reason for exclusion	Attribute code
Developed (e.g. built up area, sports facilities, playgrounds)	UD
Established woodland	UW
Land in use for arable agriculture	UA
Water feature (that looks unlikely to be drainable)	UO

3.4.3 Compiling a spatial database representing Historic landfill

Prior to the formation of SEPA in 1996, landfill sites were the responsibility of local authorities in Scotland. The approach each local authority took to recording landfill sites depended on the authorities' interpretation of UK contaminated land legislation outlined in the 1974 Control of Pollution Act and the 1990 Environmental Protection Act (DEFRA, 2012). Whilst the statutory guidance in Part 2A of the 1990 act outlines the definition of contaminated land, particularly in relation to harm to human health and non-human receptors, the determination of whether land appears to be contaminated is left up to the local authority. The main concern being the potential risk of historic landfill to 'receptors' (DEFRA, 2012) such as human health or controlled waters meaning it should be handled as contaminated land by local authorities, and therefore prioritised, inspected and recorded as such. Nevertheless, it was expected that the approach and time in which information was recorded by local authorities would differ widely, with some local authorities potentially even only pre-emptively compiling information before the Statutory Instrument of 2000.

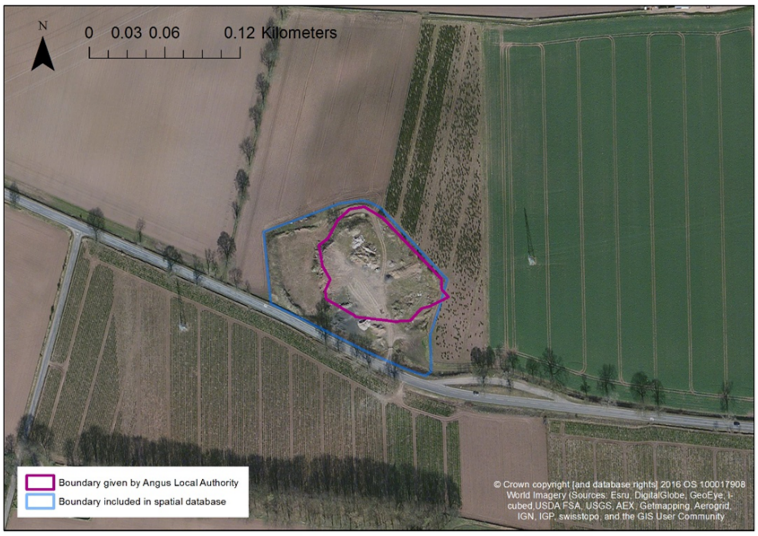
Each local authority was contacted for information on historic landfill site locations. Initial Freedom of Information requests were submitted to each local authority, however the response often lacked sufficient detail to enable sites to be suitably identified, therefore each response needed to be followed up with further requests for locational information. In many cases the contact details provided in the Scottish vacant and derelict land survey were used, alongside contaminated land officer and environmental health department contact details from authority's websites. In some cases, new Freedom of Information requests were submitted to local authorities who had not previously responded with information.

As predicted the quality and quantity of information held by each local authority differed. Four local authorities were unable to provide any information which would aid the identification of site locations. It is possible that these four local authorities, who had no information regarding historical sites, may have passed information on to SEPA on their establishment and the sites were automatically added to the list of closed landfill locations in SEPA's capacity report.

In total, 14 local authorities had GIS data representing historic landfill. Several councils had gone to great lengths in accordance with their interpretation of the contaminated land legislation - for example both Angus and Clackmannanshire had GIS shapefiles containing historic landfill alongside a further record of in-filled ground and quarries. In a number of cases the shapefile passed on from the authority contained an assortment of land types, therefore the historic landfill sites needed to be selected and extracted into a new shapefile. Each site was checked at a scale of 1:3000 or less and a coding system, similar to that used with the SEPA closed landfill sites (Table 3.3), was employed for the site boundaries that had been passed on.

The remaining 14 local authorities did not have GIS data but were able to pass on locational information regarding sites. The information from these authorities was amalgamated to form a database from which a digitisation methodology could be based. Whilst the workflow of this digitisation was similar to that used to digitise the brownfield and SEPA landfill sites, a number of additional steps were developed to aid the identification of often hard to find historic sites. The most efficient method of displaying the list of sites as points in ArcMap requires a locational reference in the form of Easting and Northing co-ordinates, therefore a number of site references passed on by local authorities had to be converted e.g. from Ordnance Survey grid reference. The points could then be displayed and overlaid on top of aerial imagery. Whilst the imagery provided a helpful guide the digitisation of many of these sites required

(a)



(b)

(c)

Figure 3.9: Use of multiple mapping sources to determine boundary of site in Angus. a) Quarry seen on historic mapping, the extent of which has been used by local authority b) Comparison of boundary given by local authority versus boundary included c) Google streetview enabling verification of includability of wider extent

the use of additional base-mapping layers to locate the historic landfill boundary. In these instances historic mapping layers provided by the National Library of Scotland and EDINA's Digimap portal proved especially helpful. Comparing historic and contemporary mapping sources highlighted features that may have been in-filled with landfill, such as old quarries or pits (see Figure 3.9). A polygon was drawn representing the approximate site boundary and was then added to the geodatabase alongside the data from the local authorities that did hold GIS information. In total 1657 sites needed to either be checked or newly created. A combination of this large number and the difficulty involved in pinpointing the exact tract of historic site boundaries because of the disparate quality in source data meant it was deemed unsuitable to include sites reported as under one hectare.

3.4.4 Compiling a spatial database representing abandoned mine land

Abandoned mine land has been considered in previous studies attempting to identify marginal land for bioenergy provision (Niblick and Landis, 2016; Mosey et al., 2007) and thus information was sought regarding the prevalence of this land type in Scotland. The liquidation of Scottish Coal and ATH resources, in 2013, impacted several opencast coal mining sites in East Ayrshire, Fife, and South Lanarkshire. Ordinarily opencast coal sites would have a restoration bond in place providing a financial warranty for land to be returned to a suitable condition once the operating licence has expired. Unfortunately, the value of this bond does not always cover the necessary restoration work required. The Scottish Government Communities Analysis Division has gone to great lengths to avoid including large areas of these sites on the vacant and derelict land survey. The survey has only recorded those identified as being 'unsafe or of very poor environmental quality and requiring further remediation' (Scottish Government, 2016d) as derelict land. Owing to the uncertainty surrounding the proportion of the site that could be covered by the restoration bond the sites impacted by the liquidation of Scottish Coal and ATH resources were deemed suitable, and the unrestored land at these sites was included within the spatial database representing underutilised non-agricultural land. East Ayrshire, Fife and South Lanarkshire were contacted for information regarding site boundaries.

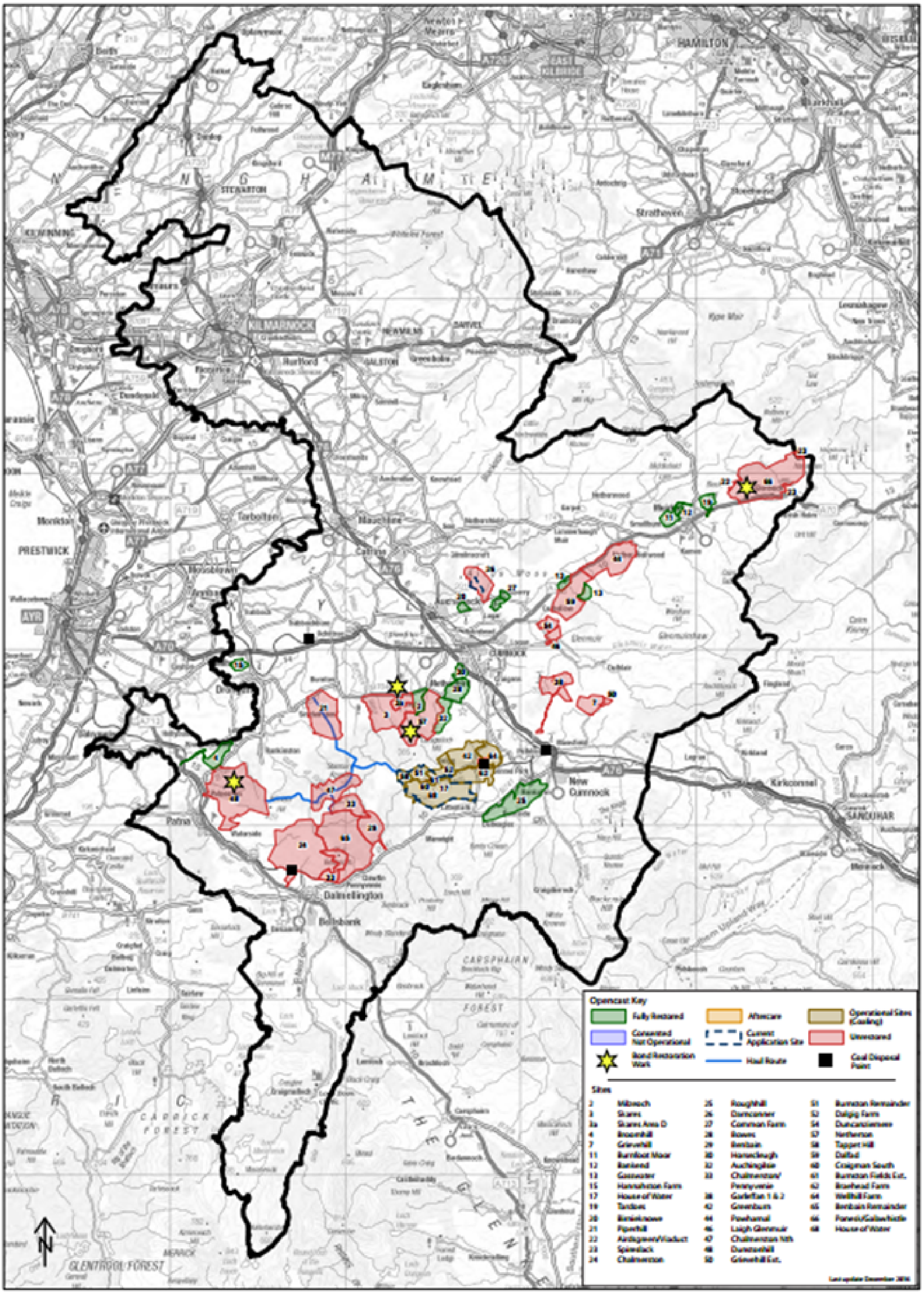


Figure 3.10: Map of unrestored mine land in East Ayrshire published in East Ayrshire's 'steps to recovery' report (East Ayrshire Council, 2013) - see Appendix A.4 for larger key and sites

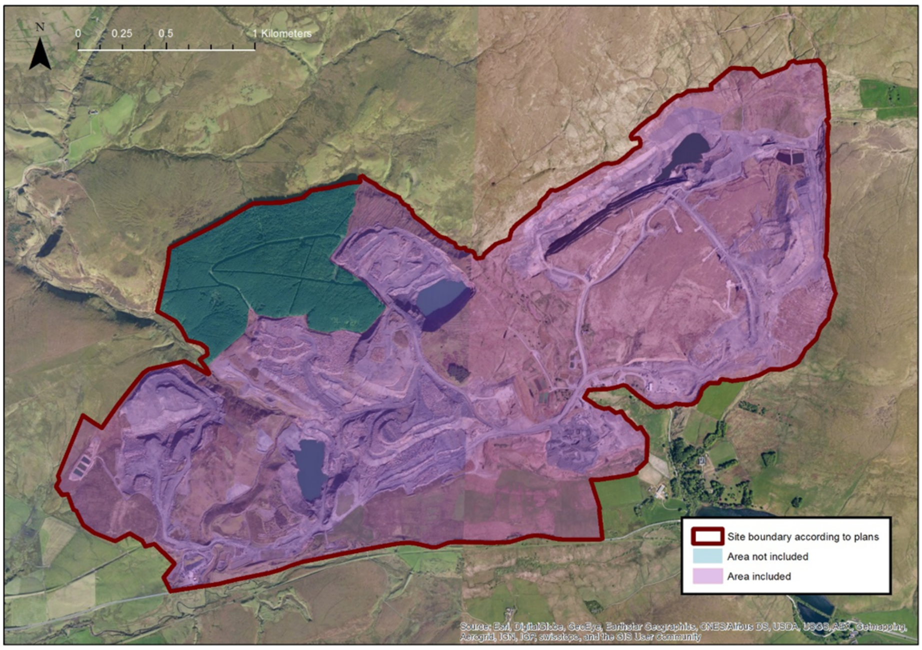


Figure 3.11: Excluding mine land that appears to have undergone restoration, area highlighted green, leaving unrestored land to be included, highlighted in purple

Whilst none of the local authorities could provide GIS data, both Fife and South Lanarkshire councils passed on a list of sites with the latter also providing location plans (Appendix A.5). East Ayrshire council have published a surface coal mining visual register (Figure 3.10) which marks out all the unrestored sites within the region. This register allowed sites to be located and, despite being a small-scale representation, it also provided a coarse guide towards identifying the extent of each site. The information received from South Lanarkshire and indicative ownership maps taken from the East Ayrshire 'Steps to Recovery' report (East Ayrshire Council, 2013), were used alongside Ordnance Survey mapping as an aid for selecting boundary locations. In total 15 sites were identified and with the information received from the local authorities the boundaries of these sites could be digitised. Each site co-ordinates were zoomed into using the ArcGIS *Go to XY tool* and, once again utilising the World Imagery base-layer, boundaries were created in a polygon shapefile. Due to the uncertainty regarding the proportion of restoration at each site that may be covered by a restoration bond the digitisation of these sites involved a great degree of care and consideration. If it appeared no restoration has taken place anywhere within the site boundary, then the entire site would be included. However, if there were portions of the site where restoration had obviously begun or if there was some established planting of woodland then these areas would not be included (see Figure 3.11). The digitised boundaries were combined in a shapefile representing abandoned mine land which could ultimately also be added, alongside the previous three land types, to the larger spatial database representing underutilised non-agricultural land.

3.4.5 Combining datasets to form the spatial database representing the theoretical landbank

The initial output representing the theoretical landbank was four shapefiles compiled as individual ArcGIS file geodatabases containing boundaries for each land type. Several steps were then taken to combine the databases together whilst avoiding geometric error and overlap which could lead to the double-counting of areas (see Figure 3.12).

The sites that were coded as suitable were selected from the closed and historic landfill databases, using the *Select by Attribute* functionality, and exported as a new shapefile. Following this step the *Multipart to Singlepart* tool, from the ArcGIS data management toolbox, was used for all the land type shapefiles to ensure each parcel of land could be assessed separately i.e. if a vacant and derelict site was separated by a feature such as a river and recorded as one site it would become two separate singlepart features for which two areas could be calculated.

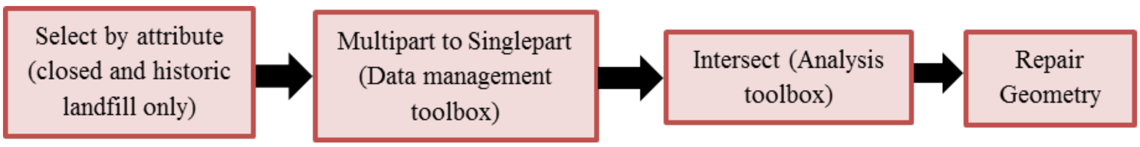


Figure 3.12: ArcGIS workflow of preparing the datasets before combining.

The *Intersect* tool from the ArcGIS Analysis toolbox was then utilised, to check for accidental overlap caused during digitisation of the closed and authorised landfill datasets, as there were several instances of adjacent sites. The tool was also used to check there was no self-intersection within all the of the datasets as a result of digitisation error. The *Repair Geometry* tool, from the Data Management toolbox, was then utilised. This tool inspects each feature class, or boundary, for geometry problems which may have arisen during digitisation including null geometries, self-intersections, empty parts and duplicate vertexes (ESRI, 2016d).

The historic landfill shapefile required additional processing steps (see Figure 3.13) due to the variety of datasets that were compiled, some of which had the potential to overlap with the other land types. The *Erase* tool from the ArcGIS Analysis toolbox was utilised to remove the vacant and derelict, SEPA closed and SEPA authorised sites that overlap with the historic landfill sites. Following this the *Multipart to Singlepart* tool was employed, this time ensuring that sites split by the erasing process can be considered individually. The erasing process can lead to the creation of sliver polygons - small, thin, isolated polygons.

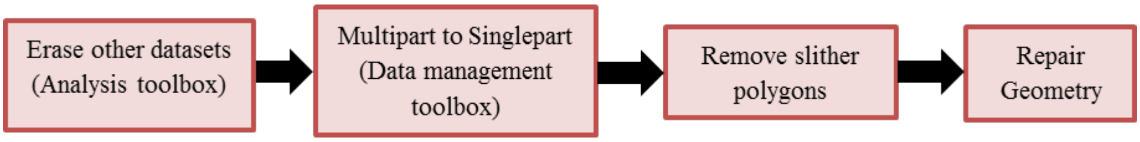


Figure 3.13: Additional preparation of historical landfill dataset before combining with other spatial databases

To avoid including these sliver polygons, a selection of polygons were excluded based on a combination of area and 'thinness'. As Merchant et al. (2008) explain thinness can be used to define the regularity of a polygon. The thinness ratio is calculated using the area and perimeter of a polygon in the following equation:

$$T = 4\pi(A/P)^2)$$

An object with a regular shape has a higher thinness ratio, with a circle giving a value of 1 and a thin strung out shape returning a value towards 0. A new field was added to the historic landfill geodatabase and the ArcGIS field calculator was used to calculate the thinness ratio for each polygon. The thinness ratio alone is not suitable for removing slither polygons - it is necessary to also consider the polygon area. This is because, as Tereshenkov (2014) explains, large polygons with a complex shape might result in a low thinness ratio. To avoid removing these large complex polygons a thinness ratio of less than 0.3 was combined with an area of less than 0.7 in a definition query to select suspect sliver polygons. These were then removed for the shapefile, leaving a representation of historic landfill with zero overlap with other land types and no sliver polygons. The *Repair Geometry* tool was used once again to remove geometry problems that may have arisen during the erase processes.

The four geodatabases were combined using the *merge* tool from the ArcGIS data management toolbox, and this ensured that no areas were double counted in the total recorded as the theoretical landbank. The final spatial database contains boundaries based on datasets for which licensing agreements had to be signed, therefore a degree of confidentially is contained within the results. Hexbinning was used to display the results whilst maintaining the anonymity of location of specific sites, as explained in more detail in box 3.3.

Box 3.3 Hexbinning: Explaining why this form of data binning was included and how it was implemented

Binning is the process of grouping points or polygons based on location (Briney, 2014). This aggregation creates a less complex, and often more meaningful map output and can also be used as an alternative to density mapping which relies on local authority boundaries. The output of binning also helps reveal density and distribution patterns that may not be clear in the source data. Furthermore, this technique allows data to be displayed whilst maintaining anonymity. Hexagonal binning, or hexbinning, is conducted by laying a hexagonal grid on top of 2-dimensional data (Briney, 2014). A hexagonal grid is often preferable as is reduces the sampling bias caused by edge effect of the grid Birch et al. (2007). Rectangular or square grids have more acute angles meaning their corners are further away from their centre (Price, 2016).

The *Create Hexagon Tessellation* geoprocessing package (Whiteaker, 2014) was implemented in ArcGIS to create a mesh of hexagons overlapping the study area - as showing in Figure 3.14. As Whiteaker (2014) explains the model uses a script to form a lattice of points, regular hexagons are then generated between the points. Once the grid is formed the area of the sites that intersect the hexagon grid can be calculated and tabulated using the *tabulate intersection* tool from the ArcGIS Analysis toobox (See workflow in Figure 3.15). This table can then be spatially joined with the original hexagon grid and the symbology adjusted to correspond to the area of land within each hexagon. The size of the hexagons can be easily changed to enable local density patterns to be highlighted.

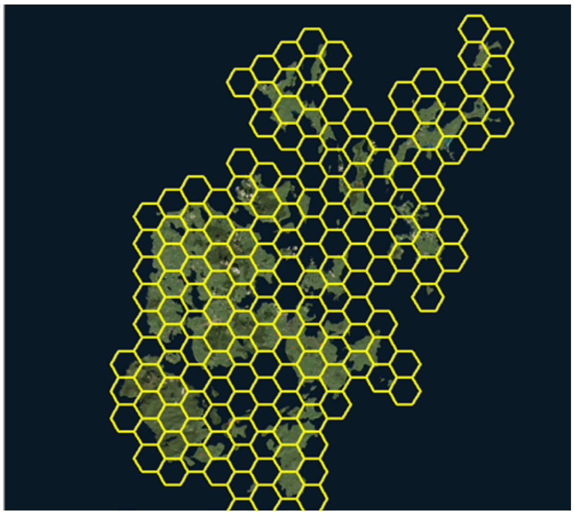


Figure 3.14: An example of a hexagonal grid over Shetland Isles which the landbank can be aggregated to

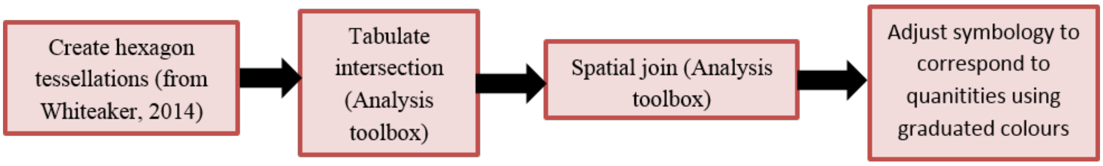


Figure 3.15: ArcGIS workflow used to create hex-grid maps

3.4.6 Further uncertainty in the measurement and representation of underutilised non-agricultural land

The creation of the spatial database representing underutilised non-agricultural land introduced several challenges in attempting to transform real-world phenomena into a GIS. Firstly, the impact of the data model used must be considered. Vector and raster representations each impose different filters on the real world, therefore each can be responsible for creating different elements of uncertainty (Longley et al., 2005). As outlined in sections 3.1.1, a vector based approach was initially adopted to achieve as accurate representation of site boundaries as possible. However, the aggregation of polygons, to preserve confidentiality of individual records, brings about a degree of uncertainty. The issue with aggregating the area of land within each hexagon is that the grid is arbitrary to the polygons representing land parcels, yet it will affect the statistics on the basis of the data being presented using the tessellations - this is known as the Modifiable Areal Unit Problem (O'Sullivan and Unwin, 2003). If the grid to which the aggregation is made was different then different patterns and relationships would be observed (O'Sullivan and Unwin, 2003). There are two aspects to MAUP. Firstly, the scale effect, a change in statistical results depending on the size of unit used (Openshaw, 1984). Secondly, the zonation or aggregation effect, whereby statistical differences can be seen depending on how the area is divided up, even at the same scale (Openshaw, 1984).

Data quality can be understood as a description of how good the data is or it's fitness for use. The quality of the data may be influenced by a range of factors in addition to the data model, including error, accuracy, precision, resolution, and generalisation (Heywood et al, 2011). Error is a flaw in the data. There are a number of ways that error can manifest within the measurement and representation process and cause further uncertainty in the results. The encoding of data from a non-GIS source into a GIS format is known as digitization, and this process can be the source of many errors. Digitisation errors can be created by either source map error or operational error. The quality of the mapping on which the digitisation is based can impact the spatial accuracy of the resulting digitised features.

Operational errors occur during the process of drawing features using a computer. According to Jenks (1981) there are two types of digitization error: psychological and physiological. Psychological errors include the challenge of identifying the true centre of a line and inability to move a cursor accurately along it (Heywood et al., 2011). This can result in lateral offset between the actual feature and digitised representation which may manifest itself as under or overshooting at corners. Physiological errors can be caused by involuntary hand movements or spasms that could cause 'switchbacks', 'spikes' or random displacements (Heywood et al., 2011) some of these errors are illustrated in Figure 3.16. In addition to the two types of error highlighted by Jenks (1981), Heywood et al. (2011) identify line thickness and method of digitisation as two further cases of operational error that can occur. The thickness of lines on base map layers is often a result of cartographic generalization (Heywood et al., 2011), most lines are drawn so that they are visible to a map user and thickness can indicate the importance of a feature. The true course of the feature being digitised can be assumed to be the

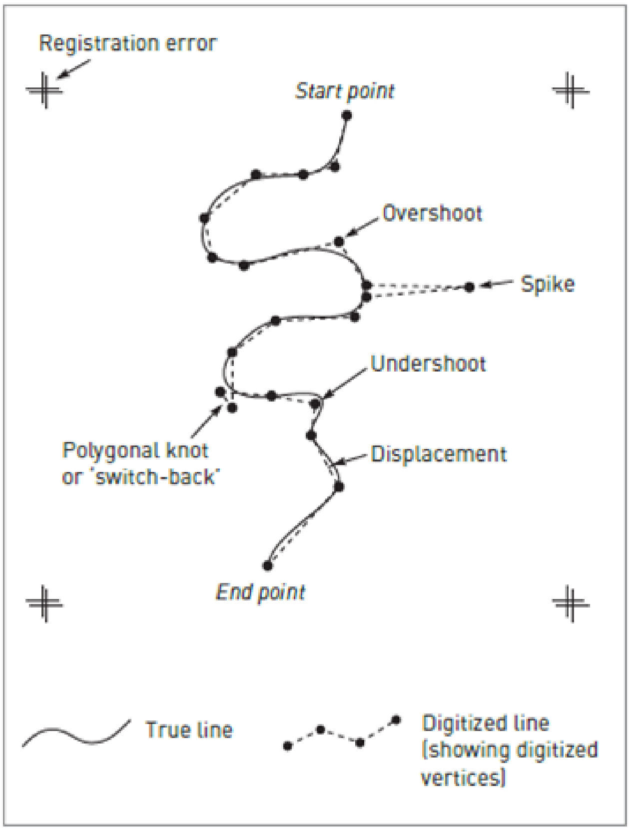


Figure 3.16: Examples of digitisation errors (Heywood et al., 2011).

mid-point of the line, however this is a difficult task for any digitiser and displacement leading to positional error in the digitised line is highly likely (Heywood et al., 2011). The method of digitisation refers to the choice of manual digitisation method: point mode or stream mode (Heywood et al., 2011). Whilst in stream mode the number of points sampled is controlled by the complexity of the line, in point mode the digitiser can decide how many sample points are used to create a representation of the line or polygon feature. Point mode was used for the digitisation of underutilised non-agricultural land, and it is important to point out that the level of generalization is therefore chosen by the digitiser who has chosen the amount of sample points to use and their location. These aspects of the operational side of digitising allude to the importance of maintaining consistency whilst creating the spatial database. Veregin (1999) describes consistency as the absence of contradiction within a database and within a geospatial context it represents conformance of the data to certain topological rules (Veregin, 1999). These topological rules are tied into the digitising process, such as ensuring only one point exists at any given location and that polygons must be left 'closed' (Veregin, 1999). The removal of such topological inconsistencies has become a rudimental function of most GIS software, allowing databases to be topologically 'cleaned' (Veregin, 1999). This has been conducted in this study as outlined in part 3.4.6 with the use of the ArcGIS *Repair Geometry* tool.

Two key influences on data quality are accuracy and precision, and it is important to distinguish between the two when discussing sources of uncertainty in the representation of a geographic phenomenon. Accuracy describes the degree of conformity an estimated value has to the true value (Maling, 1989). Veregin (1999) explained that geographic observations contain spatial, temporal and thematic components, and it is through these three aspects that the issues related to accuracy can be explored. The impact that the data model and operational choices can have on spatial accuracy have already been discussed but the temporal accuracy of a representation is often overlooked. One of the biggest limitations of compiling a spatial database is that it only provides a snapshot of the availability of land. The identification of brownfield land, for instance, was based on the Vacant and Derelict Land Survey which was published in 2013. The 2016 survey identified 14% more land, however much of this will be accounted for by the Scottish Government Communities Analysis Division's inclusion of parts of former surface coal sites, therefore there is not believed to be a large difference in vacant and derelict sites identified in 2013 versus 2016. Similarly, the SEPA closed and authorised landfill sites were located using the capacity report published in 2012, the most recent report published in 2015 has four fewer authorised sites and lists only 11 more closed sites. Nevertheless, it is necessary to clearly present the spatial database as a snapshot and therefore the resulting statistics contain a degree of temporal inaccuracy. Likewise, the representations of historic land and abandoned mine land, whilst not based on a backdated report or database, only provide a picture of the availability of this land type in 2016 when the database was created.

The use of satellite and aerial imagery during the digitisation methodology introduces a further degree of uncertainty in relation to the temporal accuracy of the data. The primary imagery used was ESRI's World Imagery (ESRI, 2017b) which is an amalgamation of data sources including Getmapping and DigitalGlobe imagery. It is difficult to date the imagery used in the identification of each site however, as the DigitalGlobe imagery is reported to range between 2009-2016 (ESRI, 2017b). This range indicates a level of uncertainty which must be projected on the findings, particularly when creating a representation of landfill and historic landfill with the additional consideration of its current use i.e. a site which has been deemed underutilised based on imagery from 2011 may no longer fit this category. This also creates difficulty when attempting to represent abandoned mine land. The liquidation of Scottish Coal and ATH Resources occurred in 2013 yet the imagery for East Ayrshire, South Lanarkshire and Fife councils, the areas where these sites are located, seems predominantly to be dated from 2011, therefore creating difficulty and uncertainty in any results when trying to judge which areas have yet to undergo restoration. The ESRI World Imagery base mapping, however, provided as up-to-date imagery as possible especially compared to Google Maps which had aerial imagery over several of the abandoned mine land sites dating from as far back as 2004. Several other secondary mapping sources (table 3.1) were used, most importantly the Digital Globe Image Finder (Digital Globe, 2017) which allowed sites to be cross-checked with as recent imagery as possible.

The thematic accuracy of any representation of geographical phenomenon can be impacted by an error in assignment of nominal class. This could be caused by misconceptions of a geographic entity as discussed in section 3.3.1. However, mistakes could also be made whilst measuring and representing the entity if parcels of land are misidentified and therefore wrongfully included as suitable land. Error in nominal class assignment can quantified using a confusion matrix showing omission and commission of correct classes. This is, however, not only a simplification of the problem as the error may be in the misallocation of boundary rather than misallocation of class but also relies on more accurate data such as ground observations (Longley et al., 2005). The problem of misallocation of classes highlights that the definition of error assumes that there is an external reality, or observable truth, which exists against which the GIS representation can be compared (Veregin, 1999) but this is not always the case. As Veregin (1999) explains the 'truth' may be unobservable e.g. historical data, or observation of the 'truth' may simply be impractical. The latter is the case with this research as ground observations were out-with the scope of the study, however future work including ground truthing could be undertaken to quantify this type of error.

The other key influence on data quality is precision. Precision describes the conformity of the measurements amongst themselves (Maling, 1989). The precision of a measurement describes how exact the description of data is, and is reflected in the number of digits used to report it. The quality and scale of base-mapping and secondary mapping layers used during the digitisation process is a major limitation on the level of precision it is possible to achieve in the representation. Each co-ordinate that is measured as part of a feature is subject to a degree of positional error related to the scale of the source mapping used. Longley et al. (2005) set out an approximate rule that 'positions measured from maps are subject to errors of up to 0.5mm at the scale of the map' (Longley et al., 2005). According to this rule of thumb, and bearing in mind that the digitisation of new features was done at a scale of at least 1:3000, the ground distance of representations of underutilised non-agricultural land are subject to 1.5m of error. However, if, as was occasionally the case, Ordnance Survey 1:25000 mapping was required to clarify a boundary this representation would be subject to a more significant 12.5m error on the ground. This represents the positional uncertainty associated with a single point and the impact this would have on the measurement of an area would depend on the amount of points that were used to make the polygon. This uncertainty means that it is unsuitable to report statistics relating to areas to several decimal places as it is important to ensure reported measurements do no mislead by giving a greater accuracy than exists in the dataset (Longley et al., 2005).

Many of the above issues impacting measurement and representation are associated with the creation of new data. However, the compilation of the spatial database has brought with it the challenge of integrating existing datasets from a different secondary sources. Whilst every effort was taken to check each dataset at an equal scale before integrating it into the spatial database it is not possible to ensure it has undergone the same level of scrutiny when being created. The reliability of exterior datasets therefore introduces the largest uncertainty and it is important to present all the available information about these datasets as thoroughly as possible in the form of metadata, as outlined in the following part 3.4.7.

The potential for gross errors to exist within these datasets coupled with the reality that some data may exist but weren't accessible or passed on when requested are the factors that could most heavily impact the reported total. Whilst future research could be undertaken to measure how minor digitisation error may propagate in measured areas of polygons, this would be eclipsed by the impact that misreporting or missing sites could have on the total area. It would be unsuitable for this thesis to present the total landbank as having a high degree of precision. Rather the spatial database provides an initial indication of the amount of this land type that exists and the methodology provides guidelines for how best to identify this land.

To summarise, whilst some degree of uncertainty is inevitable, several steps were taken during the measurement and representation of underutilised non-agricultural land in an attempt to minimise the impact of uncertainty on reliability of the results. A vector data model was chosen to ensure an accurate depiction of these land types. Additional care was taken to reduce error in the translation of information from non-GIS to GIS format. This included minimising psychological and physiological errors by selection of an appropriate line thickness for digitisation, use of point mode when drawing features and regular breaks to maintain concentration. Furthermore, a consistent scale of 1:3000 was used for digitising land parcels. Efforts were also made to use basemaps that were high resolution and as up-to-date as possible. Finally, any topological inconsistencies were removed using the ArcGIS *Repair Geometry* tool.

3.4.7 Metadata

To ensure there is confidence in the resulting spatial database, and subsequent analysis, it is important to assemble all that is known about the quality of the datasets, both new and old. This 'data about the data' allows the user to assess the database regarding its fitness-for-use by effectively providing a summary of its contents (Longley et al., 2005). An important aspect of any metadata is an insight into the lineage of a dataset. Lineage provides a record of data history including information about how it has developed from its source (Heywood et al., 2011). Lineage should provide details on the source of the data, method of capture, data model used, any transformations, editing or manipulations that have occurred, any errors that are known and what software or hardware have been used in its creation (Heywood et al., 2011). Unfortunately, it is rare to receive such a detailed record, and in the case of this research there have been few occasions where the provider of data has also provided detailed lineage information. Most GIS packages, however, perform a certain degree of metadata documentation (Veregin, 1999) and therefore some of the essential information that is required to process the data appropriately can be gained via ArcGIS. When dealing with vector data for instance, it is necessary to record the spatial coordinate system used when the data was created (Veregin, 1999). Effort was made to try and record as much information as possible regarding the various datasets that were included in the theoretical landbank spatial database and this can be found in metadata summary in Appendix A.6.

3.5 Identification of the technical landbank

For the purpose of this thesis an appropriate variation on the technical potential (Slade et al., 2009), or available potential (Voivontas et al., 2001), has been defined as the technical landbank. This represents the total area of land which can be used for bioenergy provision once a range of techno-environmental constraints are applied to the theoretical landbank. The ability to integrate data from a variety of sources as part of a decision-making process is one of the primary uses of GIS. The common GIS method to combine multiple constraining factors is via a multicriteria evaluation, otherwise known as raster overlay or sieve mapping (O'Sullivan and Unwin, 2003; Heywood et al., 2011). A GIS-based multicriteria evaluation enables the identification of land for a specific objective on the basis of numerous attributes that the selected areas must possess (Eastman, 1999). Whilst the spatial database that has been created is vector based, unfortunately overlay in a vector GIS environment is very complex, time-consuming and computationally intensive (O'Sullivan and Unwin, 2003). Furthermore, it would involve a large amount of post-process editing to ensure that all the resulting areas had correct geometry. Raster overlay, on the other hand, is relatively easy, quick and efficient (Longley et al., 2005). Multiple layers can be input using map algebra, or 'mapematics' (Berry, 1993), allowing various factors to be added, multiplied or divided to produce an output dataset. The most important aspect of raster overlay is the appropriate coding of cells according to their contents and this is achieved via reclassification which follows the process of converting a dataset to raster format. The preparation of each dataset included in the raster overlay is described in more detail in section 3.5.1.

$$\begin{array}{|c|c|c|}\hline 0 & 1 & 1 \\ \hline 0 & 0 & 0 \\ \hline 1 & 1 & 1 \\ \hline \end{array} \quad \text{X} \quad \begin{array}{|c|c|c|}\hline 1 & 1 & 1 \\ \hline 1 & 1 & 0 \\ \hline 0 & 0 & 0 \\ \hline \end{array} \quad = \quad \begin{array}{|c|c|c|}\hline 0 & 1 & 1 \\ \hline 0 & 0 & 0 \\ \hline 0 & 0 & 0 \\ \hline \end{array}$$

Figure 3.17: Explaining how cells are combined during a raster logical AND overlay with the resulting boolean layer

Once all the datasets were in raster format the process of reclassification allows all the criteria to be converted into Boolean statements of suitability. As Eastman (1999) explains the Boolean approach to spatial mapping sees areas designated a simple binary number according to whether it belongs or does not belong to a designated condition. As the example in Figure 3.17 shows, if a value of '1' is assigned to all the areas that are desired and a value of '0' to all the areas that should be excluded and the layers are multiplied, in a logical AND combination (Eastman, 1999), then cells in the output layer will only have a value of '1' if they meet all of the desired criteria. Whilst this is a powerful method of combining data and arranging analysis it does make simplistic assumptions about the data that need to be outlined.

Firstly, Boolean overlay is undertaken under the assumption that the relationships involved really are Boolean (O'Sullivan and Unwin, 2003), however the application of yes-no logic via sieve mapping doesn't represent the continuous nature of many criteria. Furthermore, simple Boolean overlay asserts the assumption that input interval or ratio data have been created without the presence of measurement error, that categorical attribute data are known to be exact, and that the representation of boundaries of discrete objects are certain and recorded without error (O'Sullivan and Unwin, 2003). However, the difficulty in creating data without measurement error, correctly assigning a classification and representing boundaries without error has been discussed in sections 3.3.1, 3.4.7 and 3.6.3.

One method for overcoming the limitations of Boolean overlay is to apply fuzzy set theory (Zadeh, 1965). Fuzzy set theory is well suited to problems where there is no clear divide between areas that are suitable and those that are not (Shelley et al., 2006), as it is a theory of graded concepts (Zimmermann, 2001). Fuzziness is typically applied to spatial boundaries, most commonly the result of a 'distance from' GIS query, however it can also be extended to describe the fuzziness of a nominal class assignment and therefore can help representations where there is a degree of vagueness in the data (Fisher, 1999), the sort of uncertainty highlighted in section 3.3.1 and 3.4.7. Another method of dealing with 'soft' information, the type of choices that involve judgement or preferences (Ahmed et al., 2010), is by using a weighted overlay technique such as the Analytical Hierarchy Process. Analytical Hierarchy Process gives a systematic approach in making decisions for site selection (Chandio et al., 2013) and revolves around assigning weights to the various input criteria according to how important they are in relation to each other and then multiplying each criterion by its assigned weight (Ahmed et al., 2010). The result is the assignment of a suitability value within a set range highlighting the most or least suitable land. The application of fuzziness or weighted overlay techniques do require further research regarding thresholds or weights used, this usually involves expert judgement and interviews.

A Boolean based methodology was utilised as part of this research as it provides a transparent and easy to follow work flow which could more easily be replicated in other settings or with applications beyond the provision of bioenergy provision in mind. Furthermore, most previous GIS-based studies have taken a boolean approach to the inclusion of factors such as slope or exclusion of protected areas (Lewis and Kelly, 2014). In the one case where no clear boolean limit was identifiable in the literature, the distance from a road, a sensitive analysis was conducted to understand the impact chosen boolean value for inclusion - this is described in section 3.5.1.3. Future research could incorporate these 'fuzzy' or weighted techniques, but as Asemi et al. (2013) point out these techniques require the integration of expert knowledge, which was beyond the scope of this study.

3.5.1 Selecting constraints to be applied

Constraints serve to delineate extents that are not suitable for inclusion (Eastman, 1999). A similar selection of constraints are applied by studies attempting to identify land suitable for bioenergy provision. Lewis and Kelly (2014) summarise the range of constraints that are applied by studies seeking to map marginal land for biofuel production. However, unlike most of those studies this research has already identified a theoretical landbank composed of suitable land types therefore there was not the same need to apply land cover constraints e.g. excluding certain urban areas or agricultural land of certain grades. Nevertheless, as Lovett et al. (2014) explain, there must be an effort made to avoid planting on sites of cultural value or areas of great biodiversity. Taking this into account, a selection of protected areas (see table 3.4) were combined to form one constraint layer. Topography is another factor that is heavily present as a constraint in land suitability studies. As Lewis and Kelly (2014) note, it was the third most considered factor amongst studies. A constraint layer was therefore created to ensure slopes at a gradient at which planting and harvesting crops would not be practical were excluded. Finally, the landbank may contain many small spread out parcels of land therefore the inclusion of two further technical constraints were required, site size and proximity to road network. This meant that sites that are particularly isolated or that are too small to be technically viable can be excluded.

There is an assortment of further biophysical and socio-economic constraints that have

Table 3.4: Table of constraints applied as part of multicriteria evaluation to identify the technical landbank - including data sources, format and date reported

Constraint	Dataset	Description	Data source and date reported	Data format
Slope (<15%)	Ordnance Survey Terrain 5 DTM	DEM produced in ArcGIS using Ordnance Survey Terrain 5 DTM	EDINA (2017) (Reported in 2013)	Raster (5×5 m)
Proximity to roads (Within 500m)	Ordnance Survey Open Roads	Buffer around main/secondary roads in Scotland clipped from Ordnance Survey Open Roads	EDINA (2017)(Reported in 2015).	Vector
Protected Areas	SSSIs	Sites of special scientific interest	SNH (2017) (Reported in 2015)	Vector
	NNRs	National Nature Reserves	(Reported in 2015)	Vector
	SPAs	Special Protected Areas	(Reported in 2015)	Vector
	LNRs	Local Nature Reserves	(Reported in 2015)	Vector
	SACSs	Special Areas of Conservation	(Reported in 2015)	Vector
	RAMSARs	Wetlands of International Importance	(Reported in 2005)	Vector

been applied in other studies (Lewis and Kelly, 2014). A common constraint that is used in the identification suitable land for biomass production are soil variables. Unfortunately, soil data is not available at a fine enough resolution to be included without undermining the efforts that have been taken to digitise the spatial database at a large scale. The national soil map of Scotland, for example, is only available at a scale of 1:25000 (UK Soil Observatory, 2017). Mapping at this scale does not provide the amount of detail to be able to infer about the soil conditions at site level. Moreover, it is likely that the soil composition at many of the land types included in the database is not necessarily similar to the surrounding area due to infilling. This research has implemented constraints that were readily available at an appropriate resolution so as not to undermine the work undertaken to identify the theoretical landbank. Further work could be conducted in the future to add additional constraints and evaluate the impact they have on the resultant technical landbank, even implementing scenarios to assess the impact of each constraint individually. The datasets representing constraints used for the multicriteria evaluation conducted as part of this research needed to be collated and prepared, ensuring that they could be integrated into the analysis with the appropriate thresholds applied.

3.5.1.1 Topography

To apply excessive slopes as a constraining factor a digital terrain model (DTM), otherwise known as a digital elevation model (DEM), needed to be obtained. Ordnance Survey's digimap portal enabled the OS Terrain DTM to be downloaded for the entirety of Scotland. These raster files, provided in ArcGIS compatible .ASC format, provide digital model representation of the Earth's surface at a resolution of 5m. This meant that the cells of the raster are 5 m x 5 m in size. The files can be downloaded in 5 km x 5 km tiles which then needed to be merged together. The *Mosaic To New Raster* tool was used from the ArcGIS Data Management toolbox to combine all the tiles, with the output location set as an empty file geodatabase and a pixel type of 32_bit_float selected to support decimals in the height data.

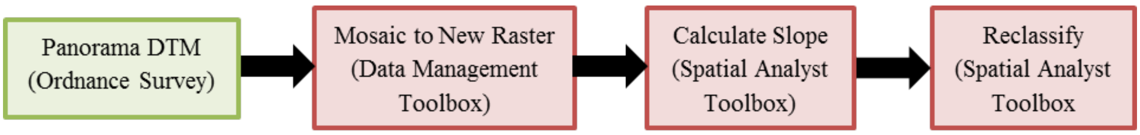


Figure 3.18: Preparation of the topography constraint layer

The slope was then calculated using the ArcGIS *Slope* tool from the Spatial Analyst toolbox. This tool calculated the maximum rate of change in height value in each cell compared to its neighbouring cells (ESRI, 2016a). The output measurement of this tool was set to percent rise. The resulting slope raster was then reclassified, using the *Reclassify* tool from the ArcGIS Spatial Analyst toolbox, so that all slopes over 15% were assigned a value of 0, whereas slopes under 15% were assigned a value of 1. Lewis and Kelly (2014) describe topography as a prime example of a threshold that is often decided by authors or a 'panel of experts' that can vary widely between studies. The value of 15% used in this study mirrors that used by Lovett et al who claim it is the 'limit beyond which planting and harvesting crops is impractical' (Lovett et al., 2014). Nevertheless, as discussed in section 3.5.1, future work could use a selection of different class thresholds to enable fuzzy analysis, as attempted by Cai et al. (2011), which better takes into account the subjective nature of includable slope.

3.5.1.2 Protected areas

Protected areas are defined by Scottish Natural Heritage as the best of Scotland's landscapes that should be managed and protected. Whilst it is presumed there will not be much overlap between underutilised non-agricultural land and protected areas it is still necessary to include this constraint to ensure these areas are excluded and the same selection of designated areas were excluded in Lovett et al.'s (2014) study into the availability of land for energy crops in Great Britain. Datasets representing Sites of Scientific Interest (SSSIs), Special Protected Areas (SPAs), Local Nature Reserves (LNRs), Special Areas of Conservation (SACs) and Wetlands of International Importance (RAMSARs) were downloaded from Scottish Natural Heritage's Natural Spaces spatial data portal.

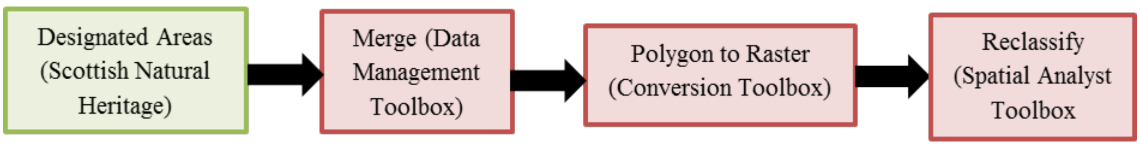


Figure 3.19: Preparation of the protected areas constraint layer

The polygon shapefiles representing each of these designated areas were combined using the *Merge* tool from the ArcGIS Data Management toolbox. The data was provided in vector format, and therefore needed to be converted to raster format using the *Polygon to Raster* tool in the ArcGIS Conversion toolbox. The raster was created with a 5 m x 5 m cell size so that it was compatible with the topography dataset. This raster surface was then reclassified, again using the ArcGIS *Reclassify* tool, so that all cells containing protected areas were given a value of 0, and the remaining cells given the value of 1 to represent their includability.

3.5.1.3 Proximity to roads

Roads are often considered in optimal location models used to locate bioenergy resources or processing facilities. However, the focus of their inclusion has often been related to transport costs with studies implementing network analysis on road systems (Khachatryan et al., 2009; Sosa et al., 2015). Unfortunately, less work has been done to assess the minimum distance a major road should be from a parcel of land to enable it to be used sustainably for bioenergy production. Malinen et al. (2001) assumed that haulage of biomass could be made up to 250 m from the roadside, however this study was only considering wood fuels from logging residues. It is unlikely that many of the sites included in the spatial database are particularly far from road networks given the sites are the result of human interference with the landscape. Nevertheless, to ensure the exclusion of any isolated sites, particularly amongst the historic landfills, a maximum distance of 500 m from an A or B road has been set as a criterion for inclusion. Given the lack of previous research justifying a suitable and acceptable distance from roads a sensitivity analysis was also conducted on this constraint to highlight the impact of changing proximity of roads on the availability of technical landbank - as described in more detail below.

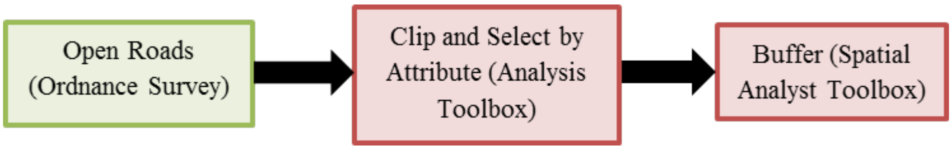


Figure 3.20: Preparation of the road proximity constraint layer

The freely available ‘Open Roads’ dataset was downloaded from Ordnance Survey. This is a national dataset for Great Britain containing over 3 million roads so it was necessary to clip this to Scotland’s extent using the *Clip* tool from the ArcGIS Analysis toolbox and boundary data from Ordnance Survey’s Open Data dataset. Once clipped, this layer was queried using the *Select By Attribute* function in ArcGIS to enable all the A and B roads to be selected and exported as a new shapefile layer. The *Buffer* tool, from the ArcGIS Analysis toolbox, was then utilised to create a polygon representing a 500 m buffer around the road features. After initial attempts to incorporate the road buffer into the raster overlay, it was found that the best way to incorporate the buffer was via a preliminary analysis step, which is outlined in the following section.

A sensitivity analysis is the study of how the variation in the output of a model can be apportioned to variations in the input (Saltelli et al, 2004). As figure 3.21 shows, a strict threshold of 50m would decrease the availability of technical landbank considerably, leaving only 12,227 ha available. However, given the input data is A and B roads, 50m is presumed to be overly strict as there is the possibility of minor roads existing that could be used with minimal disturbances over such small distances. A threshold of 250m results in 15,373 ha and a threshold of 750m results in 18,758 ha of available land - the mapped outputs of these changes can be seen in Appendix A.7. Increasing the threshold value to 1 kilometre increases the landbanks size to 19,784 ha. This represents a 14% increase in the amount of land available compared to 17,404 ha that were identified using a 500m threshold. It is worth considering the impact of this threshold when viewing the result of the multicriteria evaluation, which has been calculated using an arguably cautious threshold of 500m.

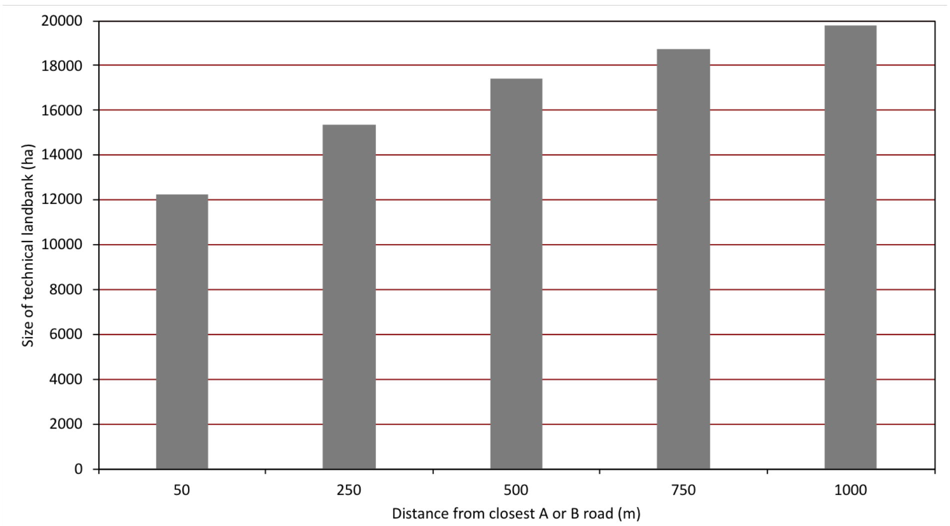


Figure 3.21: Results of sensitivity analysis conducted to establish effect of 'proximity to roads' constraint

3.5.2 Combining the constraint layers: Raster overlay in ArcGIS

Before combining the raster format constraints the *Intersect* tool was used to find all the sites within the theoretical landbank database that fall at least partly within the polygon representing 500 m from a major road. The selection of sites was then exported as a new shapefile for use for the remainder of the analysis and was converted to raster format, once again using the ArcGIS *Polygon to Raster* tool. The spatial database was therefore converted

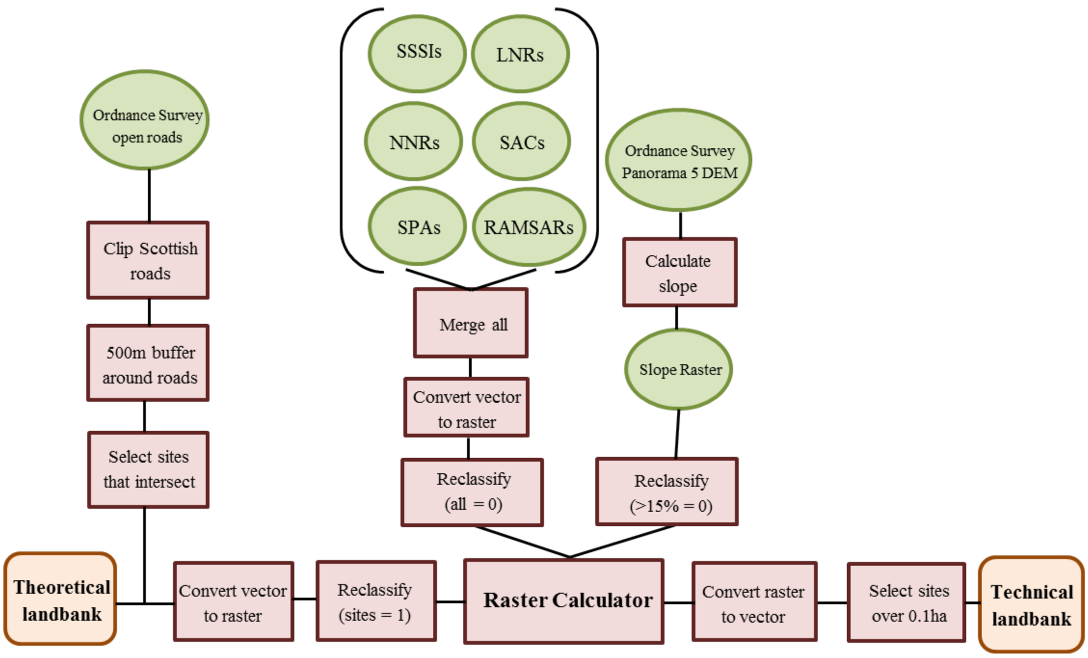


Figure 3.22: ArcGIS workflow model of application of technical constraints via multicriteria evaluation

into a continuous surface with a cell size of 5 m x 5 m, so that it would be compatible with the constraint layers. This raster was then reclassified so that all the cells containing underutilised non-agricultural sites were given a value of 1, and all other cells given a value of 0. This raster could then be combined with the remaining of the constraints using the *Raster Calculator* tool from the Spatial Analyst toolbox. This tool allows map algebra expressions to be built using Python syntax (ESRI, 2016c). Multiplication is the equivalent to a logical AND, or intersection, expression (Malczewski, 1999) and therefore the layers were combined using the following equation:

'Site_Raster' * 'Slope_Raster' * 'Protected_Areas_Raster'

Within the resulting raster only cells that contain underutilised non-agricultural land within 500 m of a road, not overlapping a protected area, with a slope less than 15% are assigned the value of 1, with all the remaining cells given the value 0.

The raster was then converted back into vector format, using *Raster to Polygon* tool from the ArcGIS Conversion toolbox, so that the final constraint, site size, could be applied. Applying the previous constraints may have created small isolated areas, especially the application of the topographical constraint. Steep slopes across part of a non-agricultural site may have broken the site up into multiple polygons. It is necessary to remove the smallest of these sites, with a minimum site size of 0.1 ha allowing sliver polygons to be excluded. This was done by adding a new field to the attribute table of the shapefile, calculating the area using the *Calculate Geometry* ArcGIS tool, then using the *Select by Attribute* ArcGIS tool to select only sites larger than 0.1 ha. The removal of sites under 0.1 ha removed 47 ha from the landbank. The removal of smaller sites has been undertaken in previous studies, with Fiorese and Guariso (2010) explaining that the smaller parcels of land cannot be justifiably included for biomass provision due to associated machinery and personnel costs.

The process of applying constraints, as shown in Figure 3.22, provides an initial insight into what proportion of the theoretical landbank could technically be used for bioenergy provision. This research has used several of the most commonly used constraints, however future work could incorporate further techno-environmental constraints providing datasets are available at a suitable resolution. It is also possible to script this analysis using Python, or ArcPY the ArcGIS built in scripting module. The automation of the overlay process in this manner would enable the application of different thresholds in differing scenarios, and even breaking down of national datasets into smaller areas to produce regional scale analysis, with the potential to highlight the impact of each individual constraints at differing scales.

3.6 Verification and validation of the multicriteria evaluation

A model that is accurate in it's prediction of a real world phenomenon enables increased credibility with decision makers (Carson, 2002). The foundation of verification and validation is the laying out of assumptions and data requirements (Carson, 2002). This section will summarise the assumptions that have been made regarding the implementation of data within the multicriteria evaluation.

Table 3.5: Summarising justification used for application of constraints as part of the multicriteria evaluation

Constraint	Threshold applied	Justification
Slope	Slopes over 15% were excluded	Slope has been previously identified in the literature as a major limiting factor for planting of biomass (Lewis and Kelly, 2014). A threshold value of 15% has been used in previous studies (Lovett et al., 2014).
Protected areas	All excluded	Previous studies have taken steps to also exclude all protected areas (Lovett et al., 2014).
Site size	Sites under 0.1 ha excluded	Smaller sites are not justifiable due to machinery and personnel costs (Fiorese and Guariso, 2010)

Verification refers to the building of an accurate model (Qureshi et al., 2000) and it is important that all choices made in building of that model can be justified. Verification of constraint thresholds used for the multicriteria evaluation have predominantly been taken from existing literature and are presented in table 3.5. No previous threshold regarding proximity to roads could be identified, therefore a sensitivity analysis was undertaken to establish the impact this constraint had on the resulting landbank. The results of the sensitivity analysis are described in section 3.5.1.3. Another element of verification is awareness of the potential sources of data error (Carson, 2002). The potential for error to impact the multicriteria evaluation is discussed in section 3.6.3.

Validation of a model establishes the level to which it achieves an acceptable level of accuracy in its prediction (Qureshi et al., 2000). It is the process of review and evaluating how a model performed (Carson, 2002). According to Carson (2002) there are two types of validation. The first is face validity, whether the output of a model is 'reasonable'. Whilst the most ideal form of face validity would be comparing the results with the real world (Kleijnen, 1995) this is often not possible therefore comparison with results produced by similar studies may be required. The most significant previous study in relation to this thesis is the work undertaken by Niblick and Landis (2016), therefore the results of this multicriteria evaluation were compared with their output in section 7.1. The second type of validation related to the impact of changing inputs within a model, or how the model reacts to a 'stress test' (Carson, 2002). Whilst a sensitivity analysis was not undertaken for all the input criteria in the multicriteria evaluation undertaken as part of this thesis, the sensitivity analysis undertaken in relation to proximity to roads shows the model is robust and repeatable.

As Carson (2002) states, no model can be 100% verified or validated. It is a matter of degree rather than a process with an end point, and continues until sufficient confidence is given (Qureshi et al., 2000). The above steps were undertaken and highlighted to ensure a sufficient level of confidence can be given to the technical landbank which resulted from the multicriteria evaluation conducted as part of this research.

3.7 Exploratory spatial data analysis techniques used to further understand the distribution of the landbanks

Exploratory spatial data analysis is a group of methods that allow the user to describe and visualise spatial distributions (Anselin, 1999). This form of analysis gives emphasis to creative display, or cartography, such as the hexbinning (see Box 3.3) but also the use of indicators to 'elicit patterns and suggest hypotheses in an inductive manner' (Anselin, 1999). This research conducted two forms of exploratory spatial data analysis. Following the creation of both the theoretical and technical landbanks a density analysis was conducted and heatmap was produced using these datasets to allow an insight into spatial distribution and the identification of clusters of sites. Further analysis was undertaken on both landbanks via the integration of other spatial datasets.

3.7.1 Understanding the spatial distribution of the landbanks

The data binning explained in Box 3.3 provided an initial visual interpretation of the distribution of sites at several scales. However, to better identify clusters within the landbank a density analysis methodology was employed on both the theoretical and technical landbanks. Kernel density estimation allows data to be aggregated within a defined search radius producing a continuous surface representing density (Chainey et al., 2008). Initially, the default ArcGIS search radius, which is calculated using a bandwidth algorithm taking into account the input data's attributes, was deemed adequate to provide an insight into the distribution of the landbanks. However, the search radius was then adjusted when attempting to identify clusters of the technical landbank, as explained in section 3.6.2.2.

The kernel density estimation required point data as an input so the databases representing the theoretical and technical landbanks were both converted from polygon to point form using the *Feature to Point* tool from the ArcGIS Data Management toolbox. However, the *kernel density* tool in ArcGIS allows the site area to be added as a population field, enabling larger sites to be weighted more heavily in the computation of the surface by determining the number of times a point is counted in the calculation (ESRI, 2017a). This added functionality allows a greater understanding of the density of underutilised non-agricultural land area rather than just the density in a number of sites. The kernel density estimation analysis results in a raster output with cells displaying the density of landbank as a magnitude per unit area within the input or default search radius. The resulting layer can be manipulated and the areas with the highest density of landbank can be exported as polygon. The clusters of technical landbank 'supply' were utilised during the further work, investigating the relationship with heat demand, in section 3.6.2.2.

3.7.2 Comparing the landbanks with other spatial datasets in order to identify significant clusters of land

Further exploratory data analysis was undertaken using secondary spatial datasets to shed further light on patterns that may exist within the distribution of the theoretical and technical landbanks. The location of the theoretical landbank was investigated in relation to deprivation. Section 3.6.2.1 outlines the utilisation of a methodological approach similar to that used in the vacant and derelict land survey (Scottish Government, 2016d) in order to highlight the proportion of underutilised non-agricultural land that occurs within Scotland's most deprived datazones. The technical landbank has been produced to find areas sutiable for bioenergy provision, and therefore this thesis has attempted to match clusters of supply of land with demand via a comparison with Scotland's heat demand mapping.

3.7.2.1 Investigating the location of the theoretical landbank relative to deprivation

To gain a better understanding of the location of underutilised non-agricultural land in Scotland relative to deprivation the methodology utilised by Scottish Government (Scottish Government, 2016d) to assess the distribution of vacant and derelict land has been expanded to compare the theoretical landbank identified in this thesis with the most deprived areas in Scotland. The SIMD, Scottish Index of Multiple Deprivation, was primarily used to investigate the distribution of the landbank in comparison to deprivation. The SIMD is a tool that identifies areas of poverty or inequality in Scotland (Scottish Government, 2016b). The index combines 38 indicators in seven 'domains': Income, Employment, Education, Health, Access to Services, Crime and Housing. These domains are then combined to create a ranking for each of the data zones, which have roughly equal population, throughout Scotland (Scottish Government, 2016b). The datazone geography with attached SIMD ranks was downloaded from the Scottish Government SIMD website (Scottish Government, 2016b). The 15% most deprived datazones, those with a rank of 1046 or less, were extracted from the downloaded dataset. This revealed the distribution of the most deprived datazones amongst local authorities, whilst also enabling the *Tabulate Intersection* ArcGIS tool to be used to calculate the total area of underutilised non-agricultural land within each of these most deprived datazones. The methodology used in the vacant and derelict land survey (Scottish Government, 2016d) uses a co-ordinate point to represent each site and assigns the area of the site to the local authority in which it is located. The methodology used in this thesis therefore provides a more robust indication of the proportion of land within each local authority, and extends the investigation beyond brownfield land to include other underutilised non-agricultural land. This analysis will allow further insight into the distribution of this landbank and highlight the local authorities with the highest proportion of underutilised non-agricultural land in close proximity to more deprived areas.

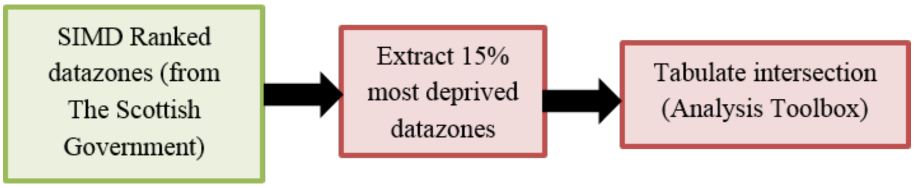


Figure 3.23: ArcGIS workflow used to assess the proportion of theoretical landbank within the most deprived datazones

3.7.2.2 Investigating the location of the technical landbank relative to heat demand

Further exploratory data analysis was undertaken using the technical landbank, which represents land that could be available for bioenergy provision or supply, and using data from Scotland's heat map as an indicator of demand. The analysis pairing supply with demand will focus on heat demand in an attempt to highlight significant clusters of underutilised non-agricultural land that could provide biomass to target this demand. Biomass feedstock is a distributed resource with a low energy density (Thomas et al., 2013). Therefore, to maintain its sustainability as an energy source transport costs must be kept to a minimum, which has led to the application of sourcing radii (Thomas et al., 2013). Thomas et al. (2013) explain that a sourcing radius of 25 km was the limit implemented in earlier studies, based on the Energy Crop Scheme funding requirements. However, updated regulations now stipulate a 'reasonable distance' therefore Thomas et al. (2013) argue that a radius of 40 km would be suitable as it is the limit in industry for small scale uses of feedstock and has been supported in subsequent literature (Thomas et al., 2013). This 40 km radius is used in the analysis conducted in this thesis although the research presented here does not include a detailed study of suitable sites for bioenergy facilities or consider specific feedstock end users such as co-firing plant, combined heat and power plant or district heating schemes as implemented in previous studies. As such this research only gives an insight into the rudimentary spatial relationship between potential heat supply and demand. It does not go into the extent to which the demand can be met by supply as this would involve the application of a range of assumptions and detailed modelling which is beyond the scope of this study. It would also require far more information on achievable yields from brownfield land, or other non-agricultural land types, than is currently available. Nevertheless, the aim of this thesis was to further an understanding of the opportunity underutilised non-agricultural land could provide and the techniques used here have been implemented to highlight key areas where future work, such as agronomic modelling or identification of suitable bioenergy plant locations, can be targeted.

Scotland's heatmap (Scottish Government, 2015) contains a layer representing heat demand. This heat demand dataset is an amalgamation of several spatial datasets with heat demand values (Scottish Government, 2015). It includes data for 3.2 million unique property reference numbers (UPRNs) with information on building properties such as floor area, age, energy efficiency, heating system and actual energy billing data (Scottish Government, 2015). This heat demand layer is then aggregated to raster cells of varying sizes, with the modelled kWh heat demand data being released at no finer resolution than 50 meter grid. Both this 50 m x 50 m raster grid, and an aggregation of demand by datazone - also released by the Scottish Government (Scottish Government, 2015) - were utilised for the exploratory analysis undertaken in this thesis.

Three different approaches were undertaken in an attempt to find spatial relationships between areas of potentially high bioenergy supply, or technical landbank, and areas of high heat demand. Firstly, an approach was taken focussing on clusters of the technical landbank, adapting the output of the kernel density technique explained in section 3.6.1 and selecting cells containing the upper quantile of density value. The sum of technical landbank within these clusters was then compared to the demand, measured in GWh/yr, within a 40km radius. Secondly, a similar approach was undertaken attempting to identify clusters of demand, using a proxy layer created from amalgamation of datazones with high heat demand density. A 40 km search radius was then implemented around the heat demand clusters and the area of landbank within this radius could be compared to the total heat demand within the clusters. The final approach attempted to locate areas with the highest heat demand and landbank supply, this enabled several case study datazones to be highlighted for potential further investigation. The methods, predominately ArcGIS based, used in each of these approaches is detailed below.

The first approach was based on clusters of the technical landbank and therefore utilised the kernel density estimation analysis outlined in section 3.6.1. However, a search radius of 10 km was implemented instead of the default search radius which enabled clusters to be identified whilst excluding outliers. Future work could implement scenarios with varying input search radius but 10 km suited the purposes of this analysis and allowed 9 key clusters with a high density of landbank to be identified.

The density value within these clusters was within the upper quantile of the all those in the kernel density surface, with a magnitude of 0.02 per square meter within the 10km search radius. This threshold value was used in the ArcGIS *set null* tool which allowed all values under 0.02 square meter to be set as a null value and therefore ignored. To convert areas from raster to vector the cells must be integers, therefore the ArcGIS *Int* tool was used. This tool converts all cell values of a raster to an integer by truncation (ESRI, 2016b). This then enabled the ArcGIS *raster to polygon* tool to be used to extract the polygons representing the 9 clusters of landbank.

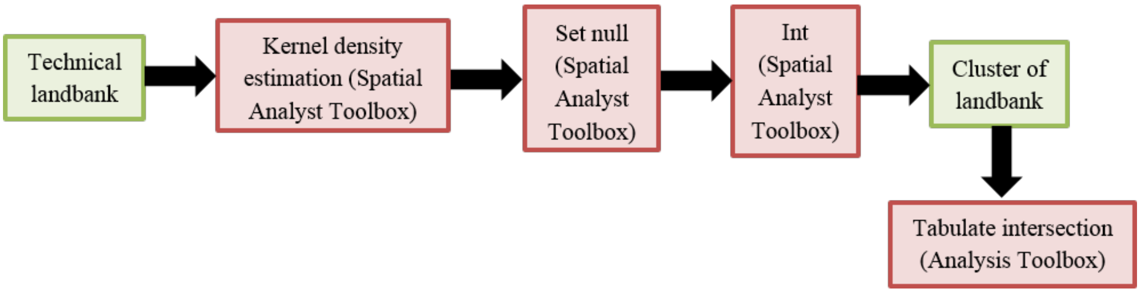


Figure 3.24: ArcGIS workflow used to identify 9 clusters of technical landbank and the calculation of area of landbank within

Once the 9 clusters had been extracted and converted to vector format the sum of the area of technical landbank within each cluster could be calculated using the *tabulate intersection* ArcGIS tool. Following this, the ArcGIS *buffer* tool was used to create a 40 km search radius around the clusters of landbank. At this stage the Scottish Government's heat demand layer, in raster format, was integrated into the analysis. The ArcGIS *extract by mask* tool was used to select all of the raster cells within each 40 km radius and extract this as a new raster layer. The ArcGIS *zonal statistics as table* tool could then be used to calculate the sum of heat demand within the 40 km search radius.

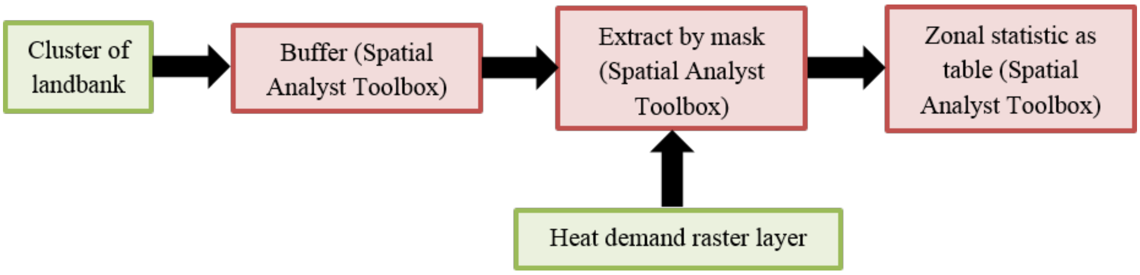


Figure 3.25: ArcGIS workflow used to calculate the sum of heat demand (GWh/yr) within a 40 km buffer of the 9 clusters of technical landbank

The second approach focused on clusters of heat demand and used the heat demand aggregated to Scotland's datazone geography made available by the Scottish Government (Scottish Government, 2015) in vector format. This also contained a value corresponding to the heat demand density for each datazone. The datazones were ranked according to the heat demand density and the 1% of datazones with the highest heat demand density were extracted as a new shapefile for the purposes of this analysis. The 70 datazones were then aggregated into clusters according to proximity. The *Aggregate Polygons* ArcGIS tool was used to combine datazones within 5 km of one another. This distance was selected as it produced 13 clear clusters and left isolated datazones to be treated as stand-alone entities. However, future research could be undertaken based on scenarios with altered distance thresholds used for the grouping of datazones. If any datazones within the same cluster had touching boundaries they were combined using the ArcGIS *dissolve* tool. The *minimum bounding* ArcGIS tool was then utilised to create a convex hull, a bounding polygon, around each cluster of datazones thus creating a proxy layer representing 13 areas of high heat demand density. The sum of the heat demand within each convex hull of the proxy layer was calculated, via the same combination of *extract by mask* and *zonal statistics as table* ArcGIS tools that were used to calculate the demand surrounding the landbank clusters in the previous stage of analysis. Following this, a 40 km buffer was created around each of the 13 clusters and the sum of the technical landbank calculated using the *tabulate intersection* ArcGIS tool.

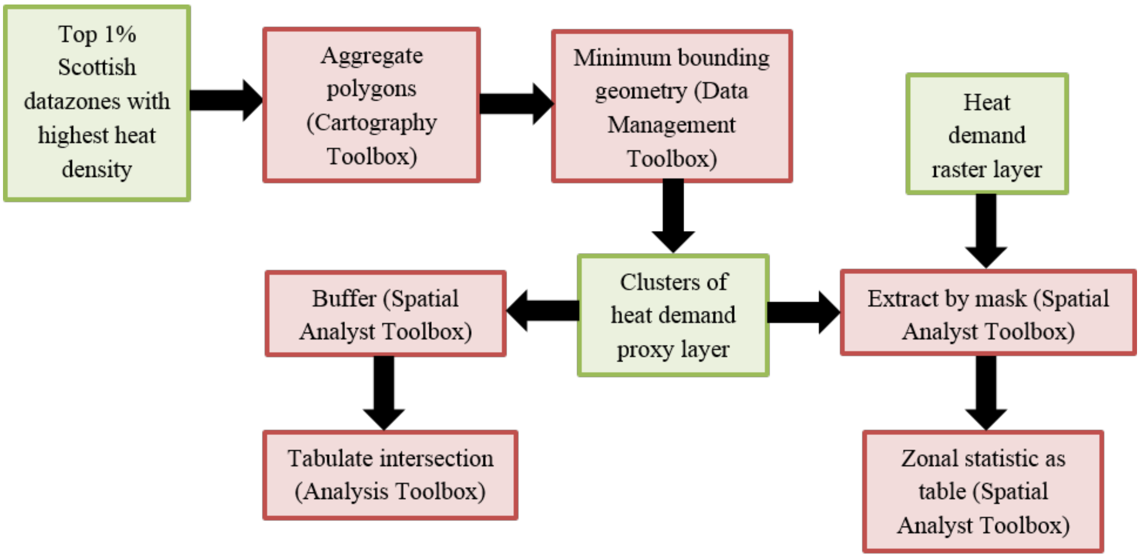


Figure 3.26: ArcGIS workflow used to produce a proxy layer representing clusters of heat demand, to calculate of the sum of heat demand within the cluster and to calculate the sum of the technical landbank within a 40 km buffer

The final approach sought to find areas with both a high heat demand density and high landbank density. This analysis enabled case study areas to be highlighted for further investigation. This analysis once again utilised the datazone geography with appended heat demand information provided by The Scottish Government (Scottish Government, 2015). The *tabulate intersection* ArcGIS tool was used again to calculate the sum of technical landbank within each datazone and the *spatial join* ArcGIS tool was then used to join these values to the datazone geography layer. The area of landbank as a proportion of the total land cover of each datazone was calculated and added as a new field. A scatterplot was then created in ArcGIS, and the datazones within the top 1% heat demand density and top 5% technical landbank density were selected and extracted as a new shapefile. These thresholds were chosen as they resulted in a manageable number of sites, four, to be selected for further analysis. However, future work could decrease the threshold. For instance, a threshold of 10% in both heat demand density and technical landbank density resulted 68 datazones being highlighted. Nevertheless, for the purposes of this thesis four datazones were selected and the ArcGIS *buffer* tool was once again utilised to create a 40 km catchment around each datazone from which the sum of technical landbank could be calculated using the *tabulate intersection* ArcGIS tool. Finally, each of the four case study datazones could be visually inspected using ESRI's world imagery basemapping and overlaid technical landbank polygons to emphasis the surrounding available landbank.

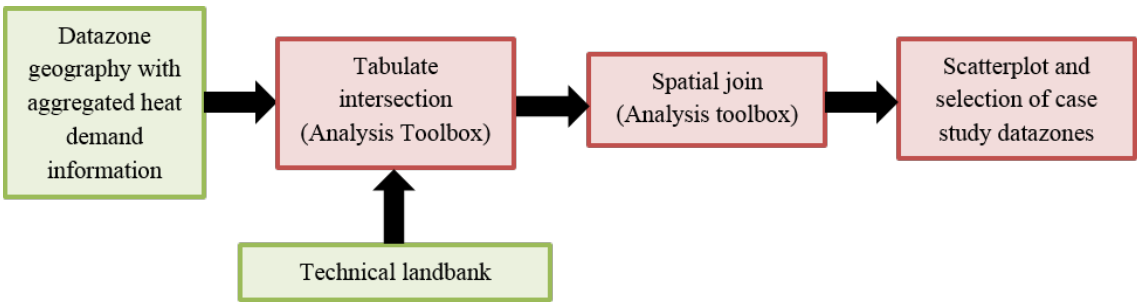


Figure 3.27: ArcGIS workflow used to identify Scottish datazone case studies with high heat demand density and high density of technical landbank

These three approaches enabled the technical landbank to be seen in the context of heat demand in Scotland, as well as providing a guide for future detailed investigation of target areas or significant clusters. Future work that could build on this foundation are discussed in more detail in section 6.2.

3.7.3 Further uncertainty in the analysis of underutilised non-agricultural land

Further investigation and manipulation of both landbanks, including the multi-criteria evaluation used to create the technical landbank, can introduce further aspects of uncertainty that must be considered when making conclusions. Uncertainties in data can lead to further uncertainties in the results of any following analysis (Longley et al., 2005). The various errors that could be introduced during the measurement and representation of phenomena, as outlined in section 3.4.7, can be propagated or even amplified by further GIS operations or analysis (Heuvelink, 1999). The two prominent areas of GIS operation where errors can be propagated are during editing and conversion, and during processing and analysis.

It is extremely rare for any map, or underlying database, to be completely error free (Heuvelink, 1999). When the newly created spatial databases are used for further analysis the error in the input will be propagated in the output (Heuvelink, 1999). However, the propagation of error can occur before any analysis is conducted, and thus care must be taken even when preparing a database for use. The conversion of GIS from one data model, vector or raster, to the other can be a major source of error propagation. During vector to raster conversion, which is used in this research prior to the raster overlay, the size of the raster can have implications for positional error (Heywood et al., 2011). A smaller cell size would allow greater precision as it enables the line of a polygon to be represented more accurately in raster form. This in turn would reduce classification error along the boundary of a polygon (Heywood et al., 2011) which is often seen in the form of 'stepped' appearance of curved polylines in raster form. According to Piwowar (1987) an optimal cell size should be a quarter of the size of the smallest polygon to ensure integrity. The rasterization used in this research used a cell size of 5m x 5m to ensure the rasterised landbank was compatible with other constraint datasets, this meant that a cell was less than a quarter of the smallest sites and is a fine enough resolution to not have a large impact when representing curved boundaries. The impact of rasterization is often similar to generalisation, and a comparable introduction of errors could occur. For instance, if polygons representing sites are less than half of the chosen cell size of the raster surface they may be lost during the conversion process (Heywood et al., 2011). Furthermore, if a polygon representing a site is strung out in part or connected by a narrow section of land, these connective areas may be lost (Heywood et al., 2011). This type of error was avoided in this research as an appropriate cell size was used. Finally, the grid orientation, origin and datum can impact the resultant raster surface. To avoid this impacting the results, all the raster surfaces were produced in parallel to the co-ordinate system used for the digitisation, British National Grid. The same extent was used during the conversion process.

Errors can also be introduced in the opposite conversion from raster to vector - a process that is used in this research to re-vectorise the technical landbank. The 'stepped' appearance caused by previous rasterization will manifest itself in the vectorised output, although this was reduced to a degree using a line-smoothing algorithm built into the *Raster to Polygon* ArcGIS tool. Furthermore, if a narrow strip connects sites, as previously described, then the conversion back to vector format compounds this separation. These small polygons would then be lost, as sites below 0.1 ha are excluded. However, this should not occur with the use of this database as a fine scaled cell size is used. Future research could be conducted to quantify the level of error introduced by these conversion processes. As Congalton (1997) explains, pre-rasterised layers can be combined with rasterised layers and a table of omission and commission created to understand the impact that the process has on the areas reported.

All data which are combined, whether it be overlaid, merged, or simply compared visually must be in the same map projection and on the same datum (Dowman, 1999). Whilst this rudimentary step was taken throughout this research, utilising the British National Grid projection and OSGB 1936 datum, error created during the measurement and representation of the landbank can still be propagated through the overlay operation that followed. The results of map overlay can only ever be as good as the worst set of data input into the operation (Heywood et al., 2011), and any positional or attribute errors that exist in the original spatial database or constraint layers will be transferred, and potentially multiplied, in the output layer (Heywood et al., 2011). Sliver polygons, a common visual effect of digitisation-based positional error that can be seen during vector overlay (Heywood et al., 2011), have been minimised during this research not only via the alternative use of raster overlay but also by ensuring all the datasets have similar scales and are appropriately aligned. However, any that are created are removed via the selection of sites over 0.1 ha as described above. A further insight into the potential level of uncertainty that is caused by propagated error could be gained in future studies via the use of error modelling. Initially, an evaluation of error propagation in areal statistics could utilise measured positional uncertainties in vertices to quantify the subsequent error in polygon area (Longley et al., 2005). Further error modelling such as epsilon modelling, used to investigate error around digitised boundaries, and Monte Carlo simulation, used to model the effects of overlay whilst inputting data containing random 'noise' (Heywood et al., 2011), could be conducted by future studies seeking to gain an insight into the potential impact of errors on the results. As Longley et al. (2005) urge, it is important to report findings using a number of digits that reflects the measurement's accuracy. Bearing this in mind, and considering the elements of uncertainty introduced at both the measurement, representation, and the analysis stage of this research, it is not suitable to present the technical landbank area found to a high degree of precision. Furthermore, the impact of gross human error in terms of misreporting or digitisation malpractice, must be taken into account and the results should therefore merely give an indication towards the role that underutilised non-agricultural land could play rather than a precise area.

Chapter 4

Assessing the potential of Scottish underutilised non-agricultural land: Theoretical landbank

As explained in section 3.1.2, the theoretical landbank is the total amount of underutilised non-agricultural land that can be identified before the application of any technical constraints. It is the hypothetical maximum amount of this land resource that exists that could eventually be implemented for uses such as bioenergy provision. The methodology, outlined in section 3.4, has been designed to create a spatial database containing several underutilised non-agricultural land types. This term has been used in an attempt to identify an alternative to agricultural land that can be used for sustainable bioenergy provision whilst avoiding land use conflicts, and the selection of lands suitable for inclusion in the Scottish context of this research is outlined in section 3.3.

This chapter will present the spatial database of underutilised non-agricultural land, breaking down the findings for each land type in sections 4.1 to 4.4 and then presenting the combined geodatabase in section 4.5. The exploratory spatial data analysis that followed, attempting to further an understanding of the distribution of this landbank, is presented in section 4.6. By providing this insight into the collective area and distribution of the theoretical landbank, the result of the application of the methodology detailed in chapter 3, this chapter will continue the exploration of the following research question:

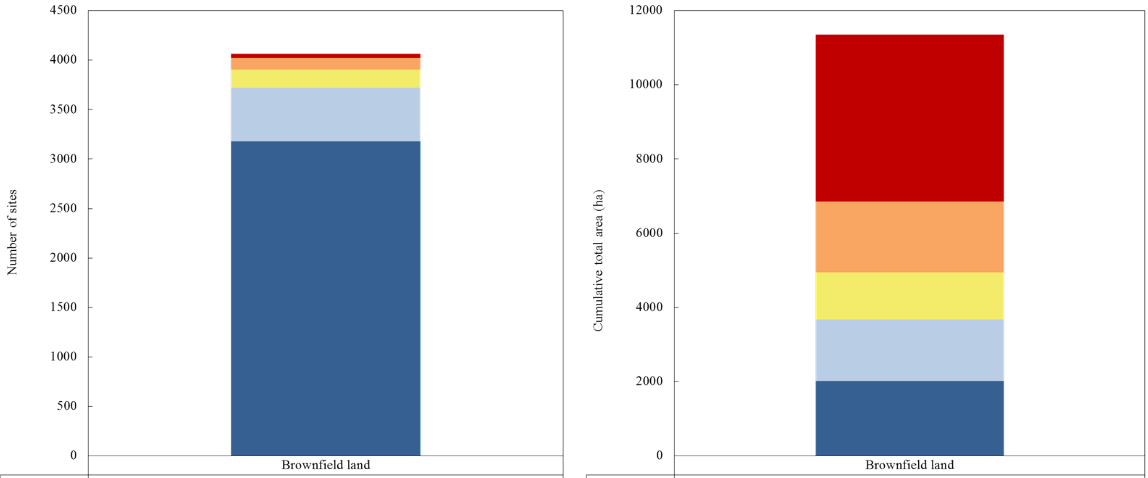
- What is the best way to identify the collective area and distribution of underutilised non-agricultural land in Scotland?

Furthermore, this chapter will contribute to the overall aim of this thesis in providing an initial insight into the opportunity that could be provided by a land resource that is commonly overlooked.

4.1 The collective area of brownfield land in Scotland

The methodology for capturing boundaries and compiling the spatial database representing brownfield land is detailed in section 3.4.1. Seven of the 33 local authorities were unable to provided site boundaries in a GIS compatible form. This meant that sites in Angus, Clackmannanshire, Dumfries and Galloway, Orkney Islands, Shetland Islands, Stirling and West Lothian local authorities had to be digitised, a total of 294 boundaries. These were combined with the boundaries that were provided by local authorities to create a spatial database with 4063 sites totalling an area of 11,351 ha. A breakdown of the total amount of brownfield land in each local authority can be found in Appendix A.7.

A site size analysis (see Figure 4.1) highlighted the high proportion of brownfield land sites within the database that are less than two hectares in size, over 75% of the sites in the database. This reflects the inclusion of small urban vacant parcels of land recorded in the vacant and derelict land survey and underlines the importance of identifying clusters of this land type for it to be viable for any potential bioenergy provision. There is also a total of 158 sites over 10 hectares. As shown in Figure 4.1, these 158 sites represent over 58% of the total brownfield land area. The larger of these sites are predominately former airfield or munition factories. However, once the largest of the sites are discounted the remainder of sites over 10 hectares have a variety of past uses, with some former tips and quarries listed alongside former steel works and hospitals.



	Brownfield land (number of sites)	Brownfield land (cumulative total area, ha)
> 30 ha	41	4498
10 to < 30 ha	117	1904
5 to < 10 ha	186	1270
2 to < 5 ha	540	1659
< 2 ha	3179	2020

Figure 4.1: Site size analysis of land parcels compiled within the brownfield land spatial database. Showing number of sites within each threshold on left and contribution to total area found on right - based on spatial database created in 2015 using the 2013 Scottish Vacant and Derelict Land Survey (Scottish Government, 2014)

As figure 4.2 shows, North Ayrshire is the local authority containing the largest amount of brownfield land with 1363 hectares, the Shetland and the Western Isles have the least with less than 20 hectares between them - expectedly given the lack of industrial or commercial development in these areas. The Highland and Dumfries and Galloway local authorities both have a high amount of brownfield land, which is to be expected as they are two of the three largest local authorities in Scotland. Once the area of brownfield land is mapped as a proportion of the total land cover for each local authority, as in Figure 4.3, it becomes clear where this land type is most densely located. The local authorities with the relatively highest proportion of brownfield land, as seen in Figure 4.2, appear to be predominately based in South and Central Scotland. In total, 8546 hectares of brownfield land are located within the Central Scotland Green Network (See map of boundary in Appendix A.8), which highlights the centrality of distribution of this land type. The Central Scotland Green Network is a National Development area where the Scottish Government's third National Planning Framework identified the need to restore and transform the landscape (CSGN, 2017). It covers much of the central belt of Scotland spanning from Ayrshire and Inverclyde to Fife and the Lothians (CSGN, 2017). The high proportion of land in these areas of Scotland reflect the

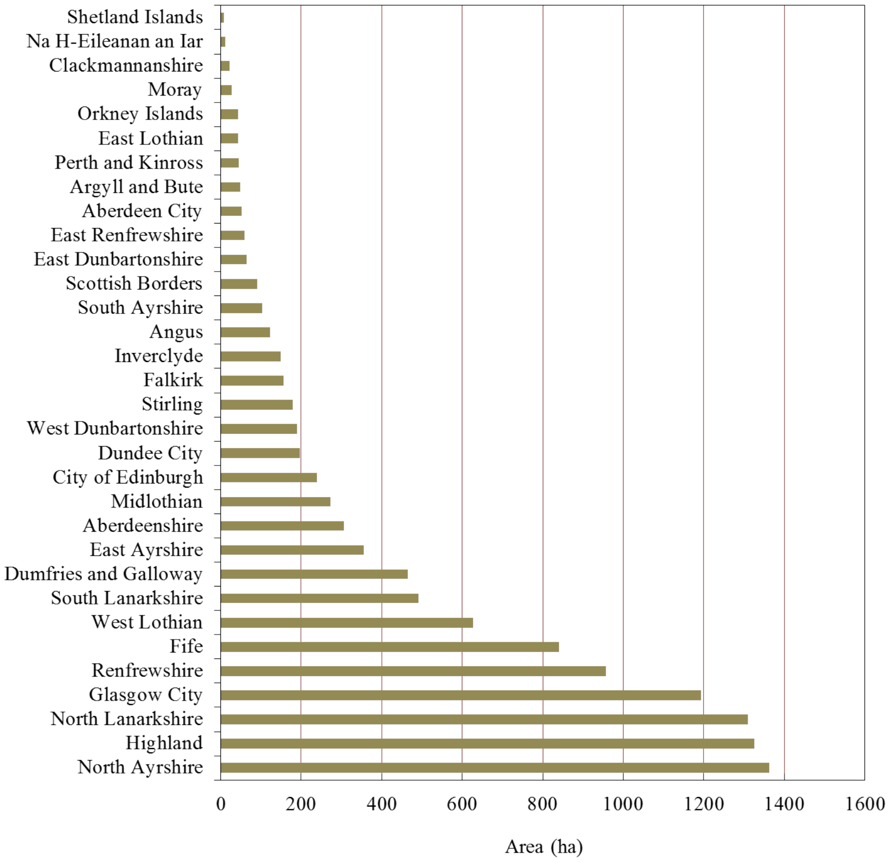


Figure 4.2: Total brownfield land area in each local authority - based on spatial database created in 2015 using the 2013 Scottish Vacant and Derelict Land Survey (Scottish Government, 2014)

region's past industrial development.

This large collective area of brownfield land located centrally is reflected when the site areas are aggregated into a hexagonal grid with 5 km side lengths (See Figure 4.4 and Appendix A.9 for alternative scale). The hexbinned mapping highlights the high density of brownfield land within the Central Belt, in addition to evident clusters in parts of Ayrshire and the East Coast of Scotland. The vacant and derelict land survey only covers vacant land in settlements with a population of over 2,000 and therefore much of the area of Scotland does not contain any brownfield land. This is reflected in the mapped output, with large areas in both the Highland and Scottish Borders local authorities containing no brownfield land.

Whilst the Scottish Vacant and Derelict Land Survey has been collecting data on the extent

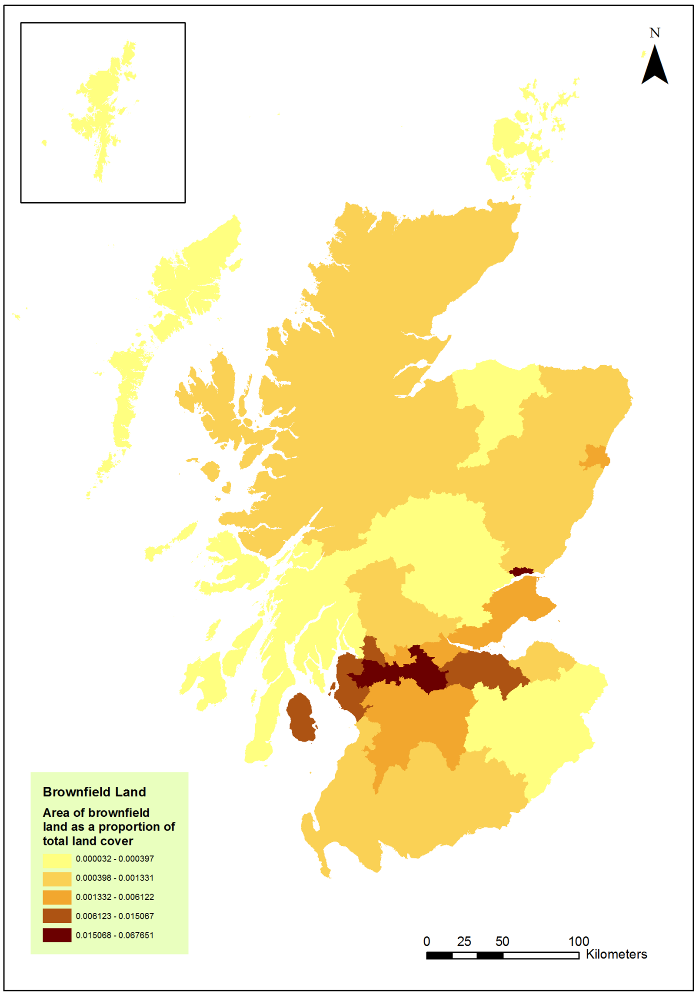


Figure 4.3: Area of brownfield land in Scotland as a proportion of total land cover in each local authority - based on spatial database created in 2015 using the 2013 Scottish Vacant and Derelict Land Survey (Scottish Government, 2014)

of vacant and derelict land in Scotland since 1988 (Scottish Government, 2016d), the spatial database compiled as part of this thesis represents the first attempt to capture a complete set of boundaries in GIS format. The spatial database created as part of this research has identified an additional 237 hectares to the 11,114 hectares reported in the survey (Scottish Government, 2014). More recently the survey has attempted to include some boundaries of sites from the local authorities that have mapped their vacant and derelict land resource (Scottish Government, 2016d). However, the report is only intended to give an initial indication of the amount of vacant and derelict land that exists and is understandably limited by the information that is relayed from each local authority which can become problematic. For

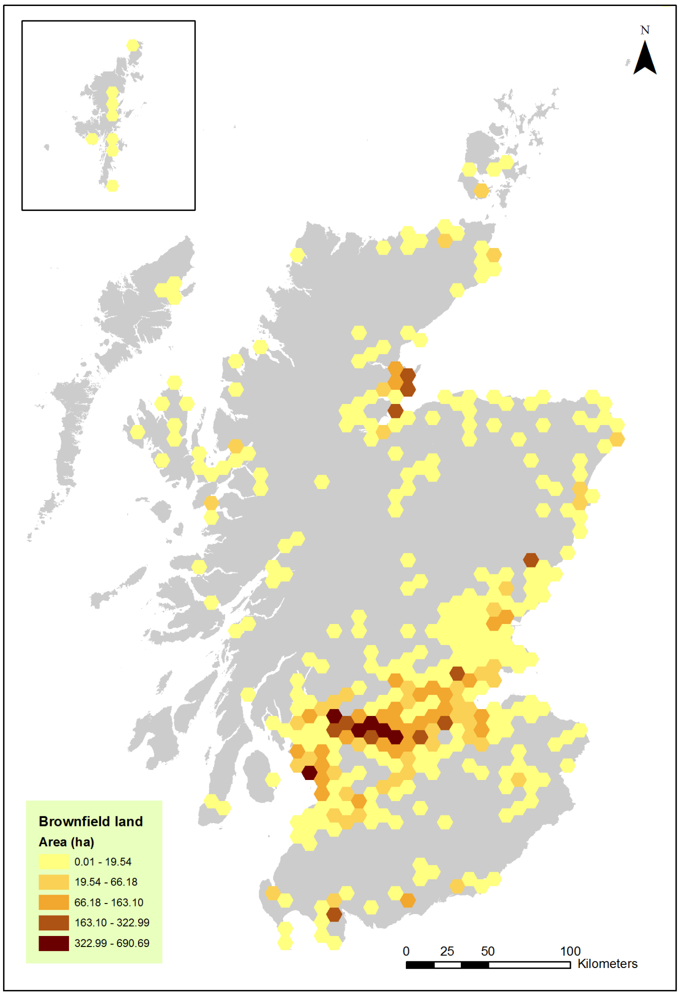


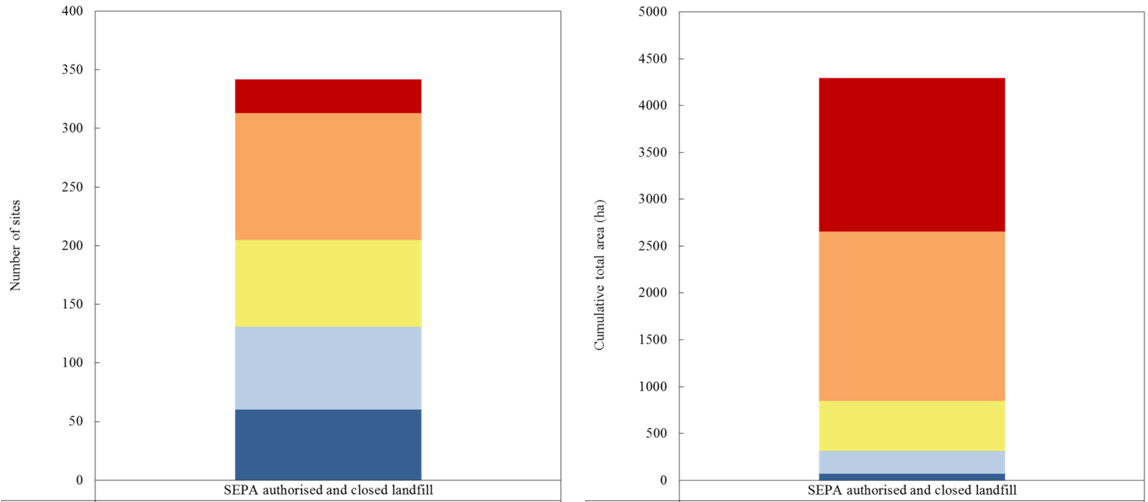
Figure 4.4: Total area of brownfield land in Scotland aggregated into a hexagonal grid with 5 km length sides - based on spatial database created in 2015 using the 2013 Scottish Vacant and Derelict Land Survey (Scottish Government, 2014)

instance, whilst compiling this spatial database it became apparent that all the areas for sites reported by the Loch Lomond and Trossachs planning authority were almost two and half times the size found once the site's boundary has been digitised via the methodology used in this research. This was presumed to be caused by the planning authority recording the site in acres, passing that figure on the Scottish Government Communities Analysis Division, and it being accidentally reported as the area in hectares in the survey (Scottish Government, 2014). The difficulties of compiling data from various sources were discussed already in sections 3.3.1 and 3.4.6, and this example is not intended to be a criticism of the survey. However, the advantage of amalgamating the data in the form of a spatial database is evident as the area of each site can be reported with greater confidence and therefore a more realistic indication of the extent of this land type can be given.

The survey does integrate information on the past use of sites as well as ownership and these attributes have not been integrated into this research. Another consideration, which became evident whilst compiling the spatial database, is the condition of the vacant and derelict land. An understanding of the levels of contamination or of building remains becomes increasingly necessary when the sites are linked to potential end uses such as bioenergy provision. The 2013 survey, which this database is based on, reports that 34% of the derelict land has some building remains and possible left-over chemicals/substances (Scottish Government, 2014) yet unfortunately no attribute information regarding the state of each site was included in the survey's database. Future work could incorporate site visits to gain a better understanding of the level of contamination or even use remote sensing techniques, such as those outline by Silvan-Cardenas et al. (2014), to give an indication as to the proportion of brownfield land that contain building remains.

4.2 The collective area of SEPA licensed landfill in Scotland

The methodology for capturing boundaries for both SEPA closed and authorised landfill sites, as outlined in section 3.4.2, involved the utilisation of the 'Landfill Sites and Capacities in Scotland' report (SEPA, 2013). Once the errors in the underlying database had been identified, See appendices A.2 and A.3, there remained 69 authorised and 273 closed landfill sites. The boundaries for both types of landfill were combined in a spatial database covering a total area of 4296 hectares. The site size analysis conducted highlights a greater range in site size amongst the SEPA landfill sites compared to the brownfield land database (see Figure 4.5), with over 60% of the landfill sites being over 5 hectares in size. These larger sites have an evident impact on the cumulative total of landfill area - with sites over 5 hectares composing over 80% of the total area found. Most of the sites under 5 hectares are classified as closed, with only 11 of the 69 authorised sites being this size. This reflects a move from small local tips to large rural landfill sites.



	SEPA authorised and closed landfill (number of sites)	SEPA authorised and closed landfill (cumulative total area, ha)
> 30 ha	29	1637
10 to < 30 ha	108	1813
5 to < 10 ha	74	533
2 to < 5 ha	71	241
< 2 ha	60	71

Figure 4.5: Site size analysis of land parcels compiled within the SEPA licensed landfill spatial database. Showing number of sites within each threshold on left and contribution to total area found on right - based on spatial database created in 2015 using SEPA report published in 2012 (SEPA, 2012)

The rurality of these sites compared to brownfield land is also mirrored in the breakdown of total area present in each local authority (Figure 4.6 and table in Appendix A.10). It is noticeable that Glasgow City and the City of Edinburgh feature much further down in terms of the ranking by the total amount of this land type within their bounds. Aberdeenshire contains the greatest amount of SEPA landfill with 517 hectares. Dundee City on the other hand contains only 3 hectares. The local authority totals suggest that in addition to high areas of landfill in central belt areas there are also high amounts in local authorities on the East Coast - with East Lothian, Fife and Angus all containing over 180 hectares each. This is also evident when visualising the area of SEPA landfill in each local authority as a proportion of the total land cover, as both East Lothian and Aberdeen City have a high density of this land type in addition to Falkirk, North Lanarkshire and Glasgow City (Figure 4.7).

The areas with a high density of SEPA landfill on the East Coast can be seen at a finer scale

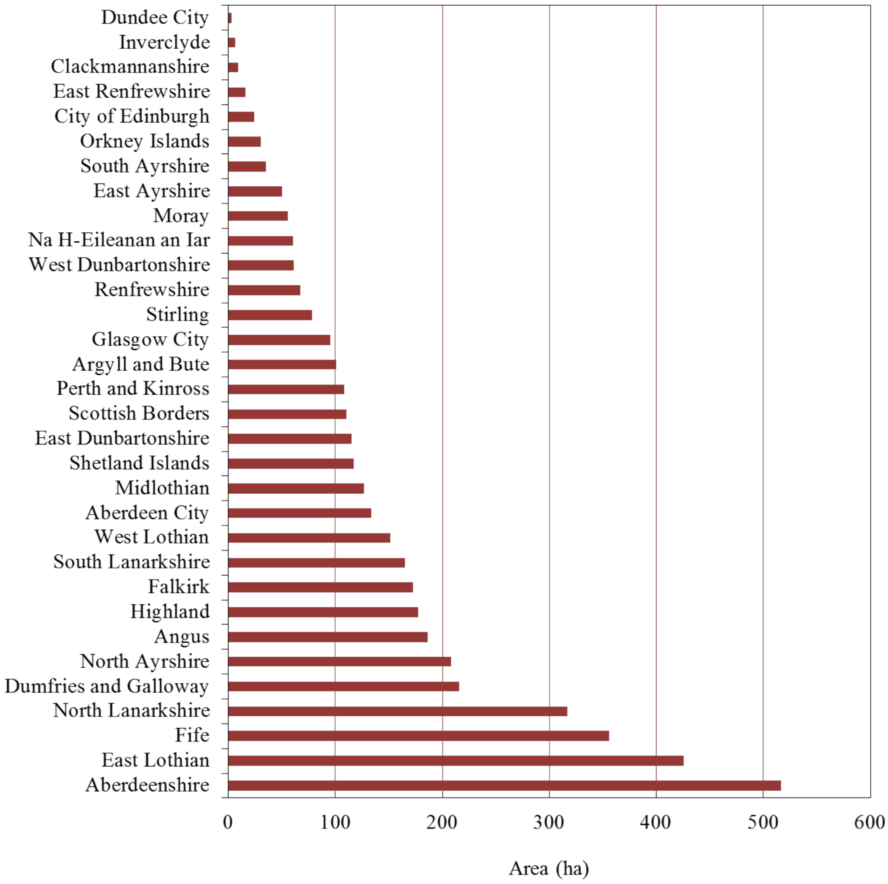


Figure 4.6: Total SEPA licensed landfill area in each local authority - based on spatial database created in 2015 using SEPA report published in 2012 (SEPA, 2012)

via the aggregation of the spatial database to the hexagonal grid (Figure 4.8, and Appendix A.11 for alternative scale). This visualisation highlights the particularly large cluster of this land type in Aberdeen City and the surrounding area. Furthermore, it is apparent that the distribution of SEPA landfill in the central belt is not continuous across the region but is in fact concentrated in several locations with the gaps between containing much less, or even none, of this land type.

The spatial database created as part of this thesis represents the first GIS boundary representation of licensed and closed landfill, as well as the first estimation of the area of this land type in Scotland - with the 'Landfill Sites and Capacities in Scotland' SEPA (2013) report only measuring size of site in terms of capacity. A site-specific approach was further

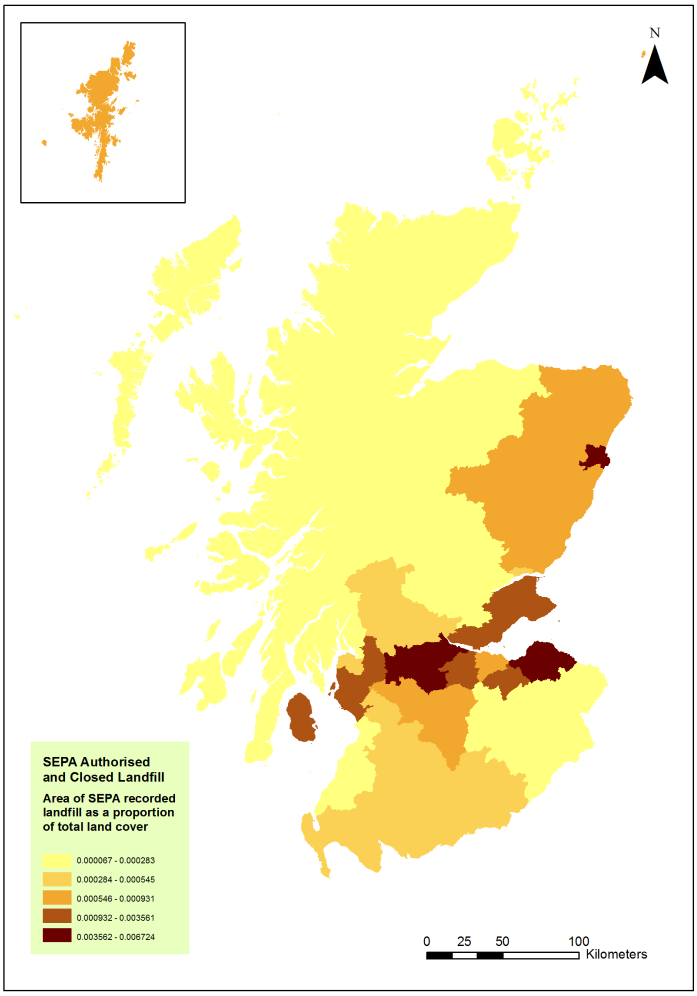


Figure 4.7: Area of SEPA authorised and closed landfill in Scotland as a proportion of total land cover in each local authority - based on spatial database created in 2015 using SEPA report published in 2012 (SEPA, 2012)

justified by the underlying errors identified in the database underpinning the original report. If areas were generated automatically, with an arbitrary buffer around sites based on the capacity, then the resulting estimation of area would be very inaccurate. Nevertheless, the digitisation methodology used here included a degree of uncertainty on occasions when the boundary is not clear and future work should consider attempting to find more information that could help locate the landfill site's limits. Finally, the totals reported for SEPA landfill in this thesis have included all of the currently authorised sites. This must be taken with the proviso that the Scottish Government are only expecting the closure of four out of five of all currently licensed landfill by 2025 (Scottish Government, 2010).

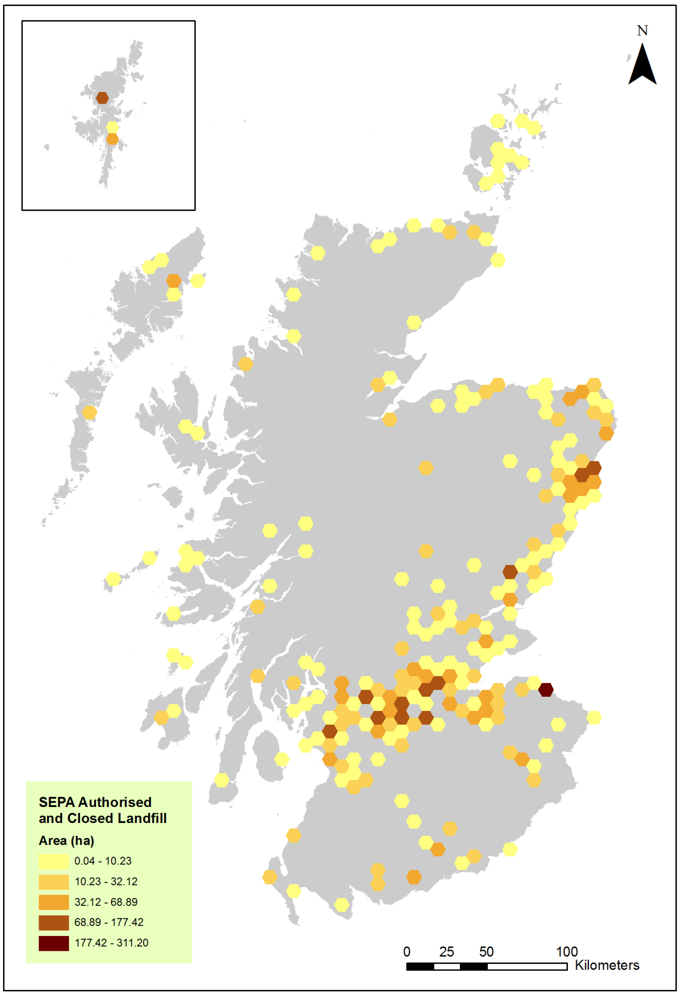
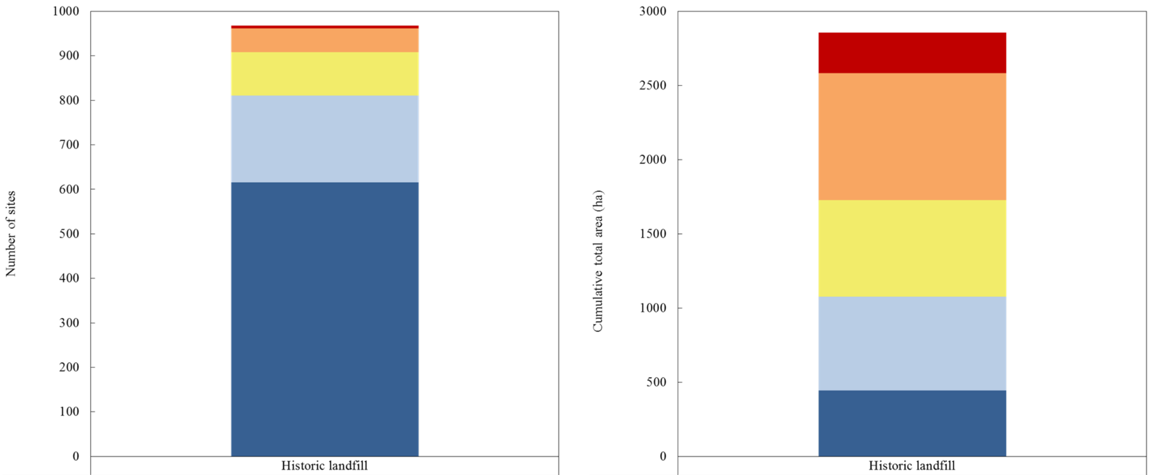


Figure 4.8: Total area of SEPA authorised and closed landfill in Scotland aggregated into a hexagonal grid with 5 km length sides - based on spatial database created in 2015 using SEPA report published in 2012 (SEPA, 2012)

4.3 The collective area of historic landfill in Scotland

The process of capturing boundaries representing historic landfill relied heavily on correspondence with local authorities. As explained in section 3.4.3, the responses varied greatly with 14 local authorities providing GIS data, 14 authorities providing a list of sites with attached locations and four authorities providing no information regarding historic landfill. The quality of the GIS datasets and the lists of sites were varied, ranging from local authorities including boundaries of all infilled ground in the GIS shapefile to anecdotal lists of sites with little information regarding location. From a meta-list containing over 1000 sites, a database of 968 identifiable sites was created. New boundaries needed to be captured for 202 of these sites. Ultimately a spatial database was created which contained 2859 hectares of historic landfill - a breakdown of the areas found in each Local Authority can be found in the table in Appendix A.12.



	Historic landfill (number of sites)	Historic landfill (cumulative total area, ha)
> 30 ha	6	274
10 to < 30 ha	54	856
5 to < 10 ha	97	651
2 to < 5 ha	195	633
< 2 ha	616	444

Figure 4.9: Site size analysis of land parcels compiled within the historic landfill spatial database. Showing number of sites within each threshold on left and contribution to total area found on right - based on spatial database created in 2016 using data collected 2015-2016

The site size analysis (Figure 4.9) highlights the difference in site characteristics between the SEPA licensed landfill sites and historic landfill sites. The historic landfill spatial database was composed of a much higher proportion of smaller sites, with over 60% of the land parcels covering less than 5 hectares. The contribution of different thresholds of site size to the overall total area found was more evenly spread than the previous land types. No sites were recorded in the local authorities of the City of Edinburgh, the Western Isles, North Ayrshire and the Shetland Isles. However, the site information for historic landfill within these authorities may have been passed on to SEPA on the creation of the first capacity report containing closed

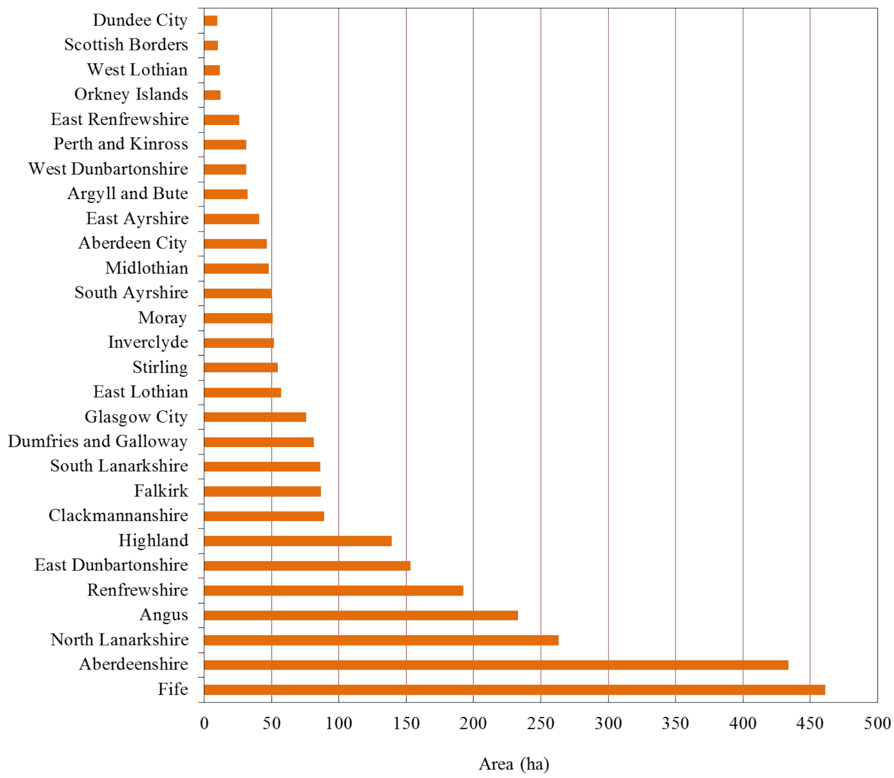


Figure 4.10: Total historic landfill area in each local authority - based on spatial database created in 2016 using data collected 2015-2016

landfill. Alternatively, the historic landfill in these local authorities may have been recorded in the respective vacant and derelict land survey and therefore may no longer be recorded separately - this would explain the high value reported for the quantity of brownfield land in North Ayrshire compared to the non-existence of any historic landfill.

Fife and Aberdeenshire local authorities had the highest area of historic landfill recorded, with 461 hectares and 434 hectares respectively (see Figure 4.10). The local authority with the next highest historic landfill area is North Lanarkshire with 263 hectares. This significant gap between the top two authorities and the remaining councils may be due to the disparity in efforts of each organisation to document past landfill sites. As discussed in section 3.4.3, the approach taken to record landfill sites by each local authority was determined by their interpretation of UK contaminated land legislation. Therefore, whilst the high quantity of land identified in Fife and Aberdeenshire is significant, it may also reflect the increased effort

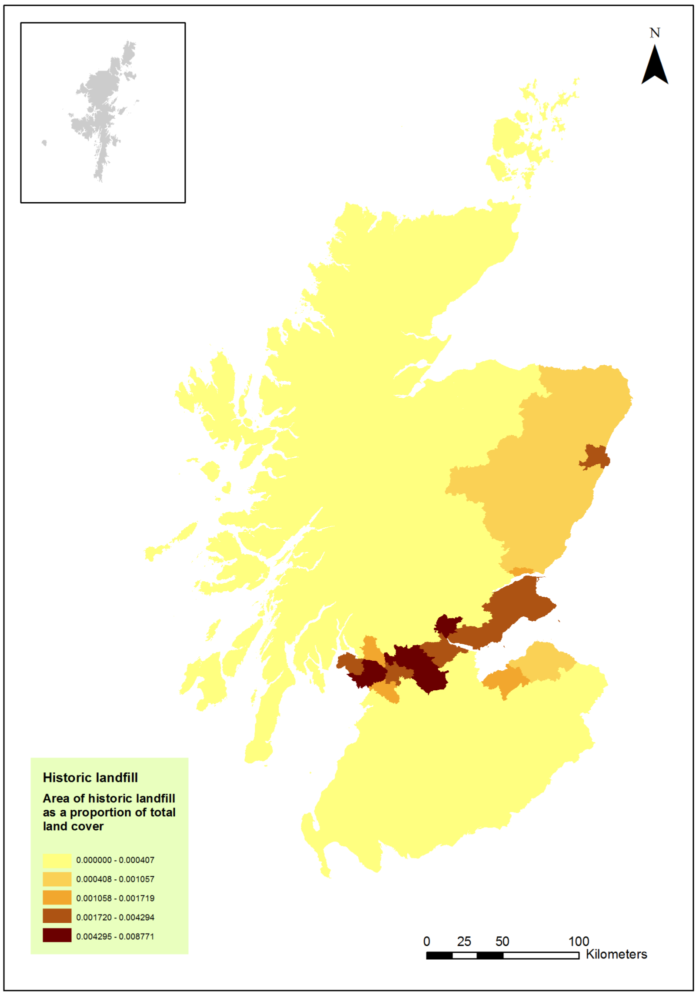


Figure 4.11: Area of historic landfill in Scotland as a proportion of total land cover in each local authority - based on spatial database created in 2016 using data collected 2015-2016

taken to record historic landfill in these regions, or conversely the lesser attempts made by other local authorities.

By visualising the historic landfill area as a proportion of total land cover in each local authority (Figure 4.11), and once again aggregating the area to the hexagonal grid (Figure 4.12 and Appendix A.13 for alternative scale), it becomes apparent that the distribution of this land type follows similar patterns identified within the brownfield and SEPA licensed landfill datasets. There is a high density of historic landfill in local authorities throughout the central belt, which is to be expected given the history of industrial development and mining in this region. There are also pockets with a high density of this land type in Fife and to the North of the East Coast, which is even more apparent on the hex-binned maps in the areas surrounding Dundee and Aberdeen.

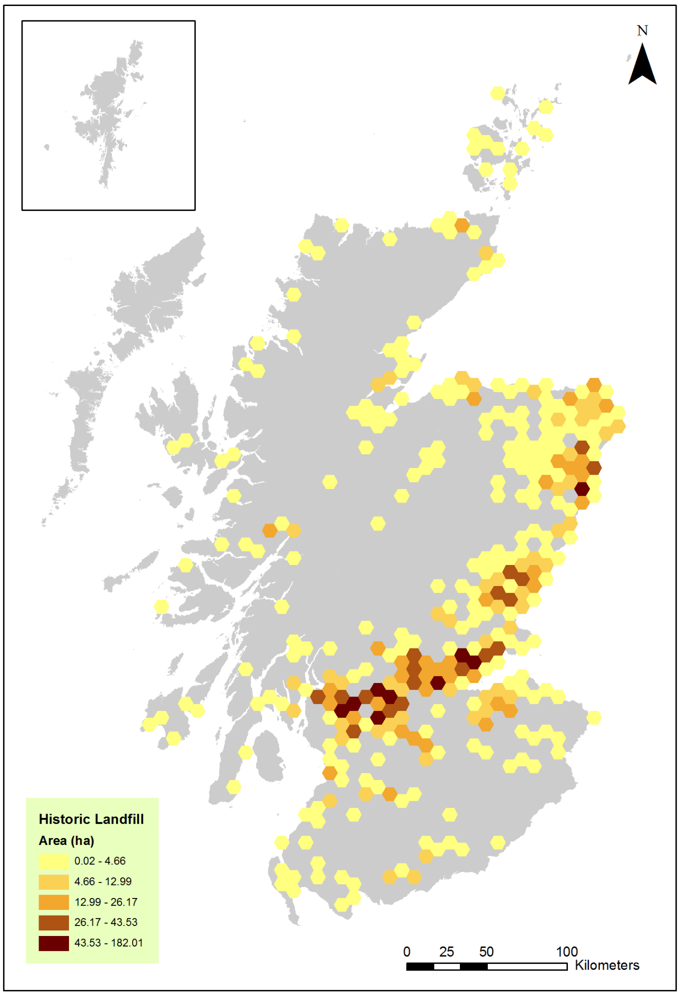


Figure 4.12: Total area of historic landfill aggregated into a hexagonal grid with 5 km length sides - based on spatial database created in 2016 using data collected 2015-2016

This is the first-time data on historic landfill has been collated, with the spatial database identifying an additional 2859 hectares of underutilised non-agricultural land. The process of creating this database has highlighted the difficulty of combining data from various sources, especially when both the conception of the entity being measured and the method used to record information varied so drastically amongst authorities. Future work could seek to provide clearer guidelines to each data provider regarding the land that they are seeking to identify, and more time would enable alternative sources of data to be identified.

4.4 An initial insight into the collective area of abandoned mine land in Scotland

The additional investigation of abandoned mine land was prompted by the liquidation of Scottish Coal and ATH resources in 2013 which affected sites in East Ayrshire, Fife and South Lanarkshire. This in turn led to the inclusion of some portions of former surface coal mines within the Scottish Vacant and Derelict Land Survey (Scottish Government, 2016d). However, only sites in East Ayrshire, where the restoration bonds were deemed insufficient, were considered and of these sites only areas that were unsafe or requiring remediation were included in the survey. This has resulted in large areas of unworked or naturalised parcels of land at the former surface coal sites being completely excluded from the vacant and derelict land survey. For the purpose of this thesis, sites in all three local authorities have been included regardless of the current restoration bond in place. However, using the methodology outlined in section 3.4.4, areas that were deemed completely restored were excluded. Ultimately this still left a large proportion of the 15 sites with the resulting spatial database containing 6523 hectares. The majority of this total was located within the East Ayrshire local authority (See Figure 4.13). In total East Ayrshire had 4853 hectares of abandoned mine land covering 3.8% of the local authority area. Whilst Fife and South Lanarkshire have much less, with 466 hectares (covering 0.4% of the local authority) and 1204 hectares (0.7%) respectively, this is still a large amount of additional underutilised non-agricultural land resource in each region.

Abandoned mine land provides a large land area, located within close proximity of Scotland's central belt (see Figure 4.14). Whilst the provision of abandoned mine land has been investigated in the past with regard to its potential as a bioenergy resource (Niblick and

Figure 4.13: Total abandoned mine land area in each local authority - based on a spatial database created in 2016 using data collected in 2016

Landis, 2016), this thesis has taken further steps to assess locations on a site-by-site basis in terms of their includability with emphasis being given to the consideration as to whether land is underutilised or not. Nevertheless, the total amount of this land type identified must be viewed with caution. The judgement of which portion of a site to include based on the level of restoration is largely subjective. The 6523 hectares identified as part of this thesis should be viewed only as a primary indication of the resource that may exist, as it only covers the sites impacted by the liquidation of Scottish Coal and ATH resources and, in the case of sites in East Ayrshire and South Lanarkshire, only included area within the location plans provided by the local authority. The process of digitisation highlighted the existence of a significant amount of seemingly underutilised non-agricultural land in close proximity to these sites. Future work could incorporate ground truthing studies to verify both the proportion of the abandoned mine land that is unrestored and also the includability of surrounding semi-restored area as an underutilised non-agricultural resource.

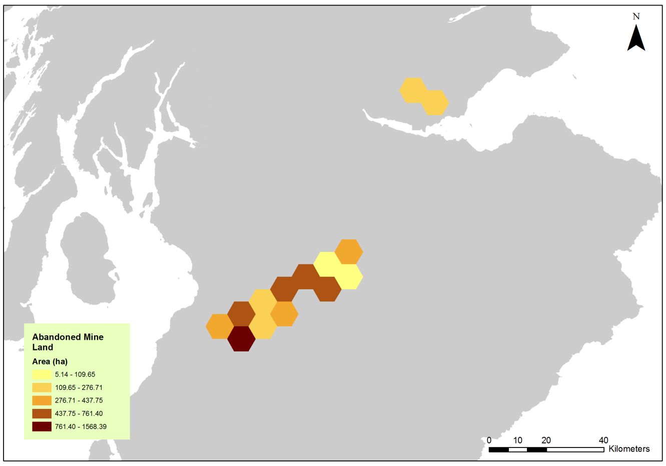


Figure 4.14: Total area of abandoned mine land in Scotland aggregated into a hexagonal grid with 5 km length sides - based on a spatial database created in 2016 using data collected in 2016

4.5 The combined theoretical landbank in Scotland

The spatial databases representing brownfield land, SEPA licensed landfill, historic landfill, and abandoned mine land were combined to form a new geodatabase representing the theoretical landbank - using the methodology outlined in section 3.4.5. The creation of a spatial database to represent brownfield land, based on the vacant and derelict land survey has resulted in the identification of 11,351 hectares of land (see Figure 4.15). In addition to this SEPA licensed landfills have been discovered to cover 4296 hectares, with historic landfill covering a further 2859 hectares. Finally, the initial investigation into abandoned mine land has found 6523 hectares of underutilised non-agricultural land spread across only three local authorities.

The methodology used to combine the datasets was designed to ensure that no land areas were double counted in the final total reported as the theoretical landbank. Once these steps were taken to reduce overlap, and the datasets were merged into one spatial database, the total amount of underutilised non-agricultural land representing the theoretical landbank was 24, 862 hectares. This is notably over double the amount of vacant and derelict land reported in the vacant and derelict land survey, previously the best indicator of the level of underutilised non-agricultural land. The theoretical landbank represents 0.32% of the total

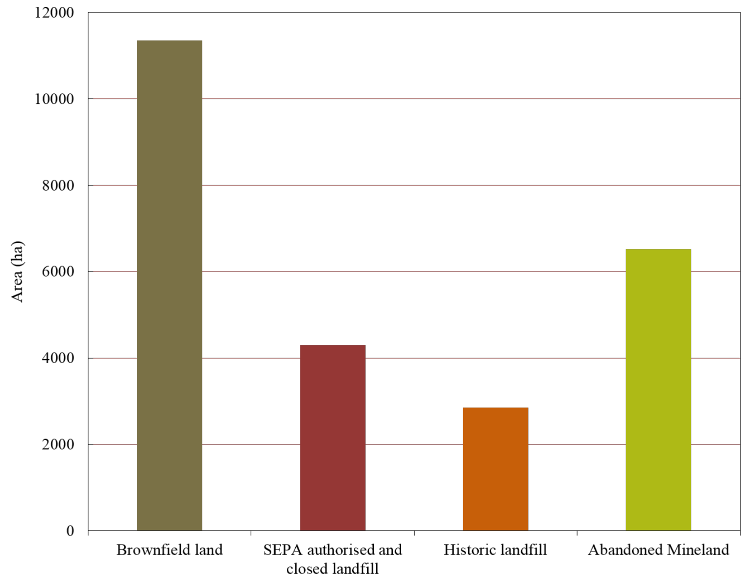


Figure 4.15: Total area identified for each underutilised non-agricultural land type - using data from 2013-16 compiled in 2016

land area of Scotland. A breakdown of the total in each local authority can be found in table 4.1.

The local authority with the highest proportion of theoretical landbank is East Ayrshire, with 5,292 hectares (see Figure 4.16), however this is largely due to the large contribution made by the abandoned mine land in this region (see Figure 4.17). The local authorities of Fife and North Lanarkshire appear to have the largest quantity of underutilised non-agricultural land if the abandoned mine land was temporarily not considered (see Figure 4.17). Conversely, the local authorities with the lowest proportion of theoretical landbank are the relatively remote regions of the Western Isles and Orkney Islands with both regions containing less than 100 hectares. The hex-binned mapping (Figure 4.18 and Appendix A.15 for alternate scale) shows the national distribution of the landbank, clearly highlighting the high density of land within the central belt region in addition to high levels of landbank South of Glasgow - presumably the influence of the high quantity of abandoned mine land in East Ayrshire and South Lanarkshire. The results show the tendency for the highest proportion of the landbank to be in regions with a history of industry and mining activities. On the other hand, it suggests the important role this land type could play in future given its proximity

Table 4.1: Total theoretical landbank area in each local authority - using spatial database containing data from 2013 - 2016 compiled in 2016

Local authority	Sum of theoretical landbank area (ha)
Aberdeen City	232
Aberdeenshire	1256
Angus	541
Argyll and Bute	181
City of Edinburgh	263
Clackmannanshire	120
Dumfries and Galloway	761
Dundee City	210
East Ayrshire	5292
East Dunbartonshire	337
East Lothian	527
East Renfrewshire	101
Falkirk	416
Fife	2123
Glasgow City	1364
Highland	1642
Inverclyde	207
Midlothian	382
Moray	133
Na H-Eileanan an Iar	71
North Ayrshire	1568
North Lanarkshire	1844
Orkney Islands	86
Perth and Kinross	182
Renfrewshire	1204
Scottish Borders	212
Shetland Islands	126
South Ayrshire	188
South Lanarkshire	1945
Stirling	312
West Dunbartonshire	278
West Lothian	761

to populated areas. The analysis in the following chapter 5 will focus further on the role of this land for bioenergy provision. Evidently, the situation of the landbank means sites could alternatively be considered for several end uses in relation to nearby populated areas, including greenspace or housing provision.

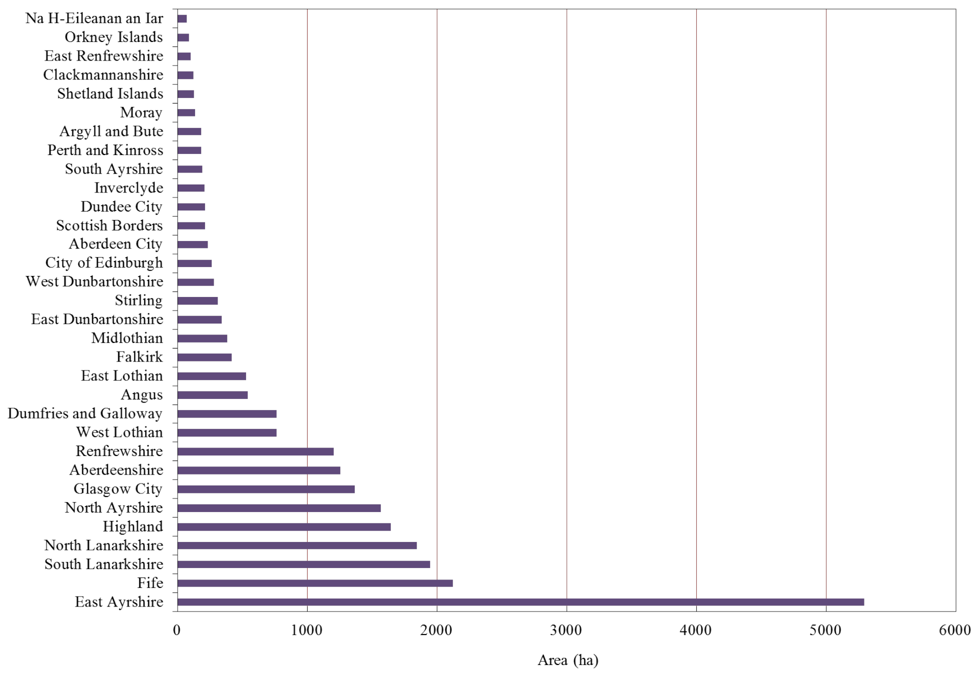


Figure 4.16: Total theoretical landbank area in each local authority - using data from 2013-16 compiled in 2016

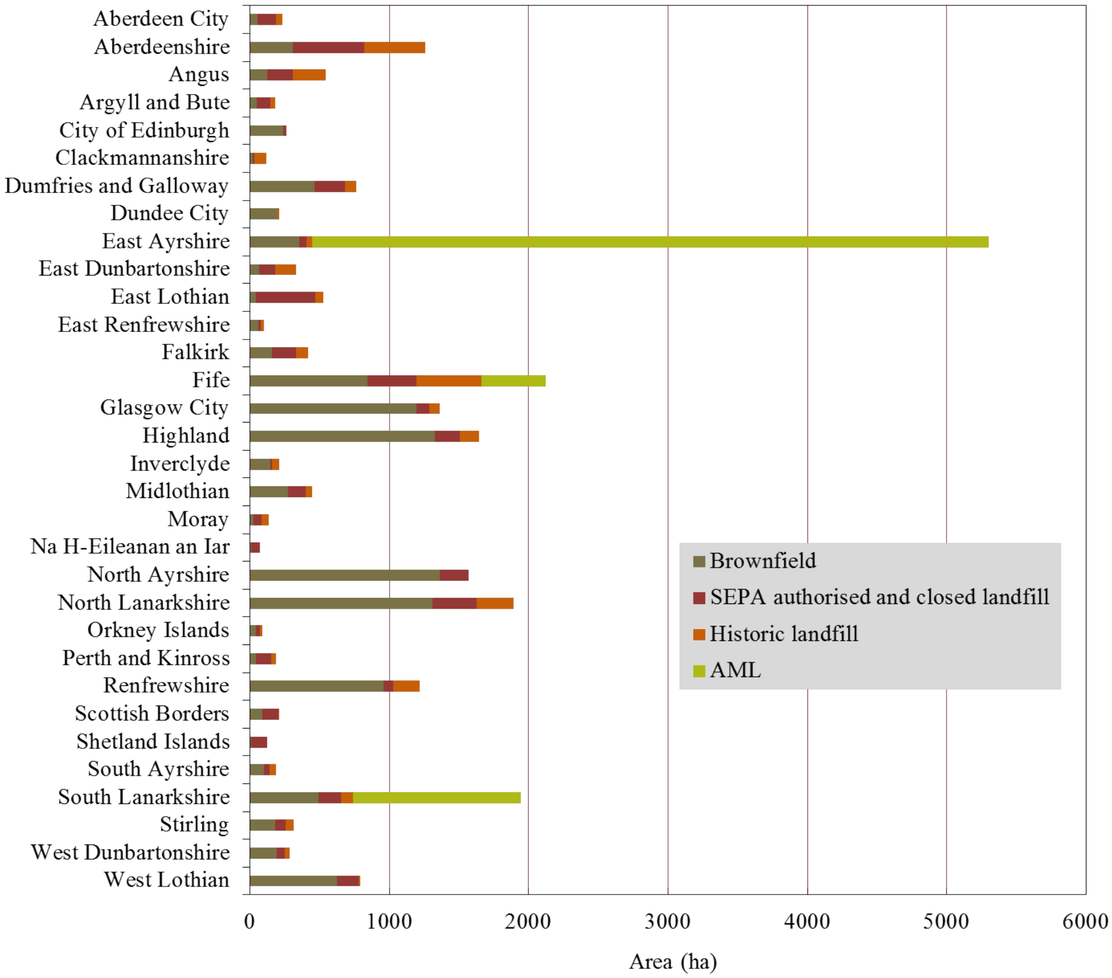


Figure 4.17: Proportion of each underutilised non-agricultural land type in each local authority - using data from 2013-16 compiled in 2016

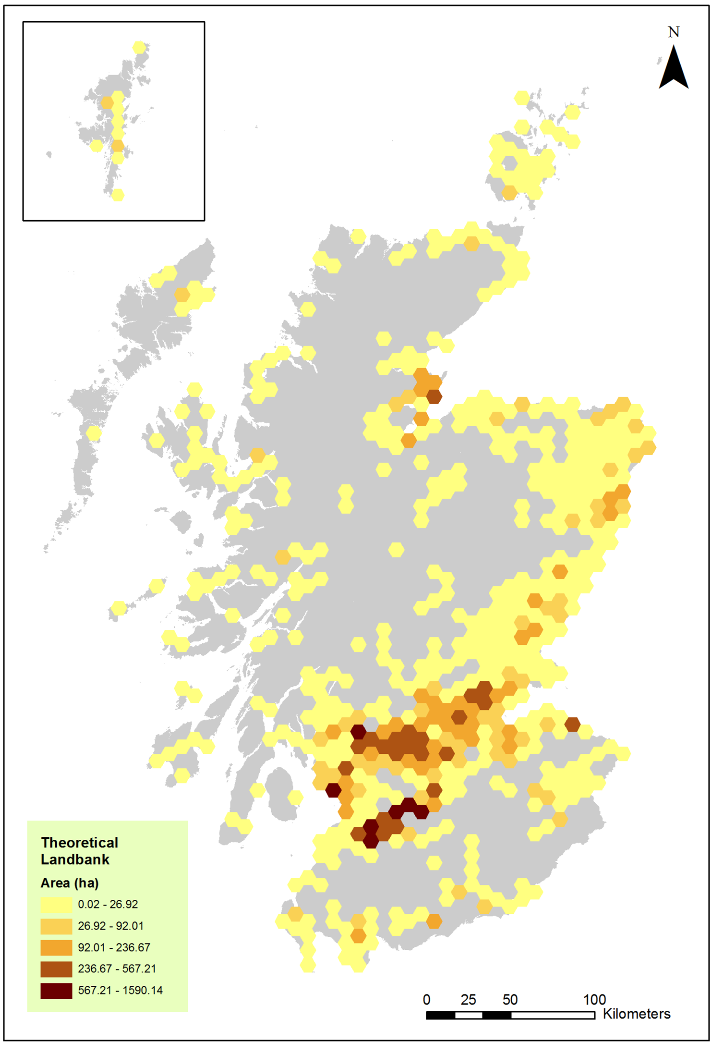


Figure 4.18: Total area of theoretical landbank in Scotland aggregated into a hexagonal grid with 5 km length sides - using data from 2013-16 compiled in 2016

4.6 Exploratory spatial data analysis to assess the distribution of theoretical landbank

Having created the spatial database representing the theoretical landbank, further exploratory spatial data analysis techniques were used to further an understanding of the distribution of the land resource in Scotland. As outlined in section 3.6.1, the first of these techniques was a kernel density estimation to try and locate hotspots of land. Leading on from this in chapter 6, the relationship between the landbank and deprivation are evaluated utilising the Scottish Government's SIMD dataset (Scottish Government, 2016b) and the methodology detailed in section 3.6.2.1.

4.6.1 Kernel density estimation

The kernel density estimation layer (Figure 4.19) was produced using points representing the location of sites in the theoretical landbank, and the size of each site was input as the population field so that larger sites are weighted heavier during the calculation of the surface. The output map (Figure 4.18) reiterates the distribution of the land resource as predominately located along the central belt of Scotland, with another band further South and some further clusters visible along the East Coast. Once again, the influence of abandoned mine land can be seen on the surface with a clear band of land across East Ayrshire and South Lanarkshire. Within this surface, it is possible to identify small, localised clusters with a higher density of landbank. This output could help target local authority's future actions by highlighting hotspots of underutilised land resource. In contrast, viewing the kernel density surface created using only the site locations (see Appendix A.16) highlights the high number of small sites in and around urban areas of Glasgow, Edinburgh, Dundee and Aberdeen - whilst also negating the influence of the few larger sites in East Ayrshire. Both density surfaces highlight key areas where further research could be conducted to understand ways this landbank could be utilised.

Some care is required when interpreting the results of the kernel density estimation. The kernel density output is a continuous surface and cells between sites are assigned a value even if

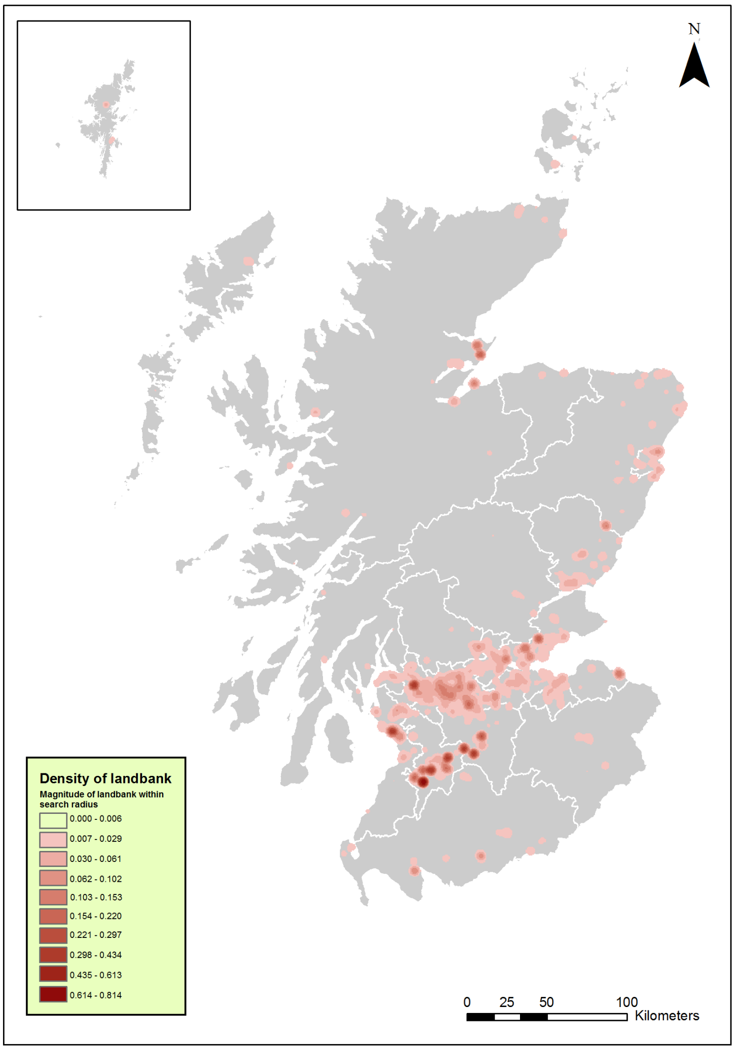


Figure 4.19: Kernel density estimation representing the density of the theoretical landbank in Scotland - using data from 2013-16 compiled in 2016

no land exists in that location. This means that the results should only be used as an indicator of hot-spots, and any future work using such a surface should calculate the cumulative area of land that is within the bounds of identified clusters. Nevertheless, the kernel density surface provides a strong visual indicator of the distribution of the theoretical landbank.

4.7 Summary of findings

This chapter has presented the spatial database representing the theoretical landbank. This is the first time an attempt has been made to create a detailed spatial database combining boundaries of these types of underutilised non-agricultural land. The creation of the spatial database representing brownfield land marks the first time a complete set of boundaries have been mapped out at a national scale for this land type. Furthermore, the inclusion and subsequent effort to create boundaries for the SEPA licensed landfill is the first time in Scotland that the size of these sites has been estimated in terms of area rather than capacity. The additional research undertaken to try and discover the extent of historic landfill, pre-SEPA licensing, has revealed an additional land resource - the spatial extent of which had not previously been considered, especially at this scale. The inclusion of abandoned mine land has highlighted several sites which provide a large additional area of underutilised non-agricultural land. The research has also presented an insight into size of sites for each land type, as well as the spatial distribution of each resource. It is possible that an even greater area of this land type could be available, given some missing responses, and therefore this initial total could be considered a minimum estimate.

The spatial database has identified 24,862 hectares of underutilised land, a resource that could be used without any impact on the availability of agricultural land. The bottom-up site based methodology used could be replicated in different settings, with the steps used to identify land types and compile a detailed national spatial database outlined in chapter 3. The theoretical landbank representes a unique insight into a previously overlooked land resource. Attitudes towards this land resource are shifting, and to fully understand the role it can play in the future a detailed understanding of its quantity and distribution is required.

This land has been identified with a focus on providing sustainable bioenergy, and in doing so has identified a theoretical landbank that could be more realistically implemented for renewable energy provision than the total area found in national studies that consider all land, including agricultural land, or ambiguously defined ‘marginal’ land. However, the landbank provides a useful resource for further investigating the opportunity provided by underutilised non-agricultural land, regardless of the intended end use, as discussed in more detail in chapter 6. The following chapter will further explore the opportunity that could be provided by this land type for bioenergy provision via a multicriteria evaluation to identify the technical landbank.

Chapter 5

Assessing the potential of Scottish underutilised non-agricultural land: Identifying the technical landbank avaliable for bioenergy provision

In the previous chapter the total area of underutilised non-agricultural land in Scotland, the theoretical landbank, was identified. This chapter will explore further the opportunity this land type could provide in terms of sustainable bioenergy provision. The technical landbank is the total amount of the identified underutilised non-agricultural land that could be utilised for bioenergy provision once a number of technical constraints are applied. A summary of these spatial constraints and the impact they had on the availability of land is discussed in section 5.1. Following this, in section 5.2, the cumulative area and an initial insight into the distribution of the technical landbank that resulted from the multi-criteria evaluation are presented. Finally, section 5.3 will outline the results of the further exploratory spatial data analysis with section 5.3.1 presenting a further insight into the spatial characteristics of the landbank. The results of the multicriteria evaluation will contribute to the following research question:

- What are the potential applications for a landbank representing underutilised non-agricultural land?

It is also hoped that the identification of the technical landbank, and the further work undertaken using this spatial database in section 6.1, will contribute the overall aim of this thesis in highlighting the opportunity this land resource may provide.

5.1 Application of land constraints via a multicriteria evaluation to identify the technical landbank

As explained in section 3.5, the best method for combining multiple constraints is via a multicriteria evaluation which selects suitable land based on its possession of a selection of attributes. The multicriteria evaluation conducted in this research can be broken down into two stages (see Figure 3.22). Firstly, parcels of land from the theoretical landbank that are within 500m of a main road were selected - using the methodology outlined in section 3.5.1.3. In order to make this selection a buffer polygon was created around the A and B roads taken from the Ordnance Survey Open Roads dataset (see Figure 5.1). This selection resulted in the exclusion of 5271 hectares worth of the theoretical landbank. Following this selection, a raster calculation was implemented to apply the remaining constraints. This calculation combined three raster layers. The first layer was the theoretical landbank within 500m of an A or B road, which had been converted into raster format. The second layer inputted into the calculation was a raster layer representing land with no slope over 15%. As explained in section 3.5.1.1, this layer was a reclassification of the slope layer (Figure 5.2) which was in turn calculated using a digital terrain model obtained from Ordnance Survey. Finally, a raster layer containing the 3,219,025 hectares covered by protected areas in Scotland was also input into the raster calculator (Figure 5.3). The output of the raster calculation was converted to vector format and the parcels of land under 0.1 hectare were removed, leading to the final removal of a further 47 hectares, leaving the resulting layer representing the technical landbank. A justification for the constraints used are outlined in section 3.5.1.

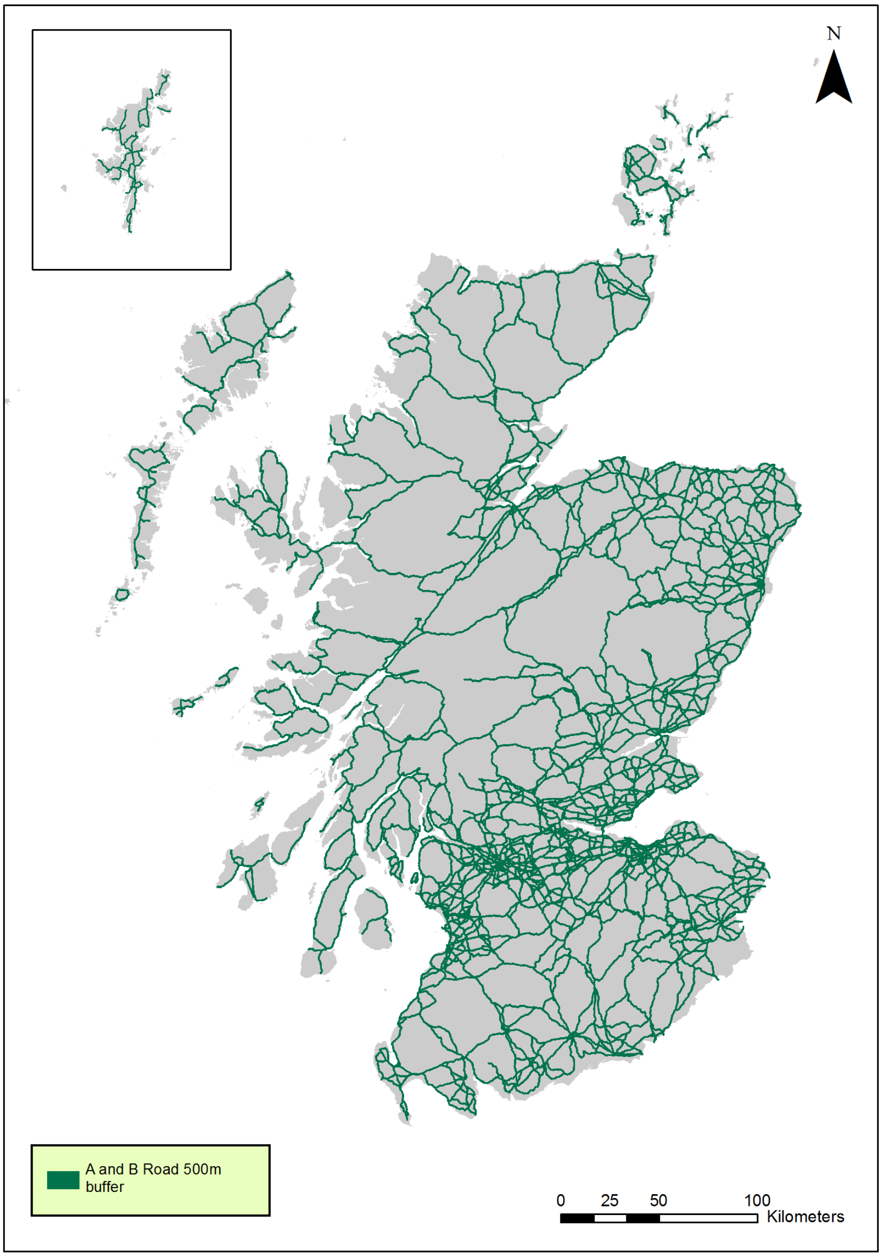


Figure 5.1: Constraint map representing the A and B roads in Scotland with a 500m buffer - created using Ordnance Survey Open Roads reported in 2015 (EDINA, 2017)

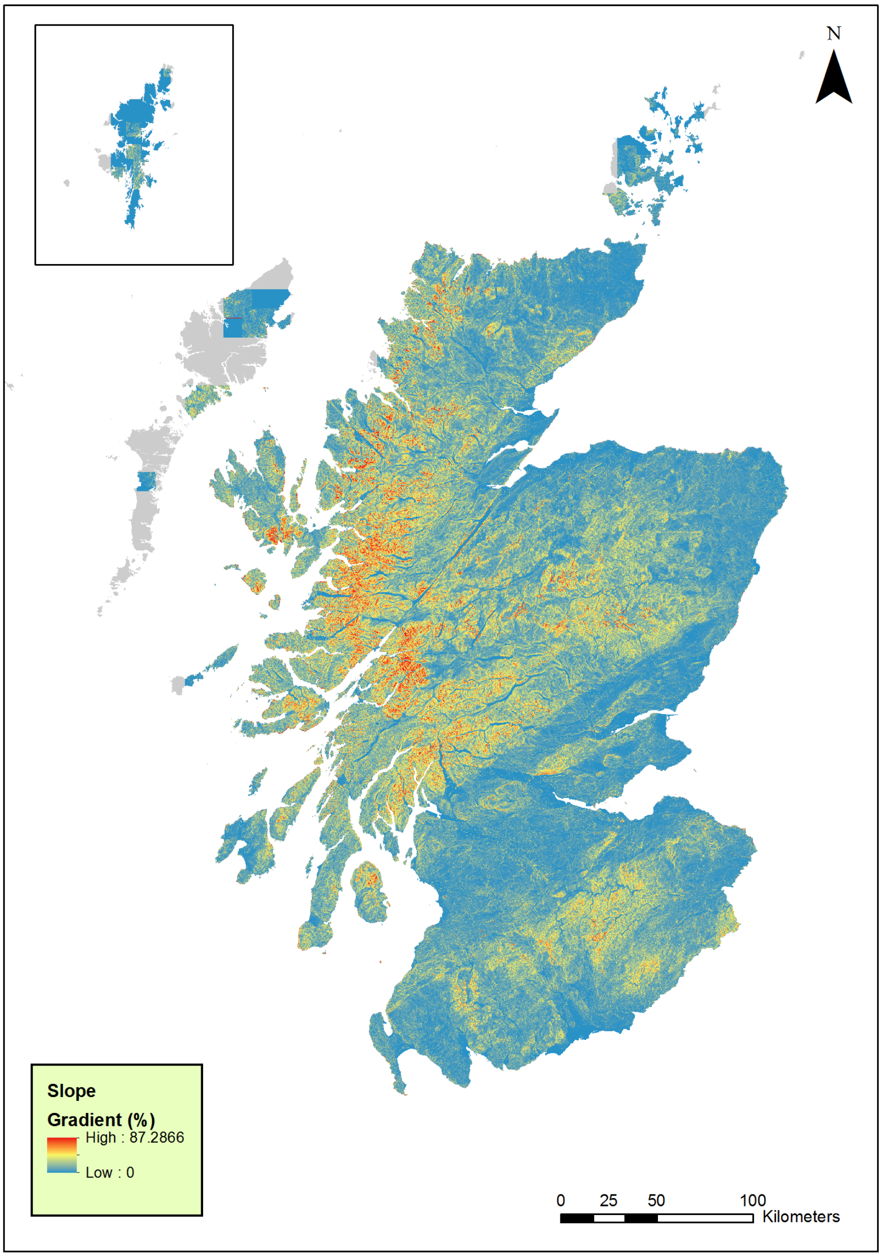


Figure 5.2: Constraint map representing the percentage slope in Scotland - created using Ordnance Survey Terrain 5 DTM reported in 2013 (EDINA, 2017)

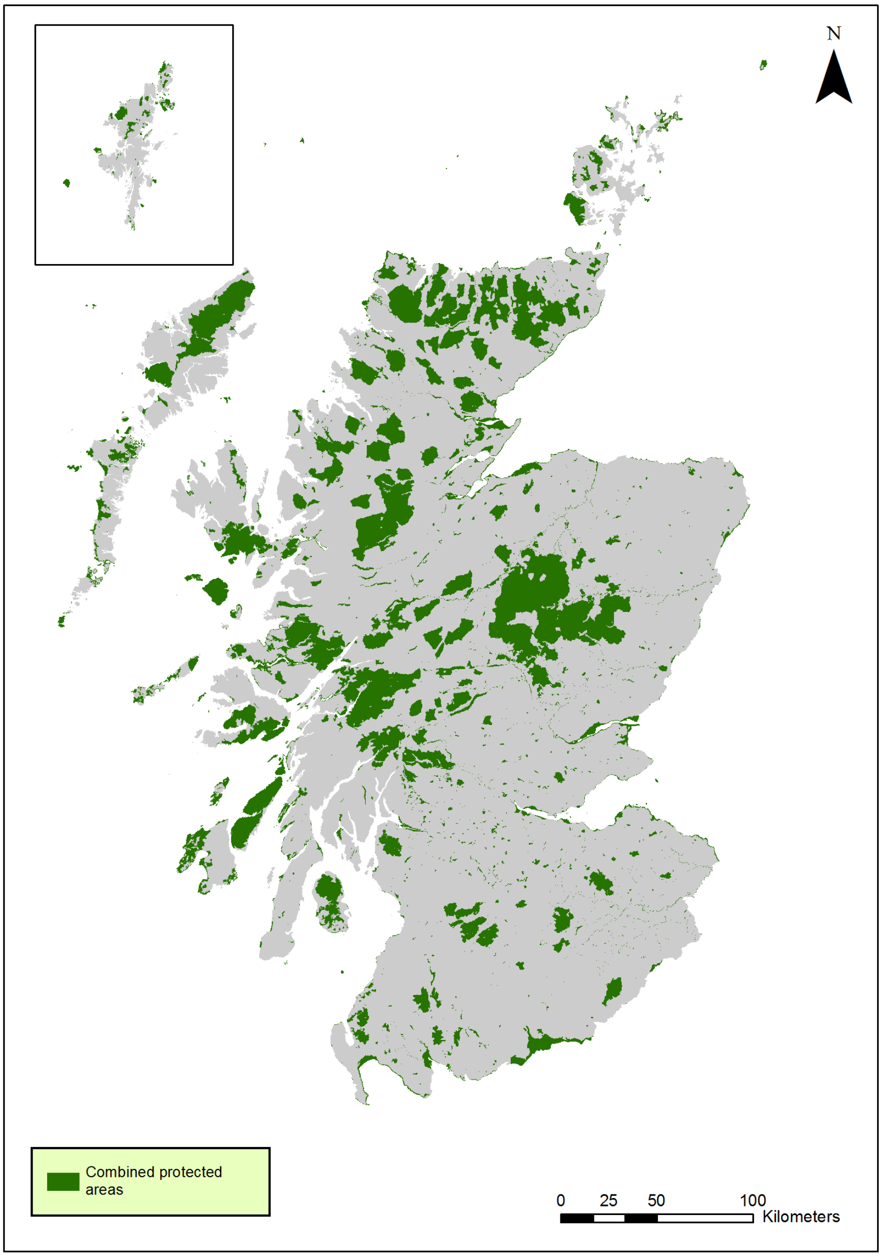


Figure 5.3: Constraint map representing the protected areas in Scotland created using protected area datasets from Scottish Natural Heritage (SNH, 2017) - all reported in 2015 except RAMSARs that were reported in 2005

5.2 The cumulative area and distribution of the technical landbank in Scotland

The result of the multicriteria evaluation was a new spatial database representing the technical landbank. The database contains 17,404 hectares of underutilised non-agricultural land that could be suitable for bioenergy provision. This equates to 0.22% of the total land area of Scotland. The local authority with the greatest amount of technical landbank is East Ayrshire with 3850 hectares (see Figure 5.4 and table 5.1). Once again this is likely due to the influence abandoned mine land has on the total amount of underutilised non-agricultural land in the area. Unsurprisingly mirroring the results for the theoretical landbank, the local authorities of Fife and North Lanarkshire have the second and third highest amount of technical landbank. These two local authorities, along with Glasgow City, North Ayrshire, Renfrewshire and South Lanarkshire contain over 1000 hectares of technical landbank. The more remote local authorities of the Orkney Islands, Shetland Islands and Western Isles have the least amount of technical landbank and along with Clackmannanshire, East Renfrewshire, Moray and Perth and Kinross contain less than 100 hectares. The impact of the application of the constraints on the amount of landbank within each local authority can be seen best when the percent decrease in available area are compared (see Figure 5.5). The impact of rugged landscapes in Shetland Islands and Western Isles is reflected in these being the local authorities with the largest percent decrease in available landbank. A decrease of 50% or over in available land was also identified in the Highland and Perth and Kinross regions.

By looking at the amount of technical landbank in each local authority as a proportion of the total land cover (see Figure 5.6), the high density of landbank in the central belt is once again highlighted. More dense areas of landbank can be seen to the West of Central Scotland, with East Ayrshire and the areas surrounding the City of Glasgow appearing to contain a high density of technical landbank. The hex-binned mapping (see Figure 5.7) illustrates the national distribution of the landbank further highlighting the high levels of this land resource in the area surrounding Glasgow and emphasising the cluster of landbank in East Ayrshire.

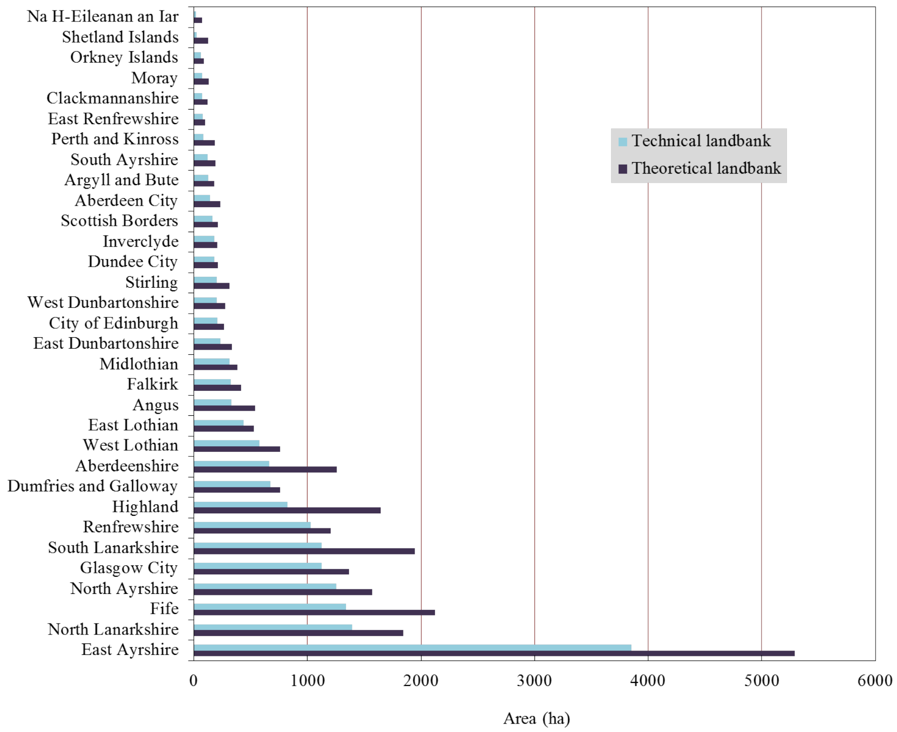


Figure 5.4: Total technical landbank area compared to the total theoretical landbank found in each local authority - based on spatial database created in 2017

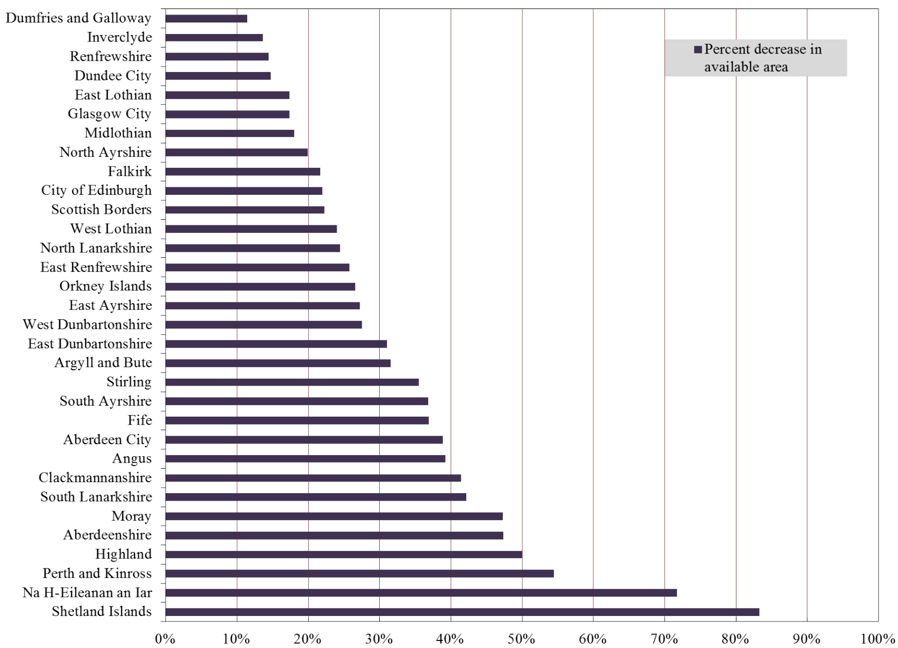


Figure 5.5: Percentage decrease in available landbank found in each local authority as a result of the application of constraints - based on spatial database created in 2017

Table 5.1: Total technical landbank area found in each local authority - based on spatial database created in 2017

Local authority	Sum of technical landbank area (ha)
Aberdeen City	142
Aberdeenshire	661
Angus	328
Argyll and Bute	124
City of Edinburgh	205
Clackmannanshire	70
Dumfries and Galloway	674
Dundee City	179
East Ayrshire	3850
East Dunbartonshire	233
East Lothian	435
East Renfrewshire	75
Falkirk	326
Fife	1340
Glasgow City	1127
Highland	821
Inverclyde	179
Midlothian	313
Moray	70
Na H-Eileanan an Iar	20
North Ayrshire	1255
North Lanarkshire	1392
Orkney Islands	63
Perth and Kinross	83
Renfrewshire	1030
Scottish Borders	165
Shetland Islands	21
South Ayrshire	119
South Lanarkshire	1125
Stirling	201
West Dunbartonshire	201
West Lothian	578

Interestingly, when comparing this map to the same produced for the theoretical landbank (see Figure 4.18), there is a clear decrease in landbank is some areas to the East of the central belt and the East Coast of Scotland.

When compared to other national studies that examine the availability of land for perennial energy crops in Scotland 17,404 hectares may not seem a large total. However, studies such as Andersen et al. (2005) and Lovett et al. (2014), who identify 1.96 Mha and 1.44 Mha in Scotland respectively, have included agricultural land classes resulting in a significantly higher total. Furthermore, compared to the total amount of land planted with miscanthus and short rotation coppice in England and Wales, a combined 10,019 hectares (DEFRA, 2017), not

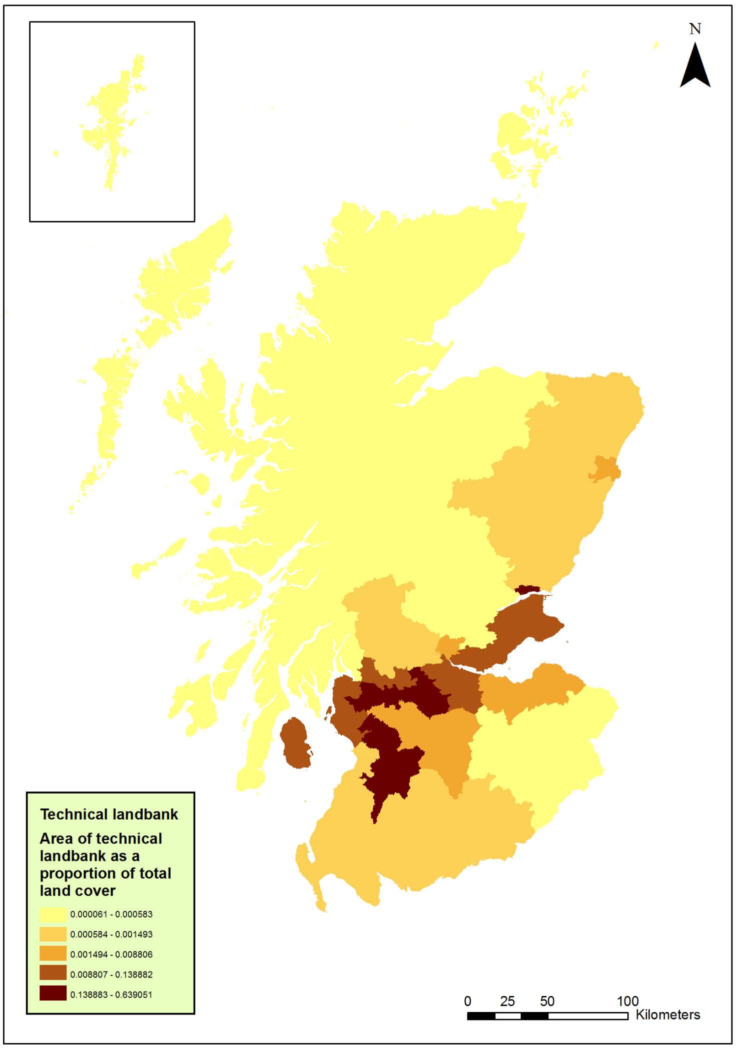


Figure 5.6: Area of technical landbank in Scotland as a proportion of total land cover in each local authority - based on spatial database created in 2017

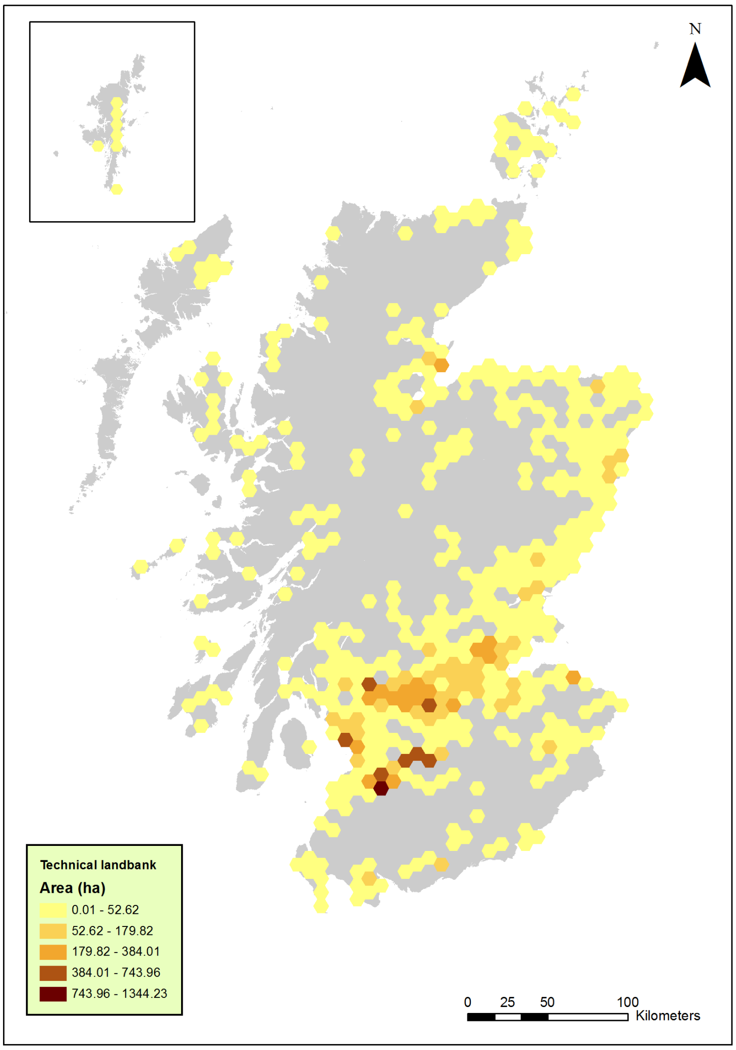


Figure 5.7: Total area of technical landbank in Scotland aggregated into a hexagonal grid with 5 km length sides - based on spatial database created in 2017

only does 1.96 Mha appear vastly unrealistic but the total amount that could be provided by underutilised non-agricultural land seems less insignificant.

5.3 Exploratory spatial data analysis to assess the distribution of the technical landbank

Having successfully implemented the multicriteria evaluation to produce a new spatial database representing the technical landbank, exploratory spatial data analysis methods were used to further an understanding of the distribution of the landbank. This involved the integration of datasets acquired from the Centre for Ecology and Hydrology (CEH, 2017) and the Scottish Government Spatial Data Infrastructure (Scottish Government, 2017c). Following this a kernel density estimation output for the technical landbank was created in an attempt to identify clusters of this land resource.

5.3.1 Furthering an understanding of the spatial characteristics of the technical landbank

The site-specific bottom-up approach taken to identify suitable land during this research differs from the raster-based approach used in GIS studies into the suitability of marginal land (Lewis and Kelly, 2014) in that the process of identification was not based on a land cover dataset. The difficulties associated with trying to identify suitable land using often low-resolution land classification data is discussed in section 3.1.1. The composition of the technical landbank according to a land cover dataset acquired from the Centre for Ecology and Hydrology (see Box 5.1) was evaluated to understand what proportion of the landbank would have been identified using the methodology often implemented by studies seeking to find suitable marginal land. This was also undertaken to highlight the limitations of selecting suitable land based on this type of source data.

Box 5.1 The Centre for Ecology and Hydrology's Land Cover Map 2015
The Land Cover Map 2015 is a national-scale dataset representing land cover derived from satellite imagery. It categorises land cover in the UK into 22 classes based on UK Biodiversity Action Plan Broad Habitats (CEH, 2017). The 25m x 25m raster land cover map, wherein each 25m pixel is assigned a Broad Habitat, was used for the purposes of this research as it is the most fine scale raster dataset.

One land type often excluded in studies trying to identify marginal land is urban areas. However, if this constraint had been applied in this research 20% of the technical landbank would have been overlooked (Figure 5.8 and table 5.2). Similarly, studies such as that conducted by Lovett et al. (2014) exclude natural and semi-natural habitats, in a study that also uses land cover data sourced from the Centre for Ecology and Hydrology. If the constraints applied

Table 5.2: Land cover types that the technical landbank intersects according the LCM2015 land cover mapping

Land cover	Area of landbank (ha)	Percent (%)
Acid grassland	1748.91	10.0
Arable and horticulture	3085.372	17.7
Bog	957.9723	5.5
Broadleaf woodland	1801	10.3
Coniferous woodland	601	3.5
Fen, marsh and swamp	62	0.4
Freshwater	297	1.7
Heather	18	0.1
Heather grassland	355	2.0
Improved grassland	3473	20.0
Inland rock	1162	6.7
Littoral rock	4	0.0
Littoral sediment	14	0.1
Neutral grassland	3	0.0
Saltmarsh	133	0.8
Saltwater	4	0.0
Suburban	1593	9.2
Supralittoral rock	15	0.1
Supralittoral sediment	91	0.5
Urban	1988	11.4

by Lovett et al. (2014) were used on the technical landbank only 38% of the 17,404 hectares would have been identified. This justifies the avoidance of a methodology that selects land from a large resolution land cover dataset as it would have been challenging to identify underutilised non-agricultural land types such as historic landfill when there is no such classification within the dataset. Furthermore, this should indirectly highlight the problematic nature of identifying ambiguously defined land types, such as marginal land, using such source datasets. Lewis and Kelly (2014) provide further criticism of the studies that use land cover datasets in a non-standardised way - with some land cover datasets containing classifications that are specific to that dataset therefore making cross study comparisons difficult.

This study has avoided integrating poor resolution thematic datasets such as land cover and soil data but this does mean little is known about the growing potential of the land identified. The Land Capability for Agriculture classification created by The Hutton Institute considers the physical characteristic of land, such as soil, climate and relief to create a ranking on the basis of its potential productivity and cropping flexibility (Hutton Institute, 2017). The prime agricultural land dataset (see Figure 5.9), provided by the Scottish Government Spatial

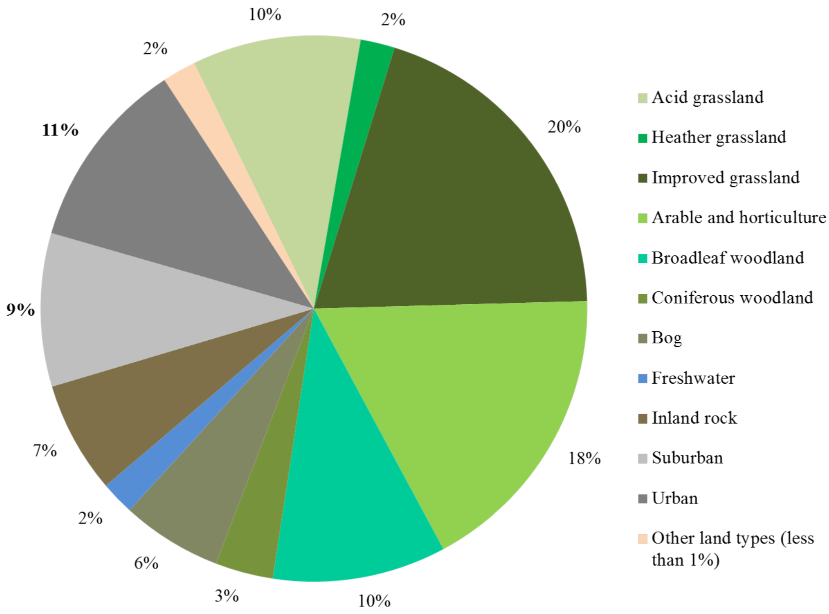


Figure 5.8: Land cover types that the technical landbank intersects according the LCM2015 land cover mapping (CEH, 2017)

Data Infrastructure (Scottish Government, 2017c), contains an amalgamation of class 1 and 2 land, that which is capable of producing a wide range of crops, from the land capability classification. 2854 hectares of the technical landbank intersects the prime agricultural land areas, an area representing 30% of the total amount of land currently planted with Miscanthus and Short Rotation Coppice in England and Wales (DEFRA, 2017). However, whilst this could be interpreted as an insight into the possibility of growing dedicated energy crops on the landbank, more realistically it proves as a warning regarding other studies that include agricultural land capability thresholds as a requirement. Lewis and Kelly (2014) report that land capability class has frequently been used as a restrictive layer to exclude prime agricultural land - with Lovett et al. (2009) restricting marginal land to areas that are levels 3 and 4 from the agricultural land classification. Care should be taken when interpreting the results from such studies as the integration of land capability classification, created in 1983 at a scale of 1:250,000 (Scotland Environment, 2017), is going to lead to errors of omission and commission.

Furthermore, it is evident that identifying the non-agricultural land types considered by this study required a bottom-up approach. Had an assumption been made that none of these sites could exist in areas overlapping agricultural land classes 1 and 2 then 16% of the technical landbank would have automatically have been overlooked. To gain a better understanding of the capability of the technical landbank for growing biomass crops, site visits are necessary and should be coupled with field trials that build on the work undertaken by Lord (2015) and WRAP (2009).

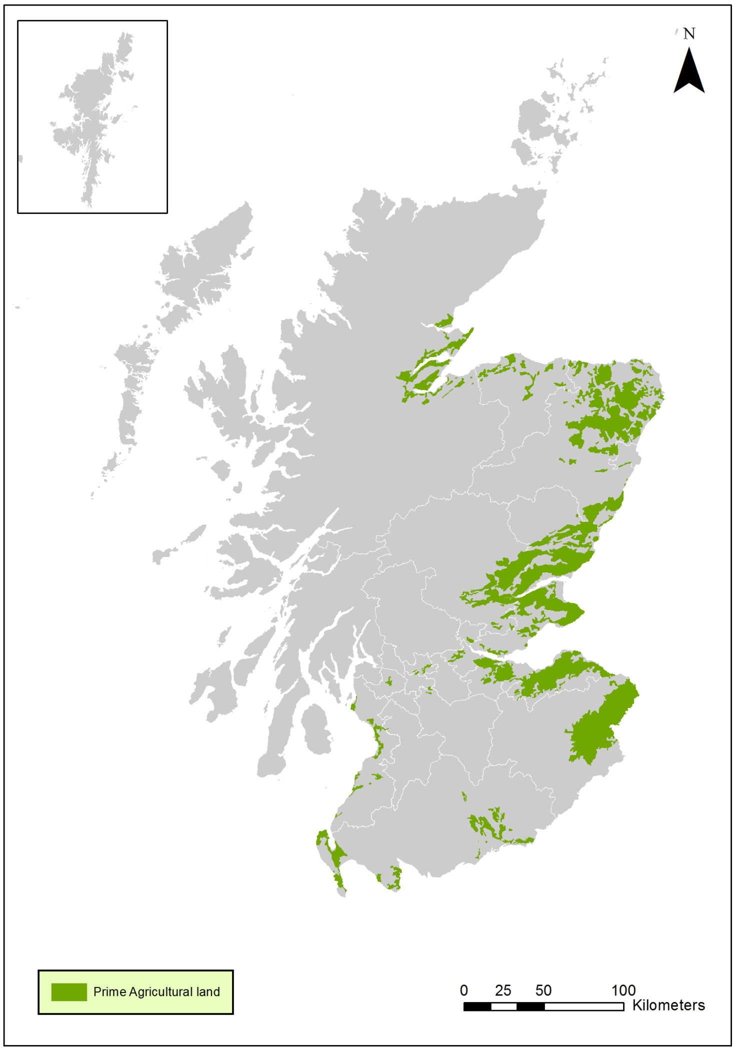


Figure 5.9: Prime Agricultural Land areas in Scotland - based on data provided by the Scottish Government Spatial Data Infrastructure in 2017 (Scottish Government, 2017c)

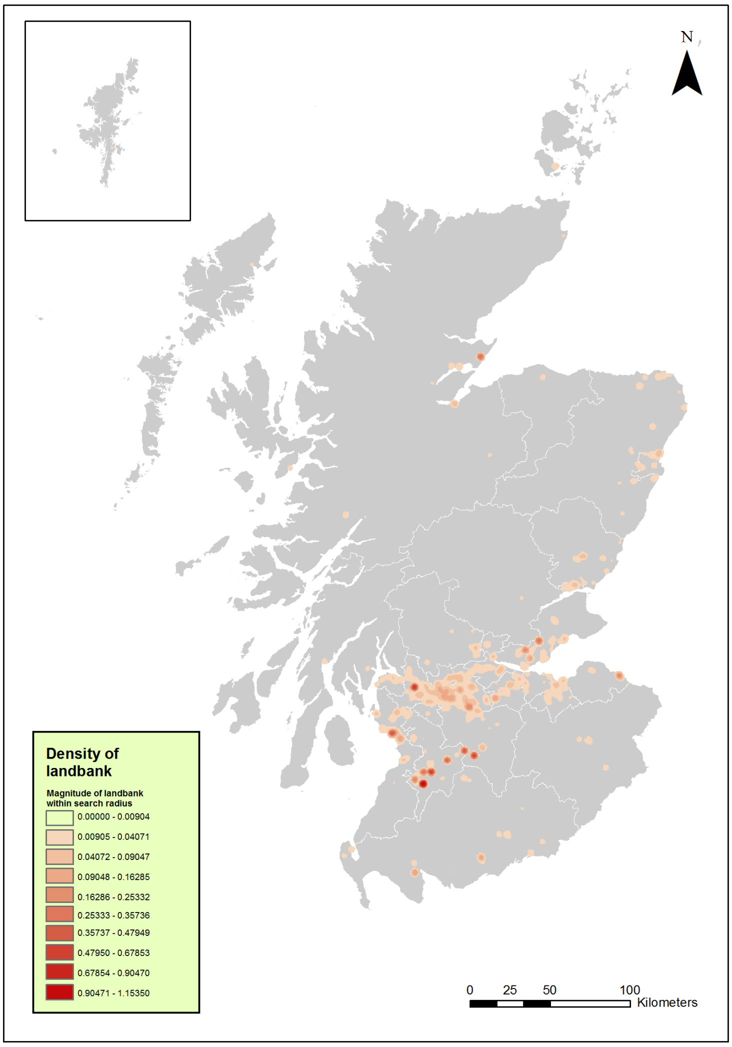


Figure 5.10: Kernel density estimation representing the density of the technical landbank in Scotland - based on spatial database created in 2017

To identify clusters within the technical landbank a kernel density estimation was undertaken (see Figure 5.10). This layer was produced using points representing the location of each parcel of land in the technical landbank, and the size of the parcel was input into the population field so that larger sites were more heavily weighted in the output surface. The default search radius was used initially, as explained in section 3.6.1. Similar to the surface created using the theoretical landbank, the output highlights several distinct clusters to the West of the central belt as well as in East Ayrshire and South Lanarkshire. It appears that the output is heavily influenced by a small number of larger sites - such as the abandoned mine land in East Ayrshire and South Lanarkshire and a brownfield land site in Easter Ross. This is also noticeable when a comparison is made with the kernel density surface created using site locations only (see Appendix A.21) which highlights that there remains a large number of small sites within and surrounding Glasgow City in addition to high density of sites around Dundee and Aberdeen City. The kernel density surfaces provide a useful visualisation of areas where future research could be targeted, and the methodology used to create these maps can be extended to extract clusters for further analysis. Clusters representing areas with a high density of landbank were utilised in this research, presented in section 6.1, as a proxy indicator of areas of supply that could be compared spatially with data related to heat demand in Scotland.

5.4 Summary of findings

This chapter has attempted to seek a better understanding of the opportunity that could be provided by underutilised non-agricultural land in terms of bioenergy provision. The application of constraints via a multicriteria evaluation resulted in the technical landbank. A total of 17,404 hectares of land were identified, the significance of which was highlighted by a comparison with previous attempts to identify land in Scotland for bioenergy provision and the total amount of land used for perennial energy crops in England. The technical landbank represents the first time a dataset consisting of only non-agricultural land types has been tested to this degree. A comparison with the most thorough of previous attempts, conducted by Niblick and Landis (2016), is undertaken in chapter 7 in an attempt to appropriately frame these findings.

Chapter 6

Opportunities arising from the creation of the landbank spatial databases

The spatial database compiled as part of this research represents not only the first set of detailed boundaries representing brownfield land at a national scale, but also the first accurate national estimation of the area of landfill and abandoned mine land. The compilation of these boundaries provides a unique understanding of the spatial distribution of the underutilised non-agricultural land resource. Both the theoretical and technical landbanks provide detailed GIS databases that can be integrated into future research to better understand the opportunity that could be provided by these vacant underused land types. Often seen as dangerous and unsightly in the past (Anderson and Minor, 2017), increasingly research has been undertaken concluding that these sites have the potential to be put to better use in the future (Kim, 2016; Kim et al., 2018). This is reflected in the number of competing uses that have been suggested for these land types, as discussed in more detail in section 2.7.3. This chapter will discuss how the landbank spatial databases could be utilised, including two examples of exploratory spatial data analysis that provide insights into significant clusters of underutilised non-agricultural land in Scotland. The following research question will be considered in this chapter:

- What are the potential applications for a landbank representing underutilised non-agricultural land?

Firstly, exploratory spatial data analysis comparing the distribution of the technical landbank, symbolising a simplistic proxy of heat energy supply, with the distribution of heat demand in Scotland is presented. This is followed by a discussion of the wider implications of access to detailed GIS data such as that created in this research in terms of alternative renewable energy provision. This discussion will not only highlight GIS methodologies with which the spatial databases can be integrated, but alterations to the multicriteria evaluation applied in this research are also suggested to enable more suitable land areas to be identified according to the desired application.

Following this, wider applications of the theoretical landbank will be discussed. This will be framed by an introduction to the principles of environmental justice, and an exploratory spatial data analysis is presented comparing the distribution of the landbank in Scotland with spatial indices of deprivation. This analysis enables significant clusters of landbank to be identified and options for further, more advanced, spatial analysis are discussed. Considering the environmental justice framing, the alternative opportunity of utilising the spatial database representing underutilised non-agricultural land for greenspace provision or housing development will be discussed alongside ways in which the database could be integrated with established GIS methods. Once again, alterations to the multicriteria evaluation, used in this research to identify land specifically for bioenergy provision, will be suggested.

6.1 Comparing spatial distribution of technical landbank and heat demand in Scotland

The identification of the technical landbank, in chapter 5, was primarily undertaken with the aim of seeking a better understanding of the role that underutilised non-agricultural land could play in terms of bioenergy provision. This focus was justified by Scotland's requirement to make progress towards the goal of achieving 11% non-electrical heat from renewable sources by 2020 - a target it is currently not on course to hit (Scottish Government, 2016a; Flynn et al., 2017). The aim of the exploratory spatial data analysis presented in this section is to identify significant clusters of vacant land. Three approaches were developed pairing the landbank with heat demand data provided by the Scottish Government (Scottish Government, 2015) as part of Scotland's heat map. The source and format of the heat demand data along with details of the methodology used in each of the three approaches, and any assumptions made, are outlined in more detail in section 3.6.2.2. This further spatial data analysis has been undertaken to provide an initial indication as to where future research could be focused rather than a final solution to Scotland's heat demand needs, as discussed further in Box 6.1. It is therefore a simplistic representation of the relationship between heat energy supply from bioenergy and heat energy demand, but it can aid the targeting of future research such as the identification of suitable locations for bioenergy conversion facilities or district heating schemes that could use the biomass grown on previously underutilised non-agricultural land.

6.1.1 Identifying clusters of supply

The first approach focused on clusters of supply identified from the technical landbank. This involved an adaption of the kernel density estimation, using a search radius of 10 km to exclude outliers and produce a layer which highlights a sufficient number of clusters that could be exported for further analysis. Nine clusters (see Figure 6.1) with a high magnitude of landbank within the 10 km search radius were selected from the kernel density estimation surface, based on having a cell value in the upper quantile of all the surface's cell. A 40 km buffer was created around these clusters (see Figure 6.2), as justified in section 3.6.2.2, allowing the area of landbank within the cluster to be compared with the sum of the heat demand within the 40 km buffer (see Figure 6.3 and Appendix A.19). This method highlighted the spatial relationship between clusters of landbank and the surrounding heat demand, although care should be taken when comparing the landbank reported in hectares and the heat demand

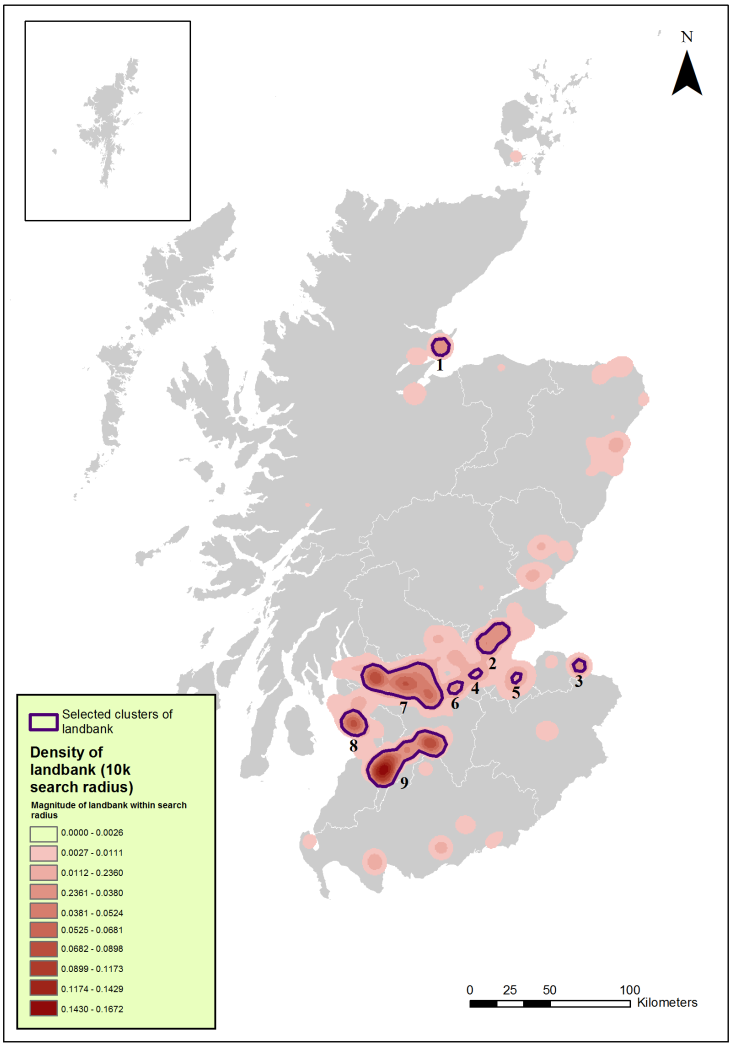


Figure 6.1: Adapted kernel density estimation surface created using the technical landbank in Scotland with 9 key clusters highlighted - based on spatial database created in 2017

presented in gigawatt hours per year, as discussed in box 6.1.

All of the clusters identified using the adaptation of kernel density estimation were situated in South central Scotland, except one cluster North of Inverness in Easter Ross. As is to be expected the larger clusters 7 and 9 contain the largest amount of technical landbank - with 4037 and 4454 hectares respectively. However, cluster 7 which is located roughly over Glasgow City has a much higher level of heat demand within a 40 km radius, with 40398 GWh/yr. The more rurally located cluster 9 has more landbank relative to the sum of heat demand, 25908 GWh/yr, within a 40 km radius. On the other hand, the clusters to the East of the central

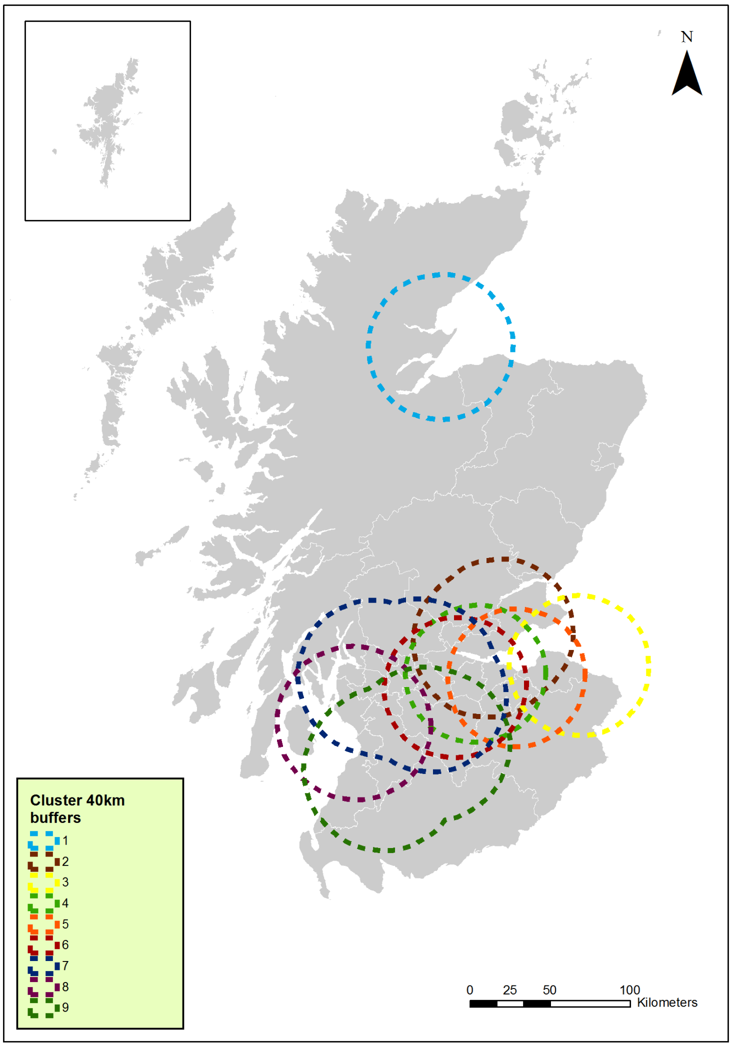


Figure 6.2: 40 km buffer areas around each of the 9 clusters of technical landbank in Scotland - based on spatial database created in 2017

belt, namely clusters 4, 5 and 6 appear to have a level of demand within a 40 km radius that far exceeds the area of landbank within the cluster.

This is a simplification of the relationship between supply and demand, as discussed in box 6.1. What it does suggest is that should the technical landbank be mobilised for bioenergy provision there is a great deal of surrounding heat demand that could be supplied. This further exploratory analysis was meant to provide a guide as to where further research could be targeted by identifying significant clustering of supply in relation to heat demand, such as that identified in cluster 7. This would suggest further work could be conducted to consider the relationship between technical landbank and heat demand in Glasgow City.

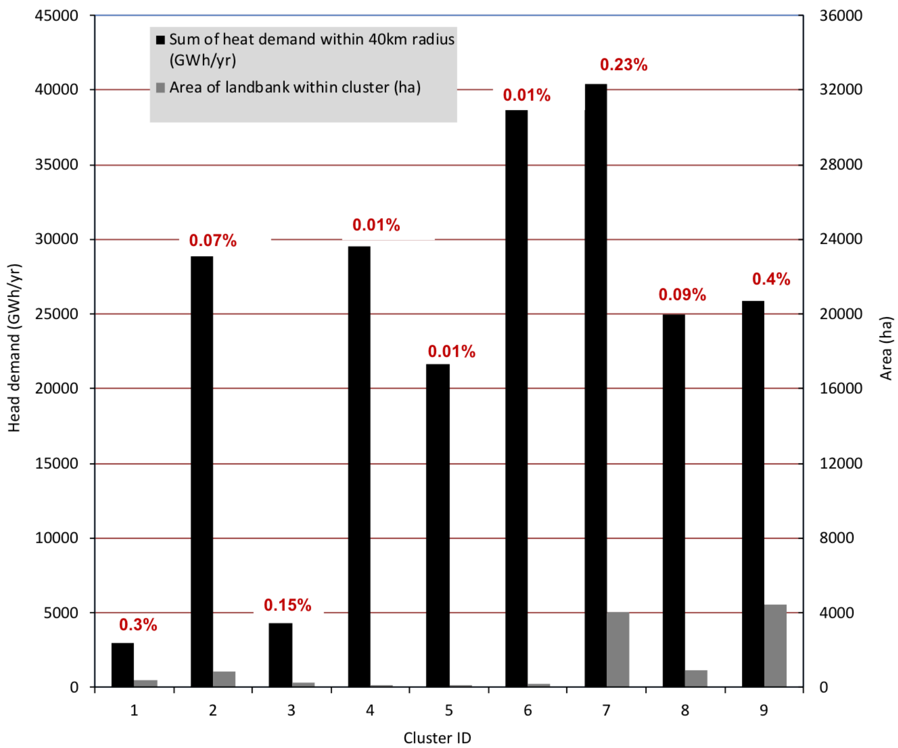


Figure 6.3: Area of landbank within each cluster (ha) compared with the sum of the heat demand within a 40 km radius (GWh/yr) with figures in red showing the proportion of demand met by landbank - based on spatial database created in 2017 and heat demand data provided in 2017

Box 6.1 Note on comparing the technical landbank supply and heat demand demand data
The exploratory spatial data analysis techniques employed in this thesis seek only to understand the rudimentary spatial relationship between potential bioenergy supply and heat demand. Whilst the findings such as those presented in Figure 6.3 show that there is an overlap between the landbank and heat demand - it does not indicate the degree to which the demand can be met. To give an insight into the relationship between the energy potential of this landbank, the annual net energy yield of reed canarygrass provided by Lord (2015) was used. Based on trial studies on brownfield land, average mechanical yield, water content at harvest, gross and net calorific values Lord (2015) report a practical net energy yield of 84 GJ ha^{-1} per year. Since this value is based on trials conducted on five, one hectare sites in North East England, extrapolating from this to the national scale of the present study is predicated on making what are probably gross assumptions related to properties of the land and conversion efficiency. However, hypothetically this value equates to 1 hectare of landbank equalling 0.02 GWh. An extension of this hypothetical calculation suggests that the 17,404 ha technical landbank has the potential to provide 6.32% of the 6,420 GWh required in order for Scotland to meet its 2020 Renewable Energy Target (Flynn et al., 2017).

This calculation does add context to the comparison of heat supply and demand conducted as part of this exploratory spatial data analysis. When viewing Figure 6.3 it is necessary to point out that the two set of axis are not equivalent and that 1000 ha of landbank would only equate to 23.3 GWh of supply per year. This indicates that in most cases the demand far outweighs the supply. It also suggests that land is going to be insufficient in all cases therefore future efforts should be focused on the clusters where the highest landbank is present, such as clusters 7 and 9, which could provide a more worthwhile contribution towards heat demand in the surrounding area.

6.1.2 Identifying clusters of demand

The second approach taken was based on clusters of demand and utilised a GIS shapefile aggregating heat demand to Scotland's datazone geography provided by the Scottish Government (Scottish Government, 2015). As the detailed methodology in section 3.6.2.2 explains, datazones with the highest heat demand density were joined according to proximity and a convex hull was created around these datazones to effectively create a proxy layer representing clusters of heat demand. The 70 datazones with the top 1% of heat demand density were aggregated to create 13 clusters (Figure 6.4). Having identified the 13 clusters, a buffer of 40 km was created (see Figure 6.5), as justified in section 3.6.2.2, and this allowed the sum of heat demand within the cluster to be compared to the area of landbank within 40 km (see Figure 6.6 and Appendix A.20).

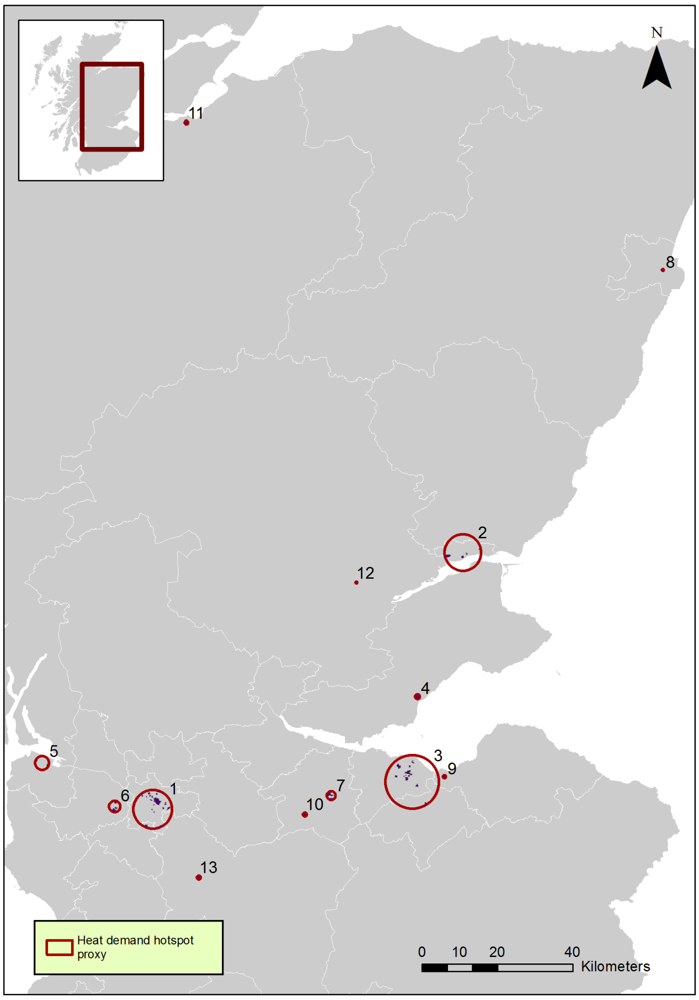


Figure 6.4: 13 clusters of heat demand created via the aggregation of the 70 datazones with the highest heat demand density - based on spatial database created in 2017 and heat demand data provided in 2017

In addition to several clusters identified along the central belt of Scotland, clusters were also located in the cities in Aberdeen, Dundee, Inverness and Perth due to datazones existing in each of these cities that are within the highest 1% in Scotland in terms of heat demand density. 7 of the clusters were made up of only one datazone, whereas the other 63 datazones were spread amongst the other 6 clusters. This is reflected in the graph (Figure 6.6) as clusters 4 and 8 to 13 are the clusters composed of only one datazone and therefore have a much lower level of heat demand compared to those clusters which contain numerous aggregated datazones. Nevertheless, the graph shows that there is still a significant amount of technical

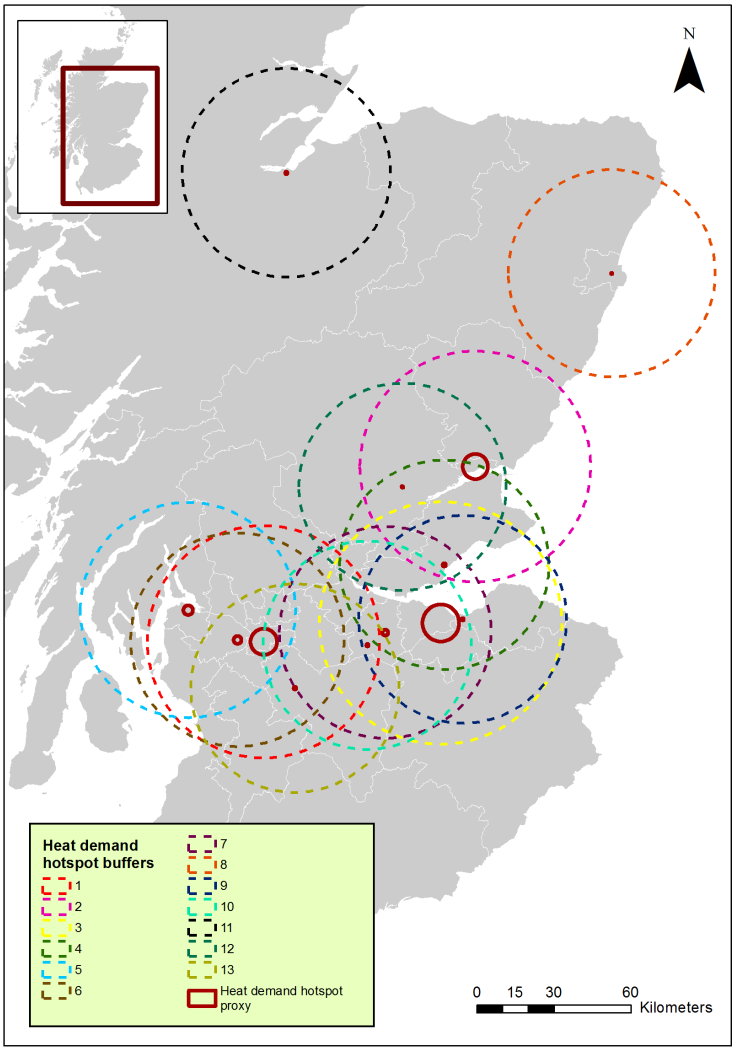


Figure 6.5: 40 km buffer areas around each of the 13 clusters of heat demand - based on spatial database created in 2017 and heat demand data provided in 2017

landbank surrounding the single datazones which could provide bioenergy to these areas of high heat demand density. Once again, arguably the most significant cluster is identified within Glasgow City - cluster 1 - which contains the highest cumulative heat demand of 7034 GWh/yr. This cluster also has the largest amount of landbank within a 40 km radius amongst all the clusters, with 8701 hectares of technical landbank potentially available for bioenergy provision. Unsurprisingly, the other two clusters with the highest level of cumulative heat demand - clusters 2 and 3 - are also based in cities, in Edinburgh and Dundee. However, the level of technical landbank within 40 km of these clusters is relatively lower. Cluster

13, which is created around the datazone of Strathaven North in South Lanarkshire, has the greatest amount of landbank relative to the amount of heat demand within the cluster - with potentially 8652 hectares which could contribute to the 42 GWh/yr heat demand. If the annual net energy yield described in box 6.1 is applied to landbank surrounding cluster 13, it could provide 201 GWh/yr. However, as previously mentioned this is an over simplification of the relationship and the calculation of net energy yield comes with many assumptions. Further research would be required to investigate if an intiative such as a district heating scheme could harness the landbank within a 40km radius of the datazone, and whether this would be a sustainable option for meeting the heat demand.

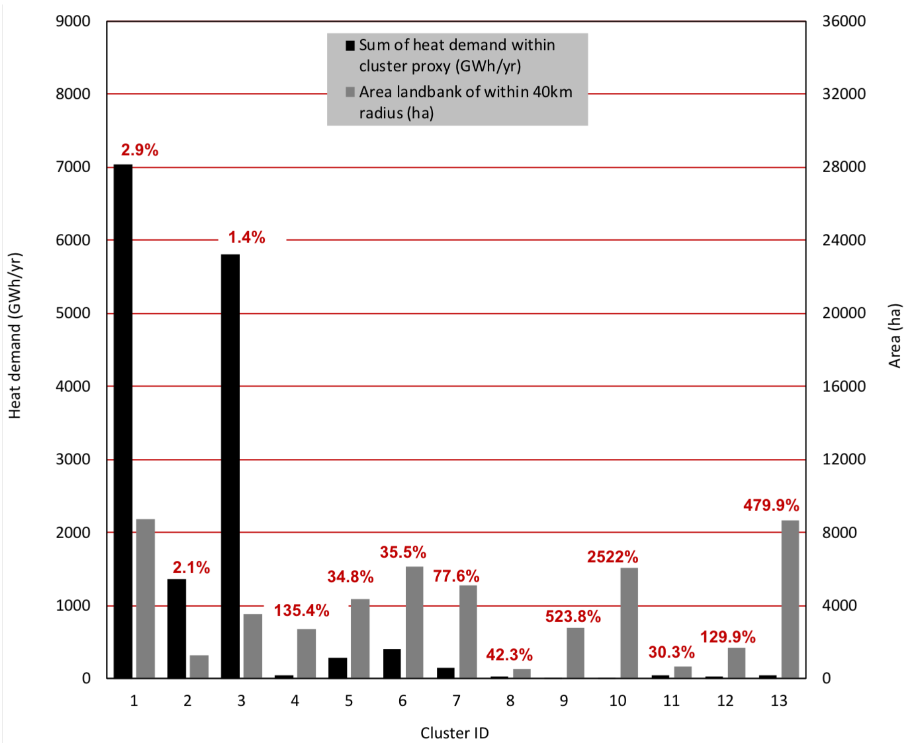


Figure 6.6: Sum of heat demand (GWh/yr) within each cluster compared to the sum of the technical landbank (ha) within a 40 km radius with figures in red showing the proportion of demand met by landbank - based on spatial database created in 2017 and heat demand data provided in 2017

This approach, which focusses on identifying clusters of demand rather than supply, could be extended in future research to include more than the just the datazones with the top 1% heat demand density. Furthermore, a wider radius could be used to aggregate datazones together to identify clusters with an even greater level of demand.

6.1.3 Identifying case studies with a combination of high supply and demand

The final approach taken in an attempt to find more significant areas of the technical landbank focused on datazone geographies where there is simultaneously a high density of landbank and heat demand. The amount of technical landbank and heat demand as a proportion of the total land area of each datazone was calculated, as outlined in section 3.6.2.2. A scatterplot graph was then created (see Figure 6.7) and four datazones with both a high heat demand density and high landbank density were selected for further analysis.

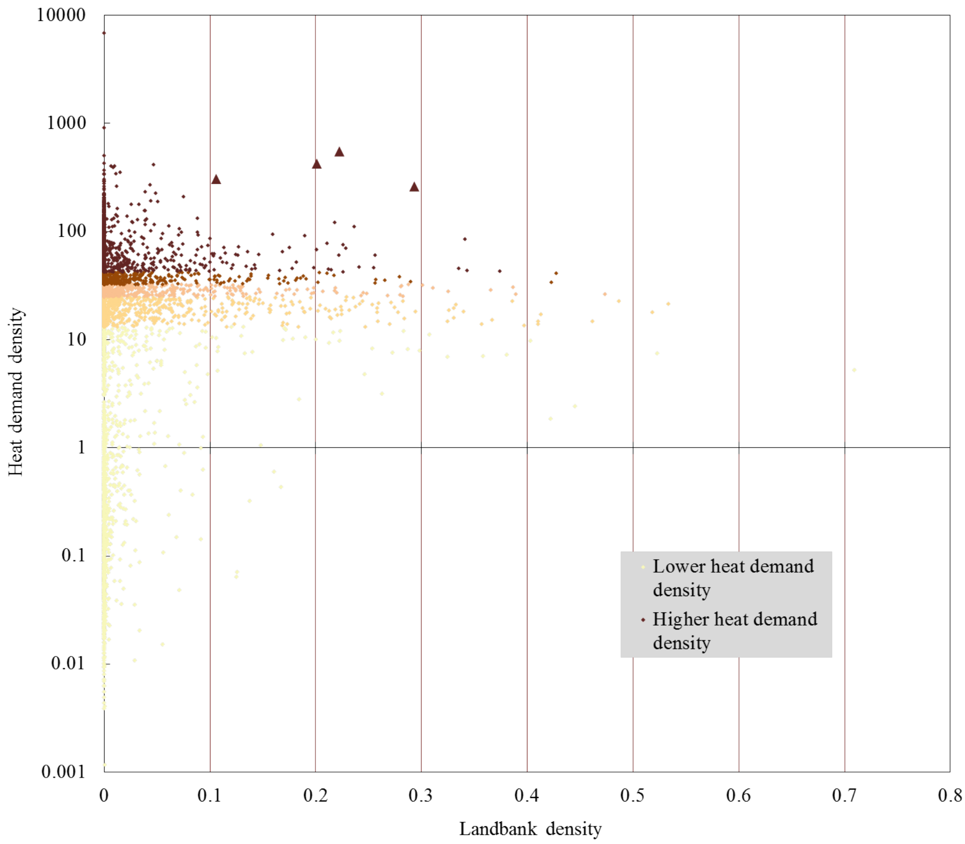


Figure 6.7: Heat demand density and landbank density of the 6,976 datazones in Scotland with the 4 selected case study sites shown by triangles - based on spatial database created in 2017 and heat demand data provided in 2017

The four selected datazones were within the top 1% in terms of heat demand density, with

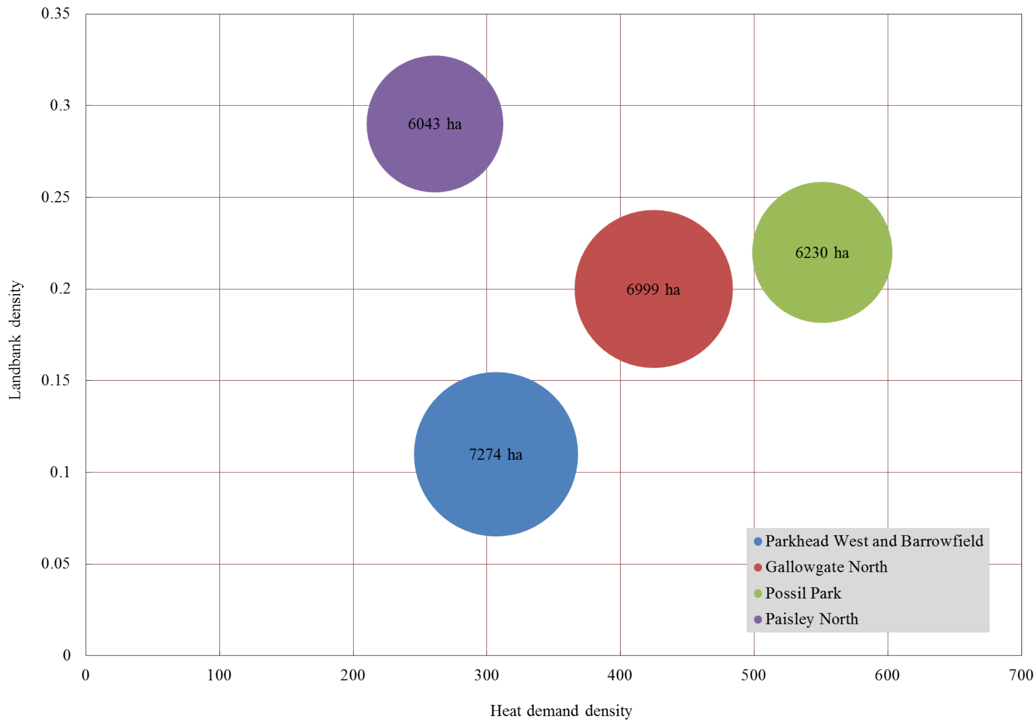


Figure 6.8: Landbank density and heat demand density of the 4 selected case study datazones with the size of bubble representing the sum of landbank within a 40 km radius - based on spatial database created in 2017 and heat demand data provided in 2017

over 167.1 GWh/yr of demand for every hectare, and were within the top 5% in terms of landbank density. All four datazones were located within the Greater Glasgow urban area - 1 in Paisley and 3 in Glasgow City. Possil Park is the datazone with the highest heat demand density, and Paisley North has the highest landbank density (see Figure 6.8). All of the datazones have more than 6000 hectares of technical landbank within a 40 km radius. The four case study datazones can be looked at individually to further an understanding of the relationship between technical landbank supply and heat demand density (see Appendix A.21).

The datazone in Paisley, 'Paisley North - 04', is 22 hectares in size and has a total heat demand of 56 GWh/yr. It is mainly composed of residential properties but also contains several large vacant and derelict sites (see Figure 6.9) and has 6043 hectares of technical landbank within a 40 km radius. The Possil Park datazone, 'Possil Park - 01', is located in the North of Glasgow. It is only 16 hectares in size yet has a sum heat demand of 90 GWh/yr - the highest heat demand density of all four case study locations. This datazone also contains a

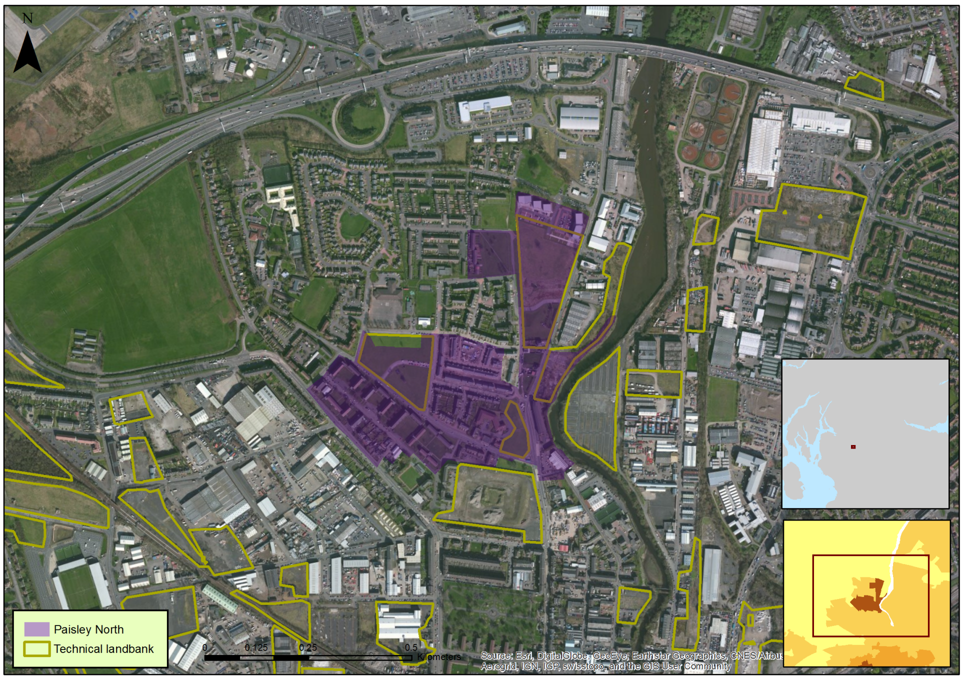


Figure 6.9: Case study map 1 - Paisley North, Paisley, Scotland - showing the datazone and the surrounding technical landbank (based on spatial database created in 2017) with ESRI's World Imagery basemapping

large housing estate and the aerial imagery (see Figure 6.10) shows that there are a number of technical landbank sites within, and in close vicinity to, the area. Furthermore, there are 6230 hectares of technical landbank within 40 km of the datazone. The datazone in Gallowgate North, 'Gallowgate North and Bellgrove - 02', is located in East Glasgow and is composed of a similar mix of residential housing alongside vacant and derelict land (see Figure 6.11). This datazone has a sum heat demand of 46 GWh/yr and has 6999 hectares of technical landbank within a 40 km radius. Finally, the datazone in Parkhead West and Barrowfield, specifically 'Parkhead West and Barrowfield - 02', is also situated in the East End of Glasgow. At 26 hectares it is the largest of the four case study datazones and it also has the largest amount of technical landbank within 40 km, with 7274 hectares. This datazone has a sum heat demand of 80 HWh/yr.

The Parkhead West and Barrowfield case study (Figure 6.12) highlights the temporal issues that arise when compiling and comparing data that were created in different years. The high heat demand value which was taken from the dataset compiled by the Scottish

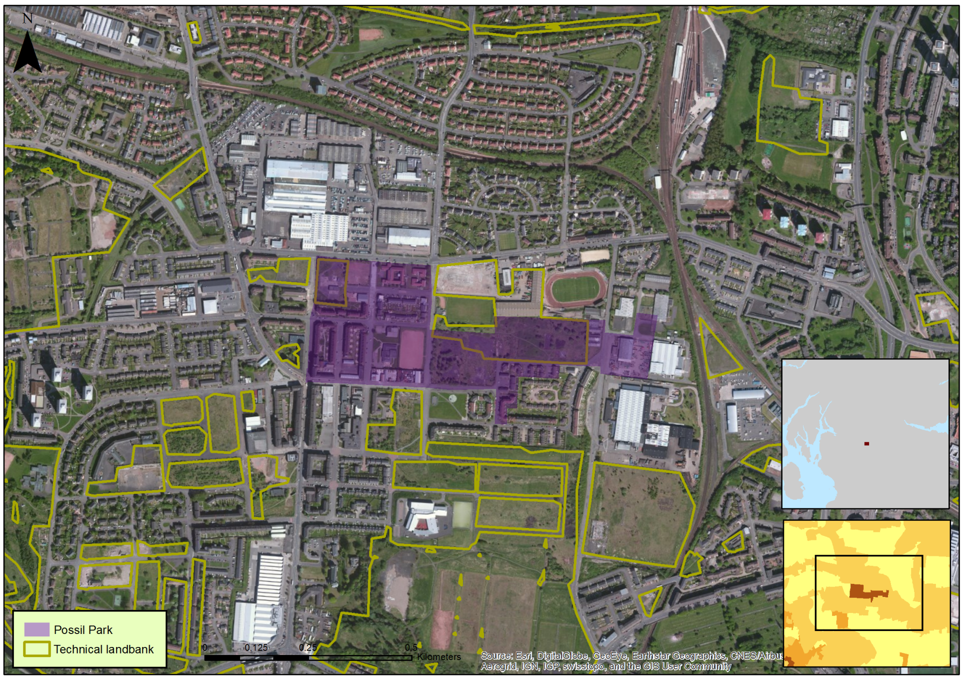


Figure 6.10: Case study map 2 - Possil Park, Glasgow, Scotland - showing the datazone and the surrounding technical landbank (based on spatial database created in 2017) with ESRI's World Imagery basemapping

Figure 6.11: Case study map 3 - Gallowgate North, Glasgow, Scotland - showing the datazone and the surrounding technical landbank (based on spatial database created in 2017) with ESRI's World Imagery basemapping

Figure 6.12: Case study map 4 - Parkhead West and Barrowfield - showing the datazone and the surrounding technical landbank (based on spatial database created in 2017) with ESRI's World Imagery basemapping

Government in 2014 doesn't make sense when the ESRI world imagery is inspected (Figure 6.12). The area seemingly contains very little housing or industrial developments. However, further investigation revealed that this was the site of several venues and the athlete's village for the Commonwealth Games in 2014. This was confirmed using Google streetview imagery, dated from 2016. Whilst this explains the high heat demand value recorded in 2014, it casts doubt on the technical landbank which contains vacant and derelict land sites from the 2012 vacant and derelict land survey, published in 2013. The large site that makes up the majority of the technical landbank in the datazone was included in the 2016 vacant and derelict land survey, and the streetview imagery confirms it has still not been developed. However, the large site to the South of the River Clyde has been converted into a new woodland park - Cuningar Loop - as part of the Commonwealth Games Legacy 2014 Project. This example highlights the need to take the technical landbank totals with caution, especially when comparing it with more contemporary datasets. The temporal accuracy of the theoretical landbank, which is the database of land on which the technical landbank was based, is discussed in more detail in section 3.4.6.

6.1.4 Reflections on the attempts to find more significant clusters of technical landbank

Whilst they are a simplification of the relationship, the three techniques implemented in this chapter provide an initial indication of the distribution of the technical landbank in relation to potential end users. It has emphasised that there is an overlap between areas of demand and potential supply, and that underutilised non-agricultural land resource could, at least in part, play a role in meeting the heat demand. It has presented an insight into the existence of the clustering of hotspots of land resource that goes beyond the initial heat map produced via the kernel density estimation in section 5.3. Limitations of each approach have been highlighted - including the issue with temporal difference in analysed datasets and an oversimplification of the supply-demand relationship. The latter would be the grounding for future work using the technical landbank identified in this research. This further exploratory spatial data analysis has highlighted key areas where such research could be targeted. The first two approaches seemingly suggesting future efforts should be aimed at Glasgow City and the final approach highlighting specific datazones such as Possil Park which has a high level of demand and a large amount of technical landbank both nearby and within a wider radius.

To fully understand the degree to which underutilised non-agricultural land can contribute to meeting heat demand, a better understanding of the yield of biomass that could be attained from these sites is required. As Slade et al. (2010) explain, to estimate future contribution from energy crops there are two approaches for estimating productive yields: empirical crop models and extrapolation from case-studies and sample plots. Surendran Nair et al. (2012) present 14 bioenergy crop models used to simulate field scale production but explain that field trials are necessary to create accurate models by improving the agronomic understanding of how soils, climate and crop management influence biomass production. Unfortunately, currently there is not enough evidence of crop yields on non-agricultural land types on which to base an agronomic model. Future research should therefore aim to build on trial studies conducted by

Lord (2015) and Smith et al. (2013) to gain a better understanding of the yields that could be achieved on non-agricultural land types. Moreover, to fully understand the role that the Scottish landbank identified in this thesis could play in terms of bioenergy provision, further research is required regarding the suitability of dedicated energy crops in Scotland. Booth (2011) claims Phalaris arundinacea, or reed canary grass, is a biomass crop better suited to Scotland due to good winter hardiness and resistance to drought and water logging. Field trials of such crops need to be conducted on underutilised non-agricultural land in Scotland to give a better indication of the yield potential of these sites.

Once a better understanding of the potential yield is achieved further research can be conducted to better comprehend the potential relationship between biomass and bioenergy conversion facilities or boiler locations. It would be possible to evaluate the contribution that biomass from underutilised non-agricultural sites can make to the 27 boilers providing over 1000 KW_{th} which currently use a total of 1,013,489 odt of woodfuel (Forestry Commission Scotland, 2017). Alternatively, research can be targeted at locating suitable sites for new bioenergy plants. Kurka et al. (2012) developed a GIS-based approach identifying suitable CHP bioenergy plant locations in Tayside and Fife, Scotland, based on regional supply and demand. Whereas Kurka et al. (2012) input sawmills, wood waste re-processors and log or pellet producers as the supply, and schools, universities, hospitals, and industrial points as a proxy for demand - the methodology could be adjusted to input underutilised non-agricultural land and clusters of heat demand as identified in this thesis.

From a policy point of view, the timing of this research is framed by the Scottish Government's commitment towards developing a new Bioenergy Action Plan (Scottish Government, 2018). The governments activity in this area will be guided by the requirement to identify bioenergy schemes that deliver greenhouse gas emission reductions, benefits communities and manages equitably the demand for land for food and energy crops (Scottish Government, 2018). There is therefore the opportunity to integrate underutilised non-agricultural land, such as the 17,404 of technical landbank identified in this thesis, into future bioenergy planning. There is then potential for biomass to be supplied without the exacerbation of food security or indirect land use change that results from the use of agricultural land.

6.2 Further applications of the technical landbank for renewable energy provision

Beyond bioenergy, underutilised non-agricultural land could play an important role in the provision of alternative renewable energy sources. Previous attempts to consider the opportunity that could be provided by some of these land types has been discussed in section 2.6. As previously highlighted, a common limitation that is cited in research into the role of these vacant land types is the availability of detailed spatial information. Detailed spatial databases such the landbank identified in this research could be integrated with these research efforts to give a more accurate understanding of the role of this land resource.

The research undertaken by the National Association of Local Government Environmental Professionals (NALGEP, 2012) investigating the role of brownfields in the cultivation of green energy provides a strong example of how the theoretical landbank representing underutilised non-agricultural land could be explored further in the future. NALGEP (2012) review the various renewable energy options that could be placed on brownfield land and points stakeholders to existing tools and screening assessment resources. In addition to biomass, the report considers wind energy and solar energy options, suggesting the use of mapped annual wind speed and solar resource to identify the most suitable sites. If spatial data was available for either of these resources at a suitable enough scale then these factors could be included in a multicriteria evaluation, similar to that conducted in chapter 5, to identify a technical landbank of underutilised non-agricultural sites that would be better suited for wind or solar energy development. London Borough of Redbridge (2010) conducted a GIS analysis that went a step further, combining a range of inputs to create energy opportunity maps. The opportunity analysis included factors such as wind speed and powerline buffers, availability of biomass from local suppliers, head and flow data relating to hydropower potential and roof space for solar installations (London Borough of Redbridge, 2010). The combination of these elements results in a visualisation of sites that have the potential for renewable energy development including district heating opportunities (London Borough of Redbridge, 2010). The detailed spatial data provided by the theoretical landbank would benefit such analysis, enabling an insight into the extent that underutilised non-agricultural land could contribute as the site of various renewable energy technologies.

The Scottish onshore wind policy statement (The Scottish Government, 2017) summarises relevant policy with regards to the consideration of underutilised land resources for renewable energy technology. It points to The Scottish Government's Land Use Strategy with includes principles for the sustainable use of land, including where land is vacant or derelict (The Scottish Government, 2017). The strategy claims these land types represent a 'significant loss of economic potential and amenity for the community concerned' and it should therefore become a priority to examine options for restoring all such lands to productive use. The creation of a detailed spatial database provides an accurate resource for examining the opportunity that could be provided from restoring these vacant and derelict land categories with this policy priority in mind.

6.3 Alternative applications for the landbanks

The theoretical landbank represents the hypothetical maximum amount of available underutilised non-agricultural land available in Scotland. The multicriteria evaluation applied to this landbank, the results of which are presented in chapter 5, was developed to identify a technical landbank that was better suited for bioenergy provision. However, as outlined in section 2.7.3, there are a range of potential end uses for the vacant underutilised land areas that have been identified. This section will elaborate on the opportunities that could be provided by this land resource and will highlight the benefit of having a detailed spatial database representing such areas. Furthermore, where applicable, alterations to the multicriteria evaluation used as part of this research are suggested as a means of identifying technical landbanks for alternative applications.

A prominent theme in research related to vacant land, particularly urban vacant land, is the impact that proximity to such spaces could have on vulnerable communities. Environmental justice is the disproportionate distribution of ‘good’ or ‘bad’ environmental factors, with all of the burdens and a lack of benefits falling upon minority or lower income populations (Chakraborty et al., 2011). Maantay (2013) argues that vacant and derelict land is one such environmental burden and should therefore be considered an environmental justice concern. Vacancy or underutilisation of land is perceived negatively and correlates with increased crime rates and decreased property values (Anderson and Minor, 2017). De Biasi (2017) even claims that vacant lots deserve criminological attention due to the relationship of sites with factors such as fear of crime. Bambra et al. (2014) argues that brownfield land is a marker for long term industrial decline and that these ‘untherapeutic landscapes’ have an impact on physical health. Bambra et al. (2014) further this claim, linking the distribution of brownfield land with indicators of morbidity, providing analysis that suggests people living in areas with higher levels of brownfield land are more likely to suffer poorer health. With this environmental justice framing in mind, exploratory spatial data analysis was undertaken comparing the distribution of theoretical landbank and indicators of deprivation in Scotland.

6.3.1 Comparing spatial distribution of theoretical landbank and indicators of deprivation

The theoretical landbank represents the first attempt to understand the extent of underutilised non-agricultural land nationally. The Scottish Index of Multiple Deprivation, as discussed in more detail in section 3.6.2.1, is a tool that identifies areas of inequality or poverty in Scotland. The index creates a ranking for each datazone in Scotland based on 38 indicators of deprivation. A datazone, or data zone, is a small-area of statistical geography used to split Scotland up into regions containing roughly equal population. For an initial comparison, the area of the theoretical landbank within each datazone as a proportion of the total land cover has been calculated (see Figure 6.13 and Appendix A.17). This initial visualisation shows several datazones with a high density of landbank within Glasgow City, in addition to a datazone on the West Coast near Irvine.

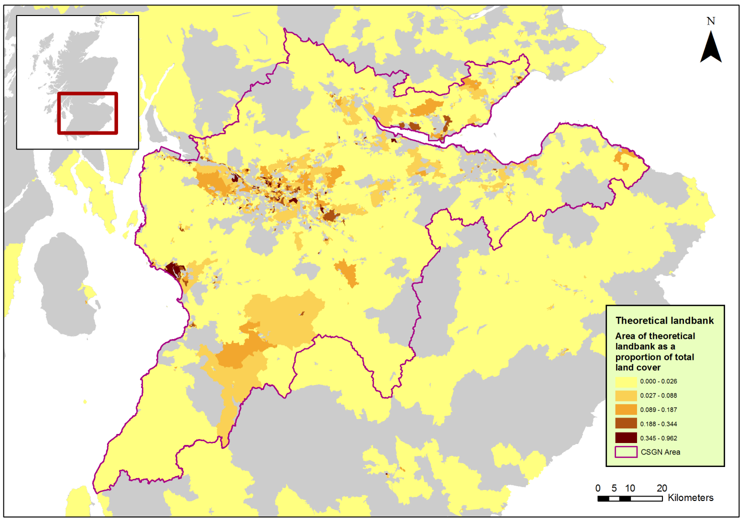


Figure 6.13: Area of theoretical landbank as a proportion of total land cover in each datazone focussing on the Central Scotland Green Network area to enable datazones to be seen - using data from 2013-16 compiled in 2016. For the whole of Scotland see Appendix A.17

Following this, the datazones ranked amongst the 15% most deprived were identified. The area of theoretical landbank situated within these datazones was calculated (see Figure 6.14 and table 6.1). In total 2263 hectares of underutilised non-agricultural landbank were situated within the 15% most deprived datazones. This represents 9% of all the theoretical landbank identified as part of this research.

Table 6.1: Theoretical landbank SIMD analysis totals - using spatial database containing data from 2013 - 2016 compiled in 2016 and SIMD data published in 2016

Local Authority	Number of Datazones	Number of Datazones in 15% most deprived	Theoretical landbank area in 15% most deprived datazones (ha)	Proportion total theoretical landbank area in 15% most deprived (%)	Total landbank area in Local authority (ha)	Proportion of theoretical landbank within 15% most deprived datazones (%)
Aberdeen City	283	9	4	0.2	232	2
Aberdeenshire	340	3	3	0.1	1256	0
Angus	155	2	0	0.0	541	0
Argyll and Bute	125	10	2	0.1	181	1
City of Edinburgh	597	59	11	0.5	263	4
Clackmannanshire	72	11	1	0.0	120	1
Dumfries and Galloway	201	13	9	0.4	761	1
Dundee City	188	55	78	3.4	210	37
East Ayrshire	163	36	768	33.9	5292	15
East Dunbartonshire	130	2	0	0.0	337	0
East Lothian	132	2	0	0.0	527	0
East Renfrewshire	122	5	3	0.1	101	3
Falkirk	214	24	16	0.7	416	4
Fife	494	69	57	2.5	2123	3
Glasgow City	746	320	745	32.9	1364	55
Highland	312	20	7	0.3	1642	0
Inverclyde	114	41	64	2.8	207	31
Midlothian	115	7	3	0.1	382	1
Moray	126	0	0	0.0	133	0
Na h-Eileanan an Iar	36	0	0	0.0	71	0
North Ayrshire	186	51	122	5.4	1568	8
North Lanarkshire	447	104	122	5.4	1844	7
Orkney Islands	29	0	0	0.0	86	0
Perth and Kinross	186	9	0	0.0	182	0
Renfrewshire	225	47	71	3.1	1204	6
Scottish Borders	143	6	7	0.3	212	3
Shetland Islands	30	0	0	0.0	126	0
South Ayrshire	153	19	2	0.1	188	1
South Lanarkshire	431	62	77	3.4	1945	4
Stirling	121	9	21	0.9	312	7
West Dunbartonshire	121	35	65	2.9	278	23
West Lothian	239	16	5	0.2	761	1

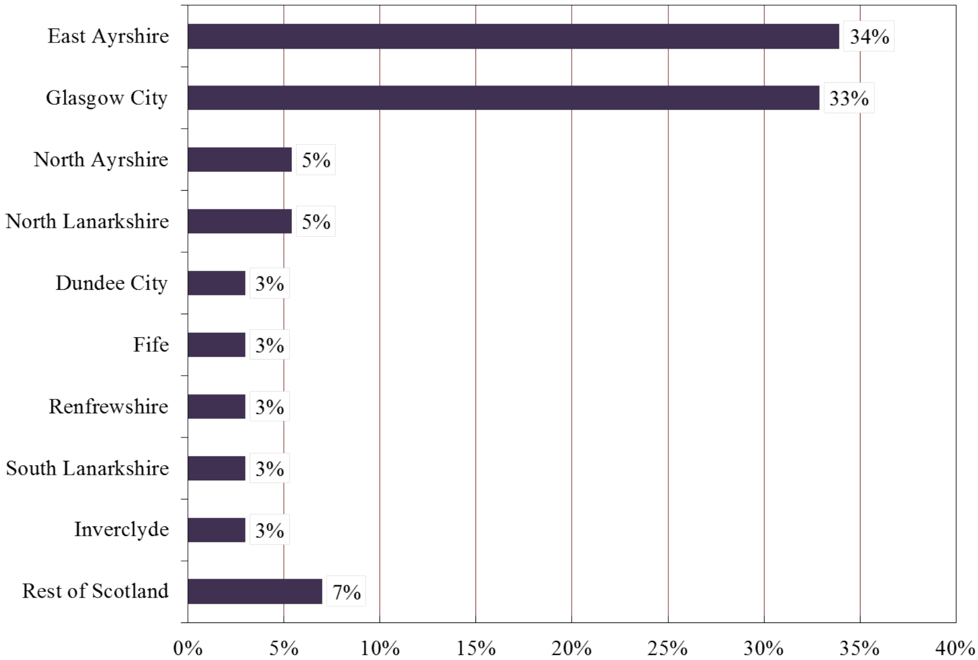


Figure 6.14: Local authorities with the greatest percentage of all theoretical landbank located in the 15% most deprived datazones in Scotland - calculated using spatial database created in 2016 and SIMD data published in 2016

East Ayrshire contains 34% of the theoretical landbank that is within the most deprived datazones (see fig 6.14) with 768 hectares of land in these areas. Glasgow City is has the second highest proportion of the total landbank situated within the 15% most deprived datazones, with 33% of the total landbank in the most deprived datazones being situated in this local authority - 745 hectares of land. Conversely, the local authorities of Moray, Western Isles, Orkney Islands and Shetland Islands have no datazones within the 15% most deprived in Scotland, therefore no land is identified in proximity to deprived areas in these regions. Furthermore, whilst Angus, East Dunbartonshire, East Lothian and Perth and Kinross do have datazones within Scotland's 15% most deprived, they did not have any theoretical landbank within those areas.

When viewed in the context of the total amount of theoretical landbank within each local authority (fig 6.15), Glasgow City has the highest proportion within the most deprived areas. 55% of the all the underutilised non-agricultural land identified in Glasgow City is

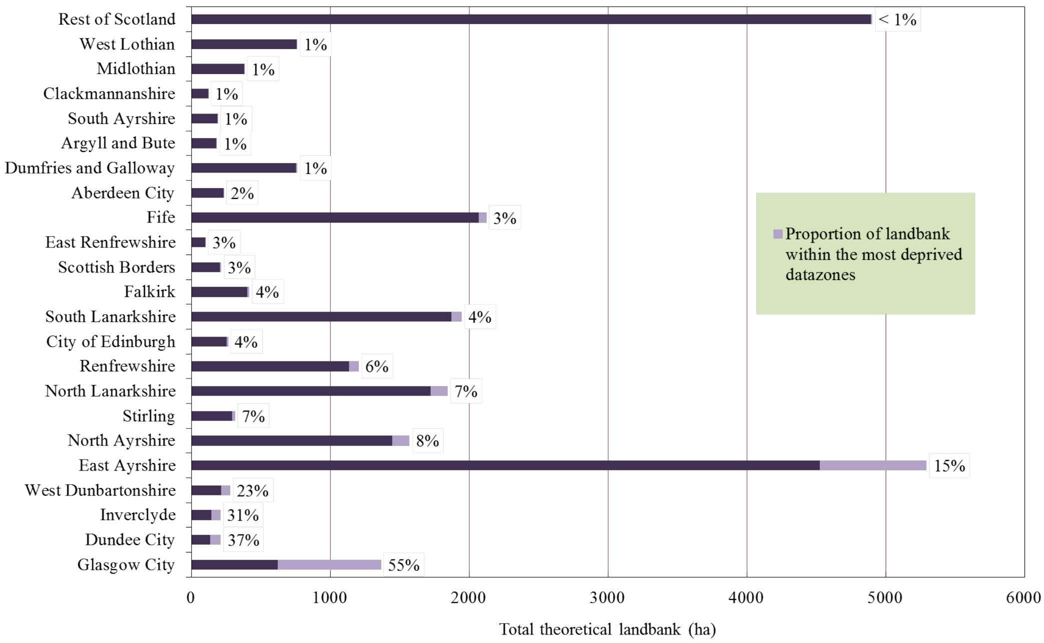


Figure 6.15: Amount of theoretical landbank located with the 15% most deprived datazones in each local authority as a proportion of the total amount of landbank in the authority - calculated using spatial database created in 2016 and SIMD data published in 2016

situated within the 15% most deprived datazones. After Glasgow City, Dundee City and Inverclyde have the highest proportion of landbank within deprived areas, with over 30% of the underutilised non-agricultural land in each authority being situated in the 15% most deprived datazones.

As outlined in section 3.6.2.1, this methodology mirrored the one utilised by Scottish Government (Scottish Government, 2016d) in relation to the vacant and derelict land. However, not only does the research conducted in this thesis extend this methodology to include all underutilised non-agricultural land, it also used site boundaries as the input for the analysis rather than a point representing the centre of a sites. This enabled a more accurate understanding of the amount of land within the most deprived areas in each local authority, and further highlights the advantages of building a spatial database containing the full extent of each site. This analysis gives an insight into the distribution of underutilised non-agricultural land in relation to deprivation. The ability to highlight regions where there is a high proportion of this land type in close proximity to deprived areas could drive the way this land is used in the future or even impact policy in relation to the reuse of brownfield land, landfill sites and abandoned mine land.

Whilst the presented analysis provides a rudimentary comparison between the distribution of underutilised non-agricultural land and deprivation it is evident that the detailed spatial database could benefit further research. As Chakraborty et al. (2011) explain GIS is well suited to investigate environmental justice although spatial data deficiencies are the most obvious barriers. There are a wide range of analysis techniques such as spatial coincidence analysis, distance-based analysis, pollution plume modelling and geographically weighted regression modelling (Chakraborty et al., 2011), all of which could integrate detailed spatial data such as that provided by the theoretical landbank. Bambra et al. (2014) utilise a linear mixed effect model to investigate associations between health outcomes and brownfield land in England. This study utilises data from the National Land Use Database, and the authors bemoan the fact this means they are required to create radii around points for further analysis, a process that involves multiple assumptions (Bambra et al., 2014). Maantay (2013) also conducts a comparison of derelict land, deprivation and health inequalities that could be furthered via the integration of more detailed spatial information. Maantay (2013) develops a scoring index for datazones based on a combination of factors such as SIMD, health indicators and proximity to vacant and derelict land which ultimately enables priority areas to be identified. Finally, Beames et al. (2018) undertakes a proximity analysis which includes an indicator based multicriteria evaluation combining several impact categories such as distance to schools, existing greenspace and shops. The multicriteria evaluation conducted in chapter 5 could combine similar categories to identify a technical landbank that could provide sustainable redevelopment options. Beames et al. (2018) declare the importance of detailed spatial data for such analysis as it integrates factors such as walking distances which are more accurately assessed when an accurate understanding of a site's boundary is attainable. This suggests that the spatial database created as part of this thesis would be an ideal resource for further investigative analysis.

By identifying areas which simultaneously suffer from higher levels of deprivation and greater quantity of underutilised non-agricultural land, these vacant and derelict land resources can be begun to be seen as an environmental justice issue. This should prompt regeneration policies that prioritise action regarding these 'stalled spaces', with the aim of reversing the negative impacts these land types have on socially and economically deprived zones within cities. This is only possible once a detailed understanding of the extent and distribution of these land types is achieved.

6.3.2 Investigating greenspace and nature opportunities that could be provided by underutilised non-agricultural land

Any assessment of the environmental burden caused by proximity to vacant and derelict land is heavily associated with calls to use this land resource as a source of greenspace or for the provision of nature. This competing potential end use is discussed briefly in section 2.7.3 and the beneficial role of biomass crops in greening has also been outlined in section 2.7.1. However, it is necessary to outline in more detail the potential role underutilised non-agricultural land could play with regard to greenspace provision and the foundation the research presented in this thesis can provide for further investigation of this opportunity.

Rather than focussing on the negative connotations associated with vacant and derelict land, increasingly it is being argued that these land types should be viewed as an environmental and social amenity (Boott et al., n.d.; Kamvasinou, 2011; Kim, 2016; Kim et al., 2018). Anderson and Minor (2017) claim that vacant land is an underexplored resource, framing the benefits of greening these areas within the three pillars of sustainability: environmental, social and economic. Regarding environmental impacts, it has been argued that these land types can play an important role for biodiversity, conservation and habitat connectivity (Lafortezza et al., 2004; Macadam and Bairner, 2012; Do et al., 2014; Anderson and Minor, 2017; Macadam et al., 2013). Furthermore, these spaces can provide carbon storage, microclimate regulation services, climate change mitigation effects, flood prevention, stormwater retention, reduce the heat island effect and aid pollination (Kamvasinou, 2011; Haase et al., 2014; Mathey et al., 2015; Anderson and Minor, 2017). It has even been suggested that these currently underutilised, neglected areas could be the source of new sustainable urban food production systems (Miner and Raftery, 2012), which could result in the provision of new jobs, reduced food miles and decreased food poverty (Haberman et al., 2014; White and Bunn, 2017).

Further social and economic benefits of utilising these spaces for greenspace provision have been suggested. Maantay (2013) argues that the greening of vacant land can improve community cohesiveness and environmental awareness, provide better neighbourhood aesthetics, decrease crime rates and create a strong focal point for cultural and educational activities. Kremer and Hamstead (2015) assert that whilst vacant land may be the by-product of decline inherent in capitalist economies, it has the potential to become crucial 'loose space' for non-capitalist production, fostering creativity and engaging marginalised communities. Elmqvist et al. (2015) also claim that these sites can be the focal point of social cohesion in urban areas as well as providing 'insurance value' to cities, aiding them to respond to climate change related events such as flooding. From an economic point of view, Zhang and Klenosky (2016) point to the positive impact conversion of previous industrial sites can have in terms of increasing property values, attracting development and promoting investment. Kim (2016) echoes this claim using Pennsylvania as a case study where greening of vacant land has resulted not only in a decrease in gun crime but also a 5% annual home value increase.

It is evident that the underutilised non-agricultural land captured in the spatial database created as part of this thesis can aid research regarding the role of vacant and neglected land in terms of greenspace provision. Previous research has highlighted that these 'in-between' spaces represent a broad and unique category of green infrastructure which could at once be low cost and socially valued (Kamvasinou, 2011). Efforts have been made to analyse the role of these land types in more detail, with Sanches and Pellegrino (2016) summarising methods of assessment for prioritising the reclamation of derelict and vacant land. These methods for assessing the prioritisation of reclamation have progressively integrated an increasing range of criteria. Herbst and Herbst (2006) provided one of the first assessments including factors relating to 'potential to experience nature', 'usability of site', 'potential users of sites' and 'importance of site in green space strategy'. This assessment investigated site characteristics and proximity to a range of indicators such as wildlife deficiency zones, greenspace networks, bike networks, schools and areas of dense populations (Herbst and Herbst, 2006). Sanches and Pellegrino (2016) included an even wider variety of assessment factors, incorporating socio-economic factors such as proximity to transport links, surrounding deprivation levels and social inclusion. These assessments rely on detailed information regarding sites, their distribution and extents such as that provided by the theoretical landbank.

Beyond these prioritising of reclamation assessments there are a variety of other models that have been developed to assess the impact of rehabilitating underutilised vacant spaces, all of which would benefit from the integration of more detailed spatial data representing the underutilised land resource. Lafortezza et al. (2004), for example, implement a GIS-based algorithm which defines which brownfield sites have the potential to sustain wildlife populations in connection with existing open space, visualising the pathways between habitat patches. Jackson et al. (2013) present a broader GIS-based mapping framework which creates 'traffic light' coded mapping representing the ecosystem service impact of land management decisions. Both studies explicitly underline the requirement for data of a sufficient quality.

Two studies that are particularly pertinent when considering the role detailed spatial information could play in understanding the opportunities provided by vacant land in Scotland have been conducted by Staples and Street (2006) and North Lankarkshire Council (2015). Both studies conduct assessments of the role of vacant and derelict land in Central Scotland. Staples and Street (2006) identify vacant and derelict land that could undergo environmental enhancement to contribute to the green network within the Glasgow and Clyde Valley area. More recently North Lankarkshire Council (2015) implemented an opportunity mapping methodology which employed GIS analysis to identify correlation and adjacency between numerous spatial indicators, including vacant and derelict land, to enable the identification of priority areas. This methodology inputs vacant and derelict land as an opportunity parameter alongside regeneration areas and underperforming greenspace and then investigates the opportunity provided by these areas regarding a set of priorities such as health and wellbeing, climate change adaptation, access to greenspace and habitat connectivity (North Lankarkshire Council, 2015). These priorities are represented by a variety of spatial datasets such as hospital admissions, surface water flooding, surrounding greenspace and Scottish Natural Heritage's priority habitat creation areas (North Lankarkshire Council, 2015). Both these studies are conducted using the vacant and derelict land survey data in the Central Scotland but could be extended to a wider selection of underutilised non-agricultural land and nationwide scale with the input of a detailed spatial database such as the theoretical landbank created as part of this thesis. Furthermore, if available at a suitable resolution, spatial datasets such as those used to represent priority indicators by North Lankarkshire Council (2015) could be integrated into a multicriteria evaluation to enable the identification of a technical landbank that could better provide green network opportunities.

The third National Planning Framework set out in Scotland has prioritised addressing the amount of vacant and derelict land (The Scottish Government, 2013), however little progress has been made as levels have remained constant (Scottish Government, 2016d). The ability to identify significant opportunities for the conversion of underutilised non-agricultural land to greenspace could aid policy implementation. Furthermore, a greater understanding of the opportunity provided by underutilised non-agricultural land could inform public policy such as the Scottish Land Use Strategy, the national planning framework and even Scottish biodiversity strategy. Furthermore, with those that live closer to greenspaces in Scotland being more likely to say their health in general has been good (Greenspace Scotland, 2012) there could even be public health policy implications of a detailed spatial understanding of currently overlooked, underperforming spaces.

6.3.3 Investigating housing development opportunities that could be provided by underutilised non-agricultural land

According to the Campaign for the Protection of Rural England, only 8% of brownfield land could be considered as having an important habitat role (Sinnett et al., 2014), according to their report this would leave a considerable amount of land left for providing much needed housing. As previously mentioned in section 2.7.3, the CPRE have claimed there is a suitable amount of brownfield land to build over 1 million homes in England (CPRE, 2018). On top of providing housing and avoiding unnecessary development of greenfield areas it has been reported that developments can have positive knock on effects for adjacent neighbourhoods (Baing and Wong, 2018).

Roncz and Szita (2010) summarise the range of assessment methods that have emerged to investigate sites in terms of their reutilisation value. These methods include ex-ante sustainability assessments, settlement planning, environmental protection assessments and material flow and life cycle assessment analysis (Roncz and Szita, 2010). Many of these assessments are site scale analysis that required detailed information about characteristics and extents of a site. Detailed spatial databases, such as that compiled as the theoretical landbank, provide vital grounding for such work and enable a platform that can be enriched with further spatial information relating to each site. Within the Scottish context, West Lothian Council have conducted an urban capacity study seeking to identify alternatives to greenfield development (West Lothian Council, 2009). The study includes brownfield land, public car parks, conversion of industrial buildings and the option of increasing density of housing on land already allocated for housing in the local plan (West Lothian Council, 2009)). The spatial database representing underutilised non-agricultural land could be integrated into similar urban capacity studies enabling an insight into the role this land resource could play in terms of housing provision at a national scale.

This chapter has presented a number of applications for a detailed spatial database representing underutilised non-agricultural land. The two exploratory spatial data analyses presented in this chapter give an insight into how more significant clusters of underutilised non-agricultural land can be identified for further assessment. The database not only lends itself to being integrated into established GIS-methodologies but the multicriteria evaluation approach used to identify the technical landbank for bioenergy provision has the potential to be adapted to investigate the opportunity this land resource could deliver regarding a variety of competing end-uses. Regardless of the specific end use, detailed spatial data enables more accurate analysis to be conducted. In many cases to further an understanding of the role this land resource can play more information is required regarding the characteristics at site-level, this is discussed in more detail in section 7.3.

Chapter 7

Conclusions and recommendations

Demand for biomass is rising fast due to the increasing inclusion of bioenergy pathways in countries' renewable energy and emission reduction strategies (Welfle, 2017). This demand is coupled with uncertainty surrounding the availability of land on which feedstocks can be sustainably produced. Agriculture already faces major challenges in delivering food security under increasing pressure from population growth and shifting consumption patterns (Popp et al., 2014). Using crop land for bioenergy provision not only exacerbates this food insecurity but the subsequent indirect land use change has been deemed to render biofuels 'worse than petroleum' (Searchinger et al., 2008). In response to the bioenergy land use dilemma, or food versus fuel debate, this thesis has aimed to understand the opportunity that could be provided by underutilised non-agricultural land types. However, in doing so it has also simultaneously provided a rigorous methodology to compile a spatial database of often 'overlooked' land types which could provide opportunities related to several end uses.

The research presented in this thesis has been framed by the 'marginal' land discourse, which has emerged as one alternative solution to the requirement for additional land. The literature review, in chapter 2, presented a discussion of the limitations of 'marginal' land approaches as well as an assessment of the extent to which these studies include non-agricultural land types. In doing so the literature review attempted to answer the following research questions:

- To what degree does the 'marginal' land discourse sufficiently identify a sustainable landbank for future renewable energy provision?
- How well understood is the contribution that non-agricultural land types could play as a source of sustainable bioenergy provision?

Having identified suitable underutilised non-agricultural land types that could be considered in Scotland, a GIS based methodology was developed to determine the quantity and distribution of this land resource. Having compiled a spatial database representing the theoretical landbank, the hypothetical maximum amount of land available, a multicriteria evaluation was undertaken along with exploratory spatial data analysis to identify significant clusters of technical landbank. Via the development of a bottom-up site-based methodology, in chapter 3, and subsequent presentation of results, in chapters 4 and 5, the following research questions were answered:

- What is the best way to identify the collective area and distribution of underutilised non-agricultural land in Scotland?

Chapter 6 provides a discussion of opportunities that could be explored using the identified spatial databases, whilst also suggesting alterations to the multicriteria evaluation in order to find technical landbanks for alternative applications. Two examples of exploratory spatial data analysis were presented, alongside further evaluation of the value of detailed spatial information representing underutilised land. In doing so this chapter sought to answer the following research question:

- What are the potential applications for a landbank representing underutilised non-agricultural land?

In this chapter a discussion of the key findings will follow, in section 7.1, outlining the extent to which these research questions have been answered. The results of this thesis will be contextualised by previous research to not only highlight its contribution to knowledge but also verify the methods used. This will lead into suggestions for future research which can build on the foundation provided by this study, and a note on future practice for the application or extension of this methodology as well as a mention of the limitations of this research.

7.1 Discussion of key findings

This research has identified 24,862 hectares of underutilised non-agricultural land in Scotland. The theoretical landbank represents both the first attempt internationally to produce a detailed spatial database of brownfield land at a national scale and the first national quantification of the size of SEPA licensed landfill sites in Scotland, for both authorised and closed, in terms of area. Furthermore, the inclusion of historic landfill and abandoned mine land has led to the identification of an additional land resource that could be considered for bioenergy provision.

Bardos (2009) has claimed that the potential exists to use a mapping approach to identify realistic opportunities for growing biomass on brownfield and contaminated land types if better quality data can be collated from data providers. The work presented in this thesis has realised that potential in the context of Scotland by providing GIS boundaries for underutilised non-agricultural land types. The initial objective for identifying this land resource was to highlight the opportunity that it could provide as a source of sustainable bioenergy. A multicriteria evaluation was therefore tailored to identify the proportion of the theoretical landbank that could be implemented with this end use in mind. The 17,404 hectares of technical landbank identified represents 74% more land than is currently planted with miscanthus and short rotation coppice in England and Wales. The use of this land for energy crops would not impact food security or cause indirect land use change.

The theoretical landbank represents 0.32% of the total land area of Scotland. When viewed in the context of previous research this is an encouragingly high proportion. The most thorough and significant previous study, in relation to the research presented in this thesis, is the national scale assessment undertaken by Niblick and Landis (2016). Niblick and Landis (2016) considered the renewable energy potential of federally funded brownfields, closed landfills and abandoned mine lands in the United States based on 3 separate databases, and found 2.82 Mha of land, 0.29% of the total land area in the United States (Niblick and Landis, 2016). The findings presented in this thesis are particularly significant when you consider that the land types included by Niblick and Landis (2016), such as federally funded brownfields, come with an assumption of land contamination. This is not necessarily the case with the land identified in Scotland. The technical landbank, and application of constraints, was the first step towards identifying significant clusters of land that could be available for bioenergy provision. The 17,404 hectares identified equates to 0.22% of the total land area in Scotland. This proportion is now lower than the 0.29% identified by Niblick and Landis (2016), as is to be expected given that there were no constraints applied in their assessment of resource availability. The research presented by Niblick and Landis (2016) suffers from the limitation that is common amongst all the reviewed literature - quality of data. Whilst Niblick and Landis (2016) compile data from several databases, the only data quality assurance undertaken is the removal of sites recorded with null or zero area, and the subsequent joined database represents sites only as points. The literature review conducted in this thesis has shown that in order to better understand the contribution that non-agricultural land could have towards the provision of sustainable bioenergy a more detailed assessment of the resource is required.

The methodology developed as part of this thesis, presented in chapter 3, provides a GIS based bottom-up approach to compile a spatial database representing underutilised non-agricultural land. GIS is a strong tool for identifying the quantity and distribution of hard to depict land use, and the integration of aerial imagery allows the current use of land to be considered. By not only identifying the hypothetical maximum amount of land available, the theoretical landbank, but also the proportion of this land that would be available once a range of technical constraints are applied, the technical landbank, the methodology enables a greater understanding of the significance of this land resource. In doing so this research has addressed a problem identified by Spiess and De Sousa (2016), who claim early assessments of brownfield land potential take a macroscopic approach. Citing Adelaja et al.'s (2010) investigation into the potential of solar and wind energy on brownfields in Michigan, Spiess and De Sousa (2016) argue that the inclusion of all identified sites for energy generation 'finds little applicability in reality'. The same criticism can be applied to the research presented by Niblick and Landis (2016) who, by representing sites merely as a set of points, are unable to discount any sites based on characteristics within their bounds such as topography. This thesis, and the methodological progression from theoretical to technical landbank, therefore has stepped beyond this macroscopic approach to give a greater insight into the opportunity that could be provided by areas of non-agricultural land for bioenergy provision.

Underutilised non-agricultural land has thus far been relatively overlooked in efforts to identify alternative land for bioenergy provision. Previously, marginal land had emerged as a potential solution to the bioenergy land use dilemma, and there has been an increase in the number of assessments into the availability of this resource. However, as discussed in chapter 2, there are a number of issues that arise related to marginal land approaches. At the forefront of these problems is the lack of a clear definition regarding what constitutes marginal land and no consistency in application of the terminology across studies. Further issues include the temporality of marginality and a tendency to shift away from an economic-based definition towards marginal land becoming an all-embracing umbrella term for idle, barren, abandoned or degraded land (Dauber et al., 2012). This leads to criticisms of marginal land, such as doubts about its fitness for use for sustainable crop growth, being applied to the wide range of land types included across the studies. Moreover, the application of a vague definition of marginal land leads to difficulty in identifying locations in practice which results in uncertainty as to how accurately sustainable land types are being targeted. Dauber et al. (2012) argue that when considering land for bioenergy provision it is imperative to take into account the true existing use of the land in contrast to a broad land use, yet most marginal land studies are reliant on poor resolution land cover datasets as the basis for the assessment of resource Lewis and Kelly (2014). This had led both to the inclusion of land that arguably cannot be used sustainably and the omission of hard to depict land uses that are difficult to capture in broad-scale geospatial datasets. Underutilised non-agricultural land provides a good example of one of those land types that is difficult to identify from low resolution land cover datasets and the approach taken by marginal land studies towards including this land resource further highlights the lack of consistency amongst studies. The analysis of the literature conducted in section 2.5 identified 15 marginal land studies which include some form of non-agricultural land. As expected the definition of marginal land employed varies amongst these studies, mirroring the findings of Lewis and Kelly (2014). The dissimilarities amongst the 15 studies extended to the selection of non-agricultural land types, therefore unsurprisingly the amount of this land resource as a proportion of the total assessed land cover varied widely from 0.005% to 24%. These findings, and the lack of consistency they reflect, suggests that there was a need to investigate non- agricultural land separately from other marginal land types, using a more robust methodology - as has been undertaken in this thesis.

Whilst the technical landbank was created with the objective of identifying land for bioenergy provision, the theoretical landbank represents a unique resource for investigating the role of these previously overlooked land types in terms of a range of end uses. Chapter 6 presented a discussion of the research efforts which would benefit from a more detailed spatial understanding of underutilised non-agricultural land, in addition to presenting two examples of exploratory spatial data analysis that can be undertaken using the databases. Three techniques were implemented comparing the supply of land with heat demand. Whilst the techniques used only evaluated the spatial relationship between potential supply from non-agricultural land and current demand, they could help target and justify future work in several ways. The first two techniques highlighted the high level of heat demand in and surrounding Glasgow City. The second and third technique highlighted specific datazones such as Strathhaven North, South Lanarkshire or Possil Park, Glasgow which have a high heat demand coupled with a large amount of technical landbank within a 40km radius. Previous efforts to compare heat supply and demand at a national scale have predominantly undertaken a raster-based modelling approach. Wang et al. (2014) for instance, divide the United Kingdom into 10km x 10km grid cells in order to model the optimal distribution of miscanthus and short rotation coppice on agricultural land and its potential contribution to heat and electricity demand. However, Blaschke et al. (2013) argue that this purely technical cell-based view of energy demand and supply may be regarded as reductionistic. Whilst this lower resolution cell-based approach may be suitable for modelling the contribution of agricultural land at a national scale, as undertaken by Wang et al. (2014), it would not be appropriate for assessing the role of non-agricultural land. The techniques utilised in this thesis have identified clusters of supply and demand at a local level where more detailed modelling could be undertaken to understand the contribution non-agricultural land supply could have towards meeting heat demand. The relationship between theoretical landbank and areas of deprivation was also explored using the Scottish Index for Multiple Deprivation dataset (Scottish Government, 2016b). This highlighted that in some areas there is a greater proportion of land falling in more deprived areas, for instance, 55% of all the underutilised non-agricultural land in Glasgow City is situated in the 15% most deprived datazones. Previously, Donaldson and Lord (2018) suggested that derelict urban land could be used for ground source heating to address fuel poverty by virtue of its spatial association with social housing in Glasgow. Similarly, the work presented in this thesis suggests there may also be additional benefits, in terms of greening and remediation, of siting dedicated energy crops on the 745 hectares of non-agricultural land in the most deprived datazones in Glasgow.

The two exploratory spatial data analyses cases provide an insight into how the opportunities provided by underutilised non-agricultural land can be further understood. However, the discussion presented in Chapter 6 highlights that the theoretical landbank could contribute detailed spatial data to a range of further research efforts, from the opportunity for greenspace provision to the provision of housing. Similarly, the multicriteria evaluation utilised to estimate the technical landbank for bioenergy provision could be altered to identify the proportion of the theoretical landbank that could provide opportunities relating to alternative end uses. The research presented in this thesis has provided a methodology enabling a detailed understanding of a land resource that is often undervalued and overlooked. This foundation can enable informed decisions to be made regarding the future use of these vacant spaces.

Finally, this thesis has also underlined the multitude of sources of uncertainty that can arise when developing a detailed representation of a land resource. It is assumed that the results presented are more susceptible to gross error due to the compilation of data from multiple sources, and therefore it was not possible to report the results with a great precision. It is, however, also apparent that the theoretical landbank is most likely inaccurate by virtue of being an underestimate, based on the missing responses from local authorities regarding historical landfill and the inclusion of abandoned mine land from only three authorities. Bardos (2009) also surmised that any such efforts to compile information on historically contaminated land in England and Wales would likely be a minimum estimate due to the mixed response of local authorities to Part 2A of the Environmental Protection Act 1990 (DEFRA, 2012). Bardos (2009) highlights an Environmental Agency report (Environmental Agency, 2007) which claims most local authorities in England and Wales had inspected less than 10% of their areas for contaminated land by the end of March 2007. If it is assumed that the rate of inspection is similar in Scotland and progress has continued at the same pace since 2007 then there is potentially an even greater amount of historic landfill area yet to be discovered.

7.2 Limitations

In terms of applicability, it has already been noted that the methodology presented in this thesis is only suitable for use within developed countries. This is due to the difficulty in categorising land as underutilised and a different approach to regeneration of waste disposal or industrial sites adopted in developing countries. Furthermore, whilst the methodology should be applicable in most developed countries, care must be taken when doing so. As Kang et al. (2013) outline, management strategies of these land types differ in different places, as such what may be considered available for regeneration in one country may not be available elsewhere.

The creation of the spatial database is an attempt to move beyond the macroscopic approach criticised by Spiess and De Sousa (2016). However, it is evident that a GIS-based methodology is still removed from the situation on the ground and can only provide an initial insight into the opportunity that could be provided by underutilised non-agricultural land. As discussed in the following section, there are a variety of methods for compiling further information about site characteristics with ground truthing providing the most reliable. These methods are necessary to ensure a sites suitability for reuse is fully understood. It is also necessary to underline that the landbanks only provide a snapshot of the availability of the underutilised non-agricultural land resource at one moment in time. This in turn affects any conclusions that can be made from further analysis which utilises the spatial databases. To appropriately address this issue the databases must be regularly updated, as discussed in section 7.5.

There are several methodological choices that were forced due to the scope of this research. This includes the choice of Boolean multicriteria evaluation and the reliance on previous literature for various availability threshold limits. In both instances the main alternatives involve stakeholder involvement to inform decision making. There are a range of stakeholders involved in regeneration of these land types and the contribution of these stakeholders alongside public participation can aid sustainable land use decision making (Rizzo et al., 2015). Calvert et al. (2013) have called for greater communication links between researchers and stakeholders via appropriately designed geoinformation infrastructures which integrate elements such as web-mapping or participatory GIS. Morio et al. (2013) have even designed a multicriteria algorithm which factors in stakeholder preferences when determining optimal land use. There is therefore scope for stakeholders to be more involved in research design and implementation than was possible during the research presented in this thesis.

7.3 Recommendations for future research

This thesis has identified the availability of underutilised non-agricultural land types within the context of Scotland. However, there is potential for the methodology to be applied elsewhere and even for further land types to be included. A natural extension of this research would involve an assessment of the non-agricultural land resource in England. Whilst the National Land Use Database provides statistics on previously developed land (Homes and Communities Agency, 2014), not only was it discontinued in 2012 but it does not give a detailed insight into the brownfield land resource. Indeed, as the Campaign to Protect Rural England report (CPRE, 2016) outlines, it provides a far from complete view. This was highlighted by pilot studies prompted by the Housing and Planning Act (Parliament of the United Kingdom, 2016) which saw a 69% increase in the amount of brownfield identified compared to that reported in the NLUD. The CPRE (CPRE, 2016) concluded that brownfield registers are urgently needed to provide a comprehensive understanding of brownfield capacity in England and any future research would need to work alongside local authorities to compile such a register before producing a detailed spatial database of sites. Nevertheless, once this preliminary step is taken the methodology presented in chapter 3 could then be used to gain an accurate representation of brownfield land and the opportunity it could play in provision of sustainable bioenergy. Additional data is already available in England regarding historic landfill sites and closed mining waste facilities (Environment Agency, 2013). In addition to applying the methodology to other locations, there is also the possibility that more land types could be included in the analysis.

Whilst the work undertaken in this thesis focussed on brownfield land, landfill and abandoned mine land, a range of additional land resources could potentially be considered regarding the potential to use them for siting bioenergy feedstocks without impacting on agriculture. Land types that could be included in future research include land surrounding active transfer stations, wind farms, infrastructure and water treatment facilities plus excess amenity land. If the methodology is extended to any of these land types more care will need to be taken to ensure only underutilised land is included. Establishing a land typology would aid future efforts to produce an inventory of underutilised non-agricultural land. Kim (2016) created a land typology for urban vacant land including 5 categories. A similar approach could be taken to form a land typology for underutilised non-agricultural land, enabling easier applications of methodologies such as the one presented in this thesis in addition to allowing a better understanding of the various obstacles of each included land type.

Whilst this thesis has sought to compile detailed boundary information on underutilised non-agricultural land, the spatial database created can be enriched with a range of additional information. One of the biggest obstacles to utilising the land types included in this research for bioenergy provision, as outlined in section 2.7.2, is poor quality site conditions such as shallow soil depth, compaction, in addition to the presence of contamination and building remains. Ground truthing of sites identified in the spatial database would be required to fully understand the conditions present and would allow the additional attribute information to be added to the GIS boundaries. Site visits would also enable a better understanding of any errors in the database and would allow boundary locations to be verified. Unfortunately, site visits may not be practical in which case other techniques could be used to gain additional information about individual sites. Burke et al. (2015), Schädler et al. (2012) and Hartmann (2014) each took different approaches to gaining further information about brownfield sites. These included site investigations coupled with mine plans to reveal potential geological hazards (Burke et al., 2015), collation of site and land use spatial information to identify the proportion of sites that require remediation and estimated clean-up costs (Schädler et al., 2012), and the integration of a business analysis of energy purpose redevelopment of specific sites (Hartmann, 2014). These three studies have shown that further research can identify additional information on a site-by-site basis to inform reuse or redevelopment options. Such an approach could be taken to enrich the spatial database compiled as part of this thesis. Furthermore, surveying methods such as the use of LiDAR data have previously been used to identify buildings or obstacles (Hermosilla et al., 2011), an approach that could be integrated into further analysis of non-agricultural site conditions. De Wet (2016) used LiDAR data alongside historic photography to increase the robustness of data about abandoned waste disposal sites in Lancaster County, Pennsylvania. The use of LiDAR by De Wet (2016) enabled a better understanding of topography, site extents and allowed depth estimates. However, the author concludes that whilst remote sensing data is useful, on site field observations, near surface geophysics mapping and sampling will always be needed to compliment remotely derived data.

7.4 Implications for academia

It is clear that a detailed understanding of these underutilised land resources could aid established fields of research to shed light on the re-use value not only for access to open space, habitat creation and avoidance of development of greenfield areas but also for community public health and neighbourhood regeneration (Maantay, 2013). Furthermore, in terms of bioenergy provision the exploratory spatial data analysis techniques conducted using the technical landbank has highlighted rudimentary spatial relationships between potential supply and heat demand and highlighted areas where future research could be targeted. To fully understand the degree to which underutilised non-agricultural land can contribute to meeting heat demand, a better understanding of the yield of biomass that could be attained from these sites is required, as discussed further in Chapter 6.

Whilst much of the research presented in this thesis is framed by the need to find sustainable land for bioenergy provision, it is notable that much of the methodology has much wider applicability. The creation of the theoretical landbank is necessary regardless of the intended end use of the land resource. The multicriteria evaluation, presented in chapter 5, was tailored to identify the proportion of the theoretical landbank that may be suitable for bioenergy provision (see Figure 7.1). However, as discussed in Chapter 6, this technique can be adapted utilising differing constraints to identify a technical landbank with an alternative regeneration option in mind.

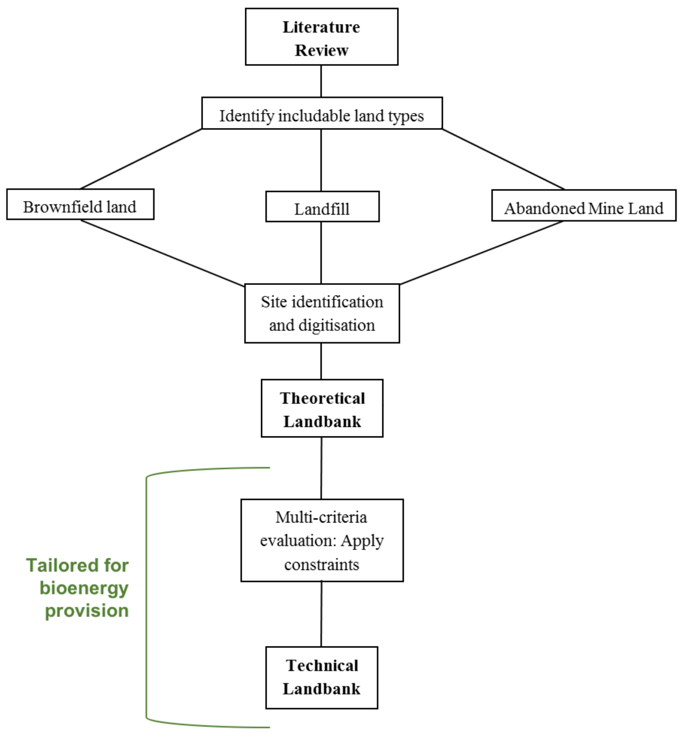


Figure 7.1: Research design implemented in this thesis highlighting general applicability of theoretical landbank - adapted from Figure 3.3

The majority of previous research efforts have focused on the role of brownfield land and the various regeneration opportunities this land type could provide. This research has shown there is a wider set of land categories that are currently underutilised and often disregarded. In grouping these land types and establishing a methodology for enabling an understanding of the quantity and distribution, a more significant collective resource can be investigated in terms of its potential future role whether that be within the bioenergy supply chain or the regeneration of deprived neighbourhoods. Furthermore, this research has set a precedent for the level of detail that should be required to make informed decisions regarding the role of this land resource. It has shown that a greater level of spatial detail should and could be achieved for databases representing underutilised non-agricultural land types.

7.5 Recommendations for future practice

From a local authority perspective, it is hoped the findings in this research will highlight the benefit of a GIS approach to data collection. Whilst the majority of authorities had GIS data regarding vacant and derelict land, there is still a lack of consistency regarding data standards which became apparent when attempting to collate datasets. Local authorities would benefit from following strict metadata standards, even across different departments within the same organisation, which will enable the data to be more readily used in the future and make integration with data from neighbouring authorities easier. It would also be beneficial for local authorities to be clearer about the extent to which they have inspected for contaminated land in response to Part 2A of the Environmental Protection Act 1990. Local authorities have the opportunity to create a detailed understanding of the underutilised non-agricultural land resource in their area, and digitised sites could be integrated into local development planning (Scottish Government, 2017a). Any attempt made by local authorities to create a spatial database must take into account sources of uncertainty that may arise and these should be addressed where appropriate.

As outlined in section 3.2.1, uncertainty can be introduced into GIS analysis at various points as attempts are made to conceive, capture and analyse real world features. Any future implementation of the methodology developed as part of this thesis needs to be aware of the key sources of uncertainty and ensure measures are taken to reduce the impact they could have on any results. Firstly, clarity in the conception of the entity being measured is vital, avoiding both vagueness and ambiguity. If the methodology presented in this thesis is to be utilised, for instance, then includable land types and the definition of 'underutilised' being employed needs to be outlined. This is particularly pertinent if the work is being conducted by a team rather than an individual, to ensure consistency in the application of methods to identify suitable land.

The creation of a spatial database can lead to introduction of further uncertainty as geographical phenomena are measured and represented. Any future work must be aware of the sources of error that may arise during the process of digitisation and take steps to reduce them, such as the consistent selection of suitable scale at which to digitise. Any future implementation of the digitisation methodology must note the quality of the base-mapping or aerial imagery data which is used as the quality of the mapping on which digitisation is based can impact the spatial accuracy of resulting digitised features. The temporal accuracy of any future attempt to compile a spatial database representing non-agricultural land types elsewhere must be considered. As previously discussed in section 3.4.6, the theoretical landbank presented in this thesis provides only a snapshot of the availability of land, and updating the database was beyond the scope of the work undertaken. However, any future attempt to compile a spatial database needs to be created using a framework that can be readily, and easily, updated with the most up-to-date data. Moreover, to avoid further uncertainty related to temporal accuracy, care must be taken to use the most up-to-date aerial imagery as the basis for digitisation because the use of these land types can often shift - particularly abandoned mine land.

One of the greatest sources of uncertainty, when implementing the methodology presented in this thesis, arises from the compilation of data from various sources. Any future work must find out as much as possible about the data which is collated. Furthermore, care must be taken to record information about datasets, attained or newly created, in the form of metadata. Suitable metadata will then reduce uncertainty at the analysis stage. Further analysis undertaken must ensure consistency in the co-ordinate system and datum applied, particularly when combining data from multiple sources. The multicriteria evaluation undertaken in this thesis involved a range of threshold values used to select suitable land which were justified where appropriate. Any future application of this approach must also justify the threshold values used. Future work could also include a sensitivity analysis, whereby each parameter is changed incrementally and the impact on the resulting area of land identified can be assessed (ESRI, 2006).

Despite the above issues related to uncertainty and data quality, the Scottish Government could extend the Vacant and Derelict Land Survey to include GIS boundaries, providing an up to date, complete and shareable resource. In doing so it can ensure INSPIRE spatial data standards are maintained and appropriate metadata is recorded (European Commission, 2018). The government has started to publish pdf maps for most local authorities' vacant and derelict land reports. However, some of these maps only contain point data whilst other authorities are missing, and none of the data is available to download (Scottish Government, 2017d). Similar efforts to the vacant and derelict land survey could be made to provide a national dataset representing historic landfill, like that available in England (Environment Agency, 2013). The availability of abandoned mine land is complex and ever changing, linked to the status of any restoration bond in place. The Scottish Government set up the Scottish Opencast Coal Task Force in 2013 to ensure the optimum outcome regarding abandoned mine land (Scottish Government, 2016c). This task force could work towards providing clearer guidance on the progress of restoration of sites, including the mapping of areas that could be temporarily or permanently planted with dedicated energy crops.

7.6 Conclusion

According to Bardos et al. (2011), current broader scale assessments of underutilised, derelict land do not withstand detailed scrutiny, instead a detailed GIS based approach is required to provide authorities with estimates of the scale of opportunity. This thesis has provided a methodology for gaining a detailed understanding of the underutilised non-agricultural land resource and in doing so has provided a framework for bettering our understanding of the opportunities that this previously overlooked land resource could represent. This research has identified a 24,862 hectare landbank in Scotland, and has explored the potential role this land could play in terms of bioenergy provision. Moreover, this research has highlighted the many applications of a spatial database representing underutilised non-agricultural land in addition to exploring methods for moving towards a technical landbank for such applications. Finally, according to Myers and Wyatt (2004) gaps in the flow of information prevent the transition from policy to reality, restricting the opportunity of sustainable allocation of resources. It is hoped that the theoretical landbank presented in this thesis can prompt an improved flow of information related to these underutilised non-agricultural land types in order for the sustainable land regeneration opportunities to be better understood.

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Appendix A

A.1 Example of end user license agreement

Ordnance Survey

Protect – contracts

Public Sector (Scotland) End User Licence

This End User Licence is made on the day of Tuesday 18th February 2014 between:

(1) **Midlothian Council** of Midlothian House, Buccleuch Street, Dalkeith, EH22 1DN (the **Licensor**); and

(2) **University of Strathclyde** of 16 Richmond Street, Glasgow, G1 1XQ (the **End User**).

Background

The Licensor is a Public Body licensed by Ordnance Survey to use Supplied Data upon particular terms. This End User Licence is entered into pursuant to the Licensor's licence with Ordnance Survey, to set out the terms upon which the End User is licensed to use Supplied Data

1 Definitions & Interpretation

Commercial Activity	means any activity which involves or is intended to involve Financial Gain.
Competing Activity	means an activity that has been determined as a competing activity, or is in the process of being reviewed, pursuant to the terms of the licence between Ordnance Survey and the Licensor.
Core Business	means any of the Licensor's public sector activity, excluding any Commercial Activity and Competing Activity.
Financial Gain	means any revenue or credit received which exceeds the incremental costs of supplying or making available to a recipient any copy of any Supplied Data. Financial Gain does not include any receipts from Statutory Charges.
End User Purpose	means the End User using the data to respond to, or interact with the Licensor to deliver or support the delivery of the Licensor's Core Business.
IPR	means intellectual property rights, including copyright, patent, trade mark, design right, database rights, trade secrets, know how, rights of confidence and all other similar rights anywhere in the world whether or not registered and including applications for registration of any of them.
Ordnance Survey	means the Secretary of State for Business, Innovation and Skills, acting through Ordnance Survey whose principal place of business is at Explorer House, Adanac Drive, Southampton, SO16 0AS.
Statutory Charge	means charges which the Licensor or End User is expressly permitted to charge pursuant to a formal written enactment of a legislative authority that governs the United Kingdom of Great Britain and Northern Ireland, Scotland, Wales, and/or Northern Ireland to which the Licensor or End User is subject.
Style Guide	means the then current version of the style guide available on Ordnance Survey's Website including electronic artwork and requirements as to the use of acknowledgements of copyright and database right ownership.
Supplied Data	means the data provided by the Licensor to the End User under the terms of this End User Licence.
Term	means the period required to fulfil the End User Purpose, which shall under no circumstances exceed the duration of the licence between Ordnance Survey and the Licensor.
Use	means copying, using and/or amending whether in electronic or paper form, only to enable the End User to undertake the End User Purpose and Using shall have an equivalent meaning.
Website	means the website http://www.ordnancesurvey.co.uk or such other website as Ordnance Survey determines from time to time.

2

2.1 In this End User Licence, unless the context otherwise requires:

2.1.1 words in the singular include the plural and vice versa;

2.1.2 references to: a) a Clause or Appendix are to a clause or appendix of this End User Licence; b) a party are to a party to this End User Licence; and c) a statute or statutory provision include any amendment, extension or re-enactment of such statute or provision.

3 Licence

3.1 In consideration of the acceptance by the End User of the terms of this Licence offered by the Licensor, the Licensor grants to the End User a non-exclusive, non-transferable licence (revocable pursuant to the terms of this End User Licence) to Use Supplied Data for the End User Purpose for the Term.

3.2 This Licence is limited specifically to the rights granted in Clause 2.1 and subject to the obligations set out in the remainder of this Licence, in particular the End User's obligations set out in Clause 3. This Licence allows the End User personally (not any affiliated body or group) to use Supplied Data only to the extent required for the End User Purpose, but does not allow the End User to use Supplied Data for Commercial Activity and/or any Competing Activity.

4 End User's Obligations

4.1 The End User shall Use the Supplied Data exclusively for the End User Purpose and for no other purpose.

4.2 The End User shall:

a) ensure that the Supplied Data is not copied, adapted, varied or modified except to and only to the extent to which any of those acts are expressly permitted by this Licence;

b) ensure that it does not use the Supplied Data for any Commercial Activity and/or for a Competing Activity;

c) not use Supplied Data for any illegal, deceptive, misleading or unethical purpose or otherwise in any manner which may be detrimental to the reputation of Supplied Data or any person;

d) use its best endeavours to use adequate technological and security measures Ordnance Survey or the Licensor may reasonably recommend from time to time, to ensure that all Supplied Data which the Licensor provides the End User and which the End User holds or is responsible for are secure from unauthorised use or access;

e) notify the Licensor and/or Ordnance Survey as soon as it suspects any infringement of Ordnance Survey's IPR and give the Licensor and Ordnance Survey all reasonably required assistance in pursuing any potential infringement or remedying any unauthorised use;

f) ensure that any copy protection measures are not altered;

g) include a background watermark to identify the source of the Supplied Data on any electronic copies of the Supplied Data at map scales of 1:10 000 or larger scale and any Addressing datasets. The watermark must appear at least once and cover at least 10% of the map image reproduced;

h) ensure that acknowledgements of copyright and database right ownership and any licence number provided with the Supplied Data are included in a conspicuous position in all copies of Supplied Data in compliance with the Style Guide; and

i) ensure that any Use of the Supplied Data must show the appropriate trade mark notations, which shall be notified to the End User by the Licensor, and shall not tamper with or remove any of the trade mark symbols or notices which are shown on any Supplied Data.

4.3 This End User Licence does not give the End User the right to sub-license, distribute, sell or otherwise make available the Supplied Data to third parties save where expressly permitted in writing by the Licensor and Ordnance Survey.

5 Termination

5.1 Either party may terminate this End User Licence with immediate effect at any time by giving notice to the other party in writing.

5.2 This End User Licence will terminate automatically with immediate effect in the event that (i) the Licensor's licence with Ordnance Survey is terminated or expires, or (ii) the End User is in material breach of this End User Licence.

The Licensor will inform the End User of such termination as soon as practicable following such termination.

5.3 In the event of termination or expiry of this End User Licence, the End User shall within 30 days of such termination or expiry destroy (or at Ordnance Survey's or the Licensor's option return) all the Supplied Data in any media which it holds or for which it is responsible (including any Supplied Data embedded in any other material) and provide, at Ordnance Survey's or the Licensor's request, a sworn statement by a duly authorised person that it no longer holds any Supplied Data.

5.4 Those Clauses intended to survive termination or expiry (including, without limitation, Clauses 1, 3.2 d) and e), 4.2 to 4.4, 5, 6, 8, 10, 11 and 12) shall continue in full force and effect notwithstanding such termination or expiry.

6 Limitation

6.1 Subject to Clause 5.2, nothing in this Licence shall make the Licensor liable in contract, delict (including without limitation negligence, pre-contractual or other representations) or otherwise arising out of or in connection with this Licence for:

a) any economic losses (including without limitation loss of revenues, profits, contracts, business or anticipated savings);

b) any loss of goodwill or reputation;

c) any special, indirect or consequential losses in any case whether or not such losses were within the contemplation of the parties at the date of this Licence.

6.2 Nothing in this Licence shall exclude or limit liability of a party for death or personal injury resulting from the negligence of that party or its servants, agents or employees or for fraudulent misrepresentation.

6.3 The Licensor and Ordnance Survey exclude to the fullest extent permissible by law all express or implied warranties.

6.4 Subject to Clause 5.2, the Licensor's total liability in this Licence in aggregate shall not exceed any sum paid by the End User for the Supplied Data.

7 Indemnity

7.1 The End User shall indemnify and keep indemnified the Licensor and/or Ordnance Survey against all their liabilities and losses and all demands, liabilities, claims made, or proceedings brought, against the Licensor and/or Ordnance Survey in respect of any loss or damage and against all costs and expenses reasonably incurred in dealing with or in settling such demands, liabilities, claims or proceedings arising from the acts, omissions or defaults of the End User relating to this Licence or from the breach of any provision of this Licence by the End User except to the extent that any such liability is directly attributable to any negligent act of the Licensor.

7.2 The Licensor shall use reasonable endeavours to notify the End User as soon as practicable of any demand or claim made, or proceedings brought against the Licensor in respect of any relevant loss or damage.

8 Variation

8.1 The Licensor shall be entitled to vary this End User Licence with immediate effect by giving notice in writing to the End User.

9 Auditing

9.1 Upon Ordnance Survey's or the Licensor's written request, the End User shall provide written evidence of compliance with its obligations under this End User Licence.

9.2 The End User shall maintain accurate and complete records of its use of the Supplied Data. Ordnance Survey and/or the Licensor (and their respective representatives) have the right on reasonable notice during business hours to enter the End User's premises and to inspect and audit its systems, operations and all supporting documentation to ensure the End User's compliance with this End User Licence and to take copies of any necessary records. The End User shall, at its expense, make appropriate employees and facilities available to provide Ordnance Survey and/or the Licensor with all reasonable assistance to enable such inspection, auditing and copying to take place.

9.3 The End User will comply with reasonable measures stipulated by Ordnance Survey or the Licensor as a result of any audit.

10 Assignment, subcontracting and sublicensing

10.1 Except as agreed in writing by Ordnance Survey, neither party is entitled to assign, license, transfer or novate any of their rights and/or obligations under this End User Licence.

11 Rights of Third Parties

11.1 Subject to Clause 10.2, a person who is not a party to this End User Licence has no right as a third party to enforce or enjoy the benefit of any term of this End User Licence.

11.2 The End User acknowledges the interest of Ordnance Survey in relation to the Supplied Data and the parties hereby confer upon Ordnance Survey the right to enforce the terms of this End User Licence and pursue any claims pursuant to this End User Licence as if it is was the Licensor.

12 Waiver

12.1 The waiver on a particular occasion by either party of rights under this End User Licence does not imply that other rights will be waived.

12.2 No delay in exercising any right under this End User Licence shall constitute a waiver of such right.

13 Governing Law and Jurisdiction

13.1 This End User Licence is governed by Scots law and both parties submit to the exclusive jurisdiction of the Scottish courts.

IN WITNESS WHEREOF these presents consisting of this and the preceding **4** pages are subscribed for the parties as follows:

Signed for and on behalf of **Midlothian Council**

Witness

Fraser James

Witness Name

Fraser James

Witness Address

Midlothian House,
Buccleuch Street,
Dalkeith,
EH22 1DN

Authorised Signatory

[illegible]

Full Name of Signatory

Stephen Grant MacPhail

Date of Signing

18/02/2014

Place of Signing

Dalkeith, Midlothian

For and on behalf of **University of Strathclyde**

Witness [illegible]

Witness Name

MICHAEL CANNON

Witness Address

University of Strathclyde
Research & Knowledge Exchange Services
50 George Street
Glasgow
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Authorised Signatory [illegible]

Full Name of Signatory

[illegible]

Date of Signing

7 March 2014

Place of Signing

Glasgow

A.2 New grid references for sites in SEPA landfill capacity report (SEPA, 2012)

License number	Operating organisation	Site name	New grid reference	Easting	Northing
WML/E/0000139	Scottish Borders Council	Caddonlee Farm Railway Cutting Landfill	NT4432635460	344326	635460
WML/E/0000072	Scottish Power Generation UK	Musselburgh Levenhall Ash Lagoons	NT3651473493	336514	673493
WML/E/0000086	Pennant Plant Ltd	Prestonholm Landfill, Dalhousie, Bonnyrigg	NT3249062463	662463	332490
WML/E/0000092	East Coast Skips	Hope Quarry Landfill, near Pathhead	NT4027062850	340270	662850
WML/E/0000115	Drum Environmental Ltd	East Gilmerton Landfill, Drum Estate	NT2964468556	329644	668556
WML/E/0000136	David Cochrane (Duns) Ltd	Catmoss Quarry, Greenlaw Moor, Greenlaw	NT7131045220	371310	645220
WML/E/0000218	D Geddes (Contractors) Ltd	D Geddes Ltd, Kinnell Quarry LF Friockheim	NO6101149423	361011	749423
WML/E/0000221	W J & R Morgan	J R Morgan,Anniston Brickworks LF,Inverkeilor	NO6640247916	366402	747916
WML/E/0000226	C & S Smith	C & S Smith, Drumsleed Sandpit LFS, Fordoun	N07313277795	373132	777795
WML/E/0000304	King Contractors (Perth) Ltd	Huntingtower Quarry, Crieff Road, Perth	NO0745324816	307453	724816
WML/E/0020023	Clackmannanshire Council	Black Devon Landfill Site, Alloa	NS8981490910	289814	690910
WML/E/0020024	Angus Council	Angus Council, Lochhead Landfill Site, Forfar	NO4801551258	348015	751258
WML/E/0020145	Lothian Recycling (1996) Ltd	Pentland Mains Landfill, Loanhead, Midlothian	NT2566865368	325668	665368
WML/E/0020152	J Haig Hamilton and Sons	West Fortune Farm Landfill, Drem	NT5334579854	353345	679854
WML/E/0020175	Lothian Recycling (1996) Ltd	Pentland Mains No.2 Landfill, Loanhead	NT2555865366	325558	665366
WML/E/0020192	Waste Recycling Group (Scotland) Ltd	Drummond Moor (No2) L/F, Rosewell, Midlothian	NT2670659586	326706	659586
WML/E/0020197	James Fairbairn	Lamberton Landfill Site, Berwick upon Tweed	NT9729457722	397294	657722
WML/N/0020000	John H Connon Ltd	Woodlands Quarry, Tulloford, Old Meldrum	NJ79666326657	379666	832657
WML/N/0020047	Mcintosh Plant Hire (Aberdeen) Limited	Backhills, Kingswells - McIntosh Plant	NJ8447506055	384475	806055
WML/N/0020066	Les Taylor Contractors Ltd	Landfill at South Auchinclech, Westhill	NJ8237808765	382378	808765
WML/N/0020067	Stewart Milne Home Options Ltd	Landfill at Lynturk, Tough, Alford	NJ6009212079	360092	812079
WML/N/0020069	Les Taylor Contractors Ltd	Landfill at Wogle Farm, Kinellar	NJ8153411847	381534	811847
WML/N/0020070	Arjo Wiggins Fine Papers Ltd	Little Clintery Landfill, Clinterty, Aberdeen	NJ8346012251	383460	812251
WML/N/0020097	Scottish Water Contracting	Elfhill Landfill Site, Easterton, Elgin	NJ2099755774	320997	855774
WML/N/0020119	John Gibbons (Contractors) Ltd	Site No 3, Middle Essie Farm, Peterhead	NK0819154314	408191	854314
WML/N/0020151	Shanks Northern Ltd	Tarbothill Farm Landfill Site	NJ9570213632	395702	813632

License number	Operating organisation	Site name	New grid reference	Easting	Northing
WML/N/0050002	Orkney Waste Management Ltd	Landfill Site at Dalespot, St Ola, Orkney	HY4539606922	345396	1006922
WML/N/0050005	Orkney Islands Council	OIC Peat Road LFS, Flotta, Orkney	ND3470292695	334702	992695
WML/N/0050029	Western Isles Council	Rueval LFS,Market Stance, Benbecula	NF8119653419	081196	853419
WML/N/0050044	The Highland Council	HC closed LFS, Ardachu, Brora, Sutherland	NC8933504727	289335	904727
WML/N/0050047	The Highland Council	HC closed LFS,Torbreck Landfill, Lochinver	NC0957224091	209572	924091
WML/N/0050061	Alcan Smeltin And Power Uk	Alcan Kinlochleven LFS, Kinlochleven, Argyll	NN1801561986	218015	761986
WML/N/0050048	The Highland Council	HC closed LFS, Crofthaugh, Brora, Sutherland	NC8965504011	289655	904011
WML/N/0050069	Private Contact	South House Landfill Site, Tankerness, Orkney	HY4976907385	349769	1007385
WML/N/0050099	Garrick Quarries Ltd	Old Lime Quarry, Garlista, Shetland	HU4300050500	443000	1150500
WML/N/0050104	Lewis Land Services	Pentland Road LFS, Marybank, Isle of Lewis	NB3876034340	138760	934340
WML/N/0050105	Western Isles Council	Old Burgh Tip LFS, Marybank, Isle of Lewis	NB4033933166	140339	933166
WML/W/0000019	George Munn & Others	Mid Auchencarroch Farm Landfill, Site 3	NS4136382324	241363	682324
WML/W/0000051	Parker Bros Ltd	Hayston Garage, Kirkintilloch	NS6450073900	264500	673900
WML/W/0000063	East Dunbartonshire Council	Broomhill Landfill Site, Kirkintilloch	NS6627074786	266270	674786
WML/W/0000103	J Mchugh	Waterbank Farm, Waterbank Rd, Carmunnock	NS6023756274	260237	656274
WML/W/0000106	South Lanarkshire Council	Newlandsmuir Landfill, Gardenhall, East Kilbride	NS6082353053	260823	653053
WML/W/0000143	Law Mining	Rigmuir Farm, Chapelton	NS6739852027	267398	652027
WML/W/0000156	Avonside	G. Craig, Avonside Landfill (Closed), Drumclog, Strathaven	NS6300037000	263000	637000
WML/W/0000200	Castelli & Gurola (Uk) Ltd	Boyds Farm Landfill, Eaglesfield	NY2250073400	322500	573400
WML/W/0000251	Barr Environmental Ltd	Clayshant Landfill,Sandhead, Stranraer	NX1115952596	211159	552596
WML/W/0000262	Dumfries & Galloway Council	Lochwhinyeon (sludge lagoon), Twynholm	NX6300061200	263000	561200
WML/W/0000283	Scottish Water	Laurieston Forest, Sludge Disposal Site	NX6639363584	266393	563584
WML/W/0020069	North Lanarkshire Council	Dalmacoulter Landfill Site, Airdrie	NS7665067682	276650	667682
WML/W/0020123	Balfour Beatty Construction Limited	Creagan Bridge Appin	NM9770044100	197700	744100
WML/W/0020136	Gartverrie Ltd	Gartverrie Ltd, Star Works LF, Glenboig	NS7276168941	272761	668941
WML/W/0020146	West Of Scotland Water	Gorbals WTW Landfill, Darnley	NS5258158642	252581	658642
WML/W/0020156	West Of Scotland Water	Birdston STW - Transfer Station, M of Campsie	NS6561175627	265611	675627
WML/W/0000186	W H Malcolm Ltd	Shewalton Sand Quarry	NS3290036915	232900	636915
WML/E/0000051	J M Kennie (Demolition) Ltd	Auldcathie Landfill, Winchburgh	NT0744675764	307446	675764
WML/E/0000076	J R Dale	Scoughall Landfill, Scoughall Farm, N Berwick	NT6170283032	361702	683032
WML/E/0000077	J Haig Hamilton & Sons	Field at West Fortune Farm	NT5336279983	353362	679983

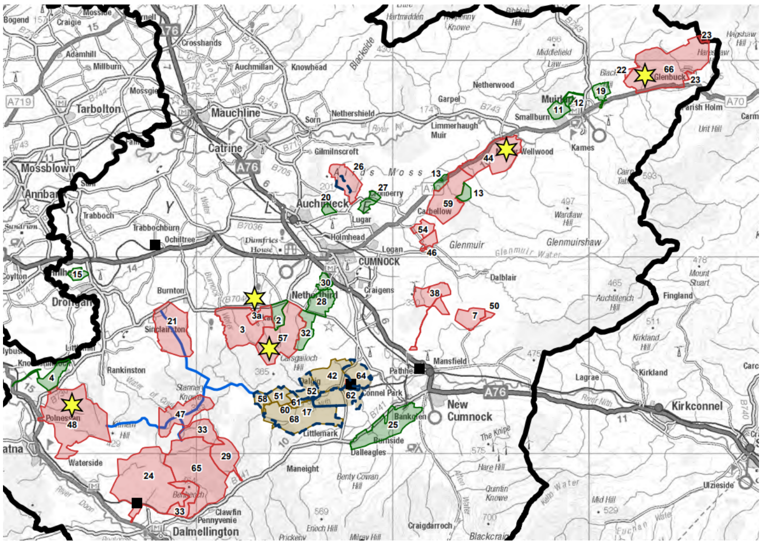
License number	Operating organisation	Site name	New grid reference	Easting	Northing
WML/W/0020041	Argyll & Bute Council	Dalinlongart LFS, Sandbank, Dunoon	NS0762764704	207627	664704
WML/W/0000139	Messers George Raeburn	Earnockmuir Farm Landfill, Hamilton	NS6879452393	268794	652393
WML/E/0000218	D Geddes (Contractors) Ltd	D Geddes Ltd, Kinnell Quarry LF Friockheim	NO6093550022	360935	750022
WML/E/0020152	J Haig Hamilton and Sons	West Fortune Farm Landfill, Drem	NT5284780041	352847	680041
WML/E/0000072	Scottish Power Generation UK	Musselburgh Levenhall Ash Lagoons	NT3596273585	335962	673585
WML/N/0020098	Highland Council	Highland Coun,Granish L/F,Aviemore,Inverness	NH9028114932	290281	814932
WML/E/0020192	Waste Recycling Group (Scotland) Ltd	Drummond Moor (No2) L/F, Rosewell, Midlothian	NT2674959742	326749	659742
WML/E/0000298	Binn Landfill (Glenfarg) Limited	NEM Ltd, Binn Farm LF, Glenfarg, Perth	NO1778714258	317787	714258

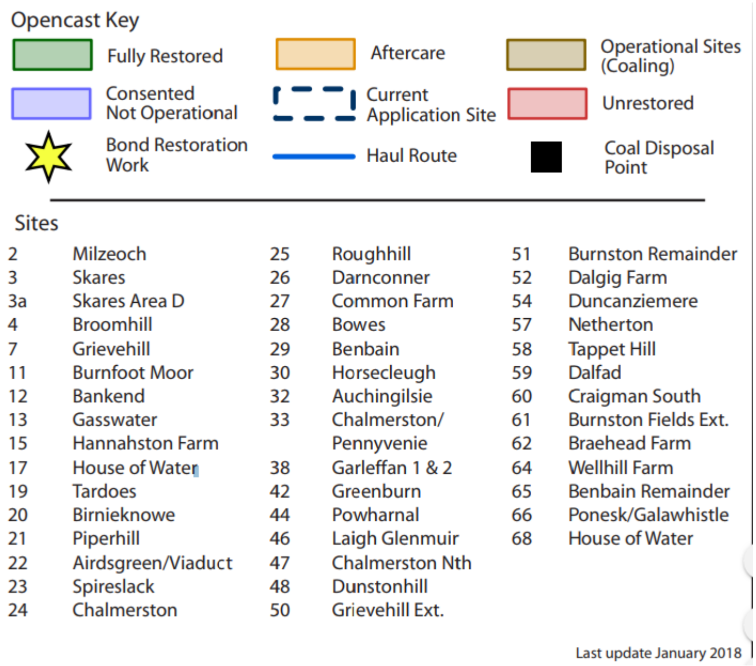
A.3 List of sites that could not be included from SEPA landfill capacity report (SEPA, 2012)

License number	Operating organisation	Site name	Grid reference	Reason for exclusion
PPC/E/0020057	Waste Recycling Group (Scotland) Ltd	Oatslie Sandpit Landfill-Roslin-Cleugh Road	NT 26422 62707	On SVDLS
WML/E/0000049	Henry Giles Haulage Contractors	Drumshoreland Bing, Pumpherston	NT 07550 70006	On SVDLS
WML/E/0000053	Mardon Plant Hire Ltd	Hillhouse Farm Landfill, Kirknewton	NT 11493 67378	Unclear boundary
WML/E/0000057	Pumpherston Oil Company Ltd	Drumshoreland Road, Pumpherston	NT 07539 69547	Change of use - golf course
WML/E/0000073	Blue Circle Industries Plc	North Quarry Cement Works, Dunbar	NT 70463 77128	Unclear boundary
WML/E/0000084	Tarmac Ltd	Melville Sand Pit By Lasswade	NT 29650 66575	On SVDLS
WML/E/0000141	Scottish Borders Council	Corsbie Dean, Berwickshire	NT 60700 44190	Change of use - buildings
WML/E/0000132	R W & P Millican	Heughead Farm, Reston, Eyemouth	NT 87722 62594	Change of use - farm
WML/E/0000264	Levenmouth Auto Breakers	Aberhill Metals,Old Leven Colliery LF, Methil	NO 37407 00439	Change of use - sewage works
WML/E/0020015	Grant Construction Services	Grant Constrctn, Dodhead Links LF Burntisland	NT 24847 87029	Change of use - golf course
WML/E/0020047	Midlothian Council	Drummond Moor (No1) Landfill Site, Penicuik	NT 27000 60045	On SVDLS
WML/E/0000310	J & R Mitchell	Pairney Quarry Landfill, Auchterarder	NN 97721 12980	On SVDLS
WML/N/0020123	Oosterhof & Co	Lower Tyacksnook, Lonmay, Fraserburgh	NK 03362 59526	Unclear boundary
WML/N/0020190	Bruce Plant Ltd	Bruce Plant Ltd, Badentoy Industrial Estate	NO 90234 97322	Unclear boundary
WML/N/0050003	The Highland Council	HC Stoneyfield LFS, Newmore, Invergordon	NH 68550 71250	Unclear boundary
WML/N/0050005	Orkney Islands Council	OIC Peat Road LFS, Flotta, Orkney	ND 34716 92622	Unclear boundary
WML/N/0050009	Orkney Islands Council	OIC Gallow Tuag Quarry LFS,South Walls,Orkney	ND 30492 89687	Unclear boundary
WML/N/0050059	The Highland Council	HC Bettyhill LFS, Bettyhill, Sutherland	NC 73731 60310	Unclear boundary
WML/N/0050084	Alcan Smeltin And Power Uk	Alcan Lochaber Smelter LFS, by Fort William	NN 12646 74920	Change of use - buildings
WML/W/0000015	T/A Don Construction	Dalreoch Quarry, Renton Road, Dumbarton	NS 38800 76100	On SVDLS

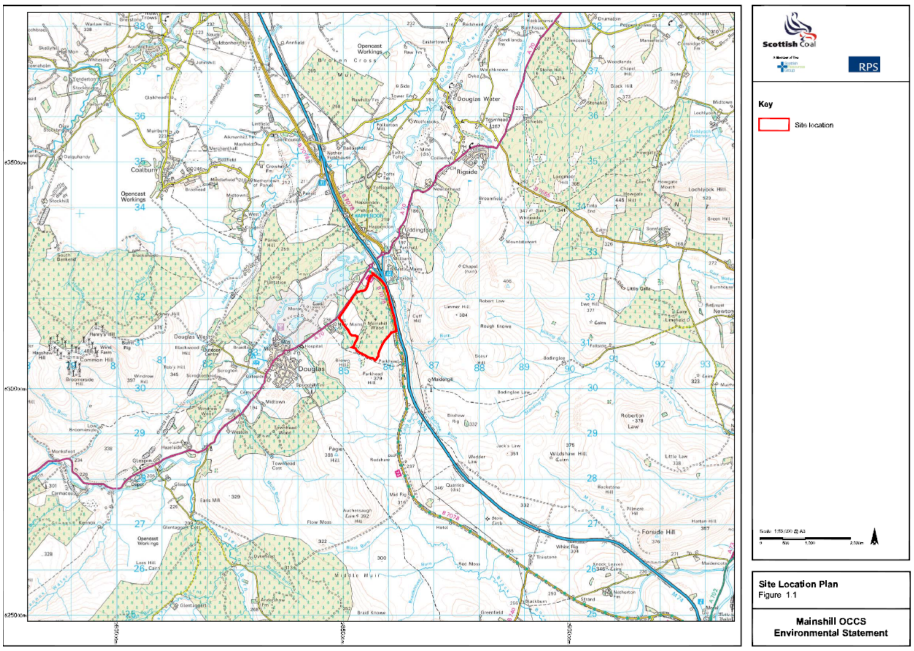
License number	Operating organisation	Site name	Grid reference	Reason for exclusion
WML/W/0000019	George Munn & Others	Mid Auchencarroch Farm Landfill, Site 3	NS 4136382324	Unclear boundary
WML/W/0000054	George Beattie & Sons Ltd	Colzium Quarry LF, Kilsyth	NS 72545 78790	Change of use - golf course
WML/W/0000058	James S Reid	Redmoss Farm, Lennoxtown	NS 64068 76023	Change of use - farm
WML/W/0000066	North Lanarkshire Council	Hope Park Landfill Site, Croy	NS 71800 75900	Already exists - One removed
WML/W/0020159	North Lanarkshire Council	Hope Park Landfill Site, Kilsyth	NS 71800 75901	Already exists - One removed
WML/W/0000067	Mr David Morton	Hayston Farm, Kirkintilloch, Glasgow	NS 64146 74405	Change of use - farm
WML/W/0000070	Biffa Waste Services Ltd	Pilmuir Quarry Landfill Site, Newton Mearns	NS 52063 54304	Change of use - water
WML/W/0000071	City Of Glasgow	Kilgarth L/F Site, Gartgill Rd, Coatbridge	NS 71894 67499	On SVDLS
WML/W/0000073	J&A Plant Services	Beithglass Quarry, Skelmorlie	NS 19909 67230	On SVDLS
WML/W/0000106	South Lanarkshire Council	Newlandsmuir Landfill, Gardenhall, East Kilbride	NS 60862 52931	Unclear boundary
WML/W/0000107	Corus Strip Products Uk Ltd	Clydebridge Works Landfill, Ballochmill Rd, Glasgow	NS 63243 62100	Change of use - buildings
WML/W/0000132	G Raeburn	Auchentibber Landfill, Newhousemill Rd, East Kilbride	NS 67328 53598	Unclear boundary
WML/W/0000133	Culdaff Construction Ltd	Calderside Farm Landfill, Auchentibber	NS 66476 54942	Unclear boundary
WML/W/0000240	Barr Ltd	Hollybush Farm Landfill Site	NS 48879 29775	Unclear boundary
WML/W/0000241	John Wilison & Son (Coyton) Ltd	Old Toll Garage (Landfill), Drongan	NS 44602 18741	On SVDLS
WML/W/0020041	Argyll & Bute Council	Dalinlongart LFS, Sandbank, Dunoon	NS 07665 64940	Unclear boundary
WML/W/0020146	West Of Scotland Water	Gorbals WTW Landfill, Darnley	NS 52406 58331	Unclear boundary
WML/W/0020163	Beithglass (Landfill) Ltd	Beithglass Quarry LFS, Skelmorlie	NS 19909 67230	Already exists - One removed
WML/E/0000011	Private Contact	Caddonlee Farm Railway Cutting Landfill	NT 4432635460	Already exists - One removed

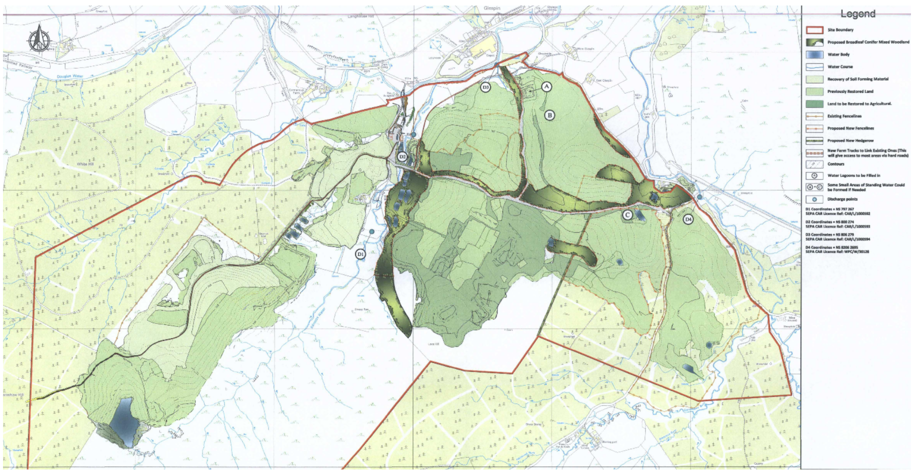
A.4 Larger key and site-view of unrestored mine land in East Ayrshire published in East Ayrshire's 'steps to recovery' report (East Ayrshire Council, 2013)

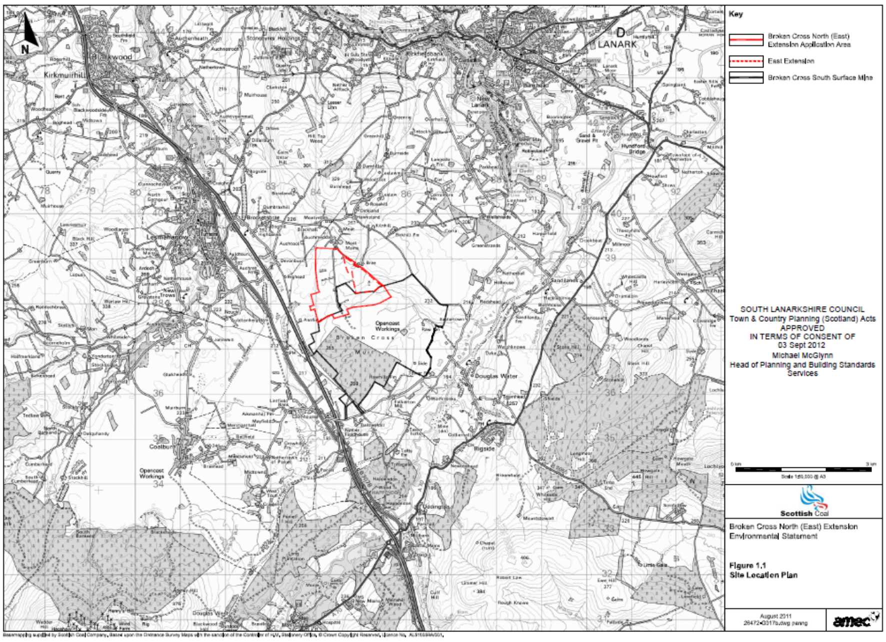




A.5 South Lanarkshire mine land location plans - provided by local authority on 23/08/16







LANARK
Key
Broken Cross North (East) Extension Application Area
East Extension
Broken Cross South Surface Mine
SOUTH LANARKSHIRE COUNCIL
Town & Country Planning (Scotland) Acts
APPROVED
IN TERMS OF CONSENT OF
03 Sept 2012
Michael McGlynn
Head of Planning and Building Standards Services
0 km
3 km
Scottish Coal
Broken Cross North (East) Extension
Environmental Statement
Figure 1.1
Site Location Plan
August 2011
amec

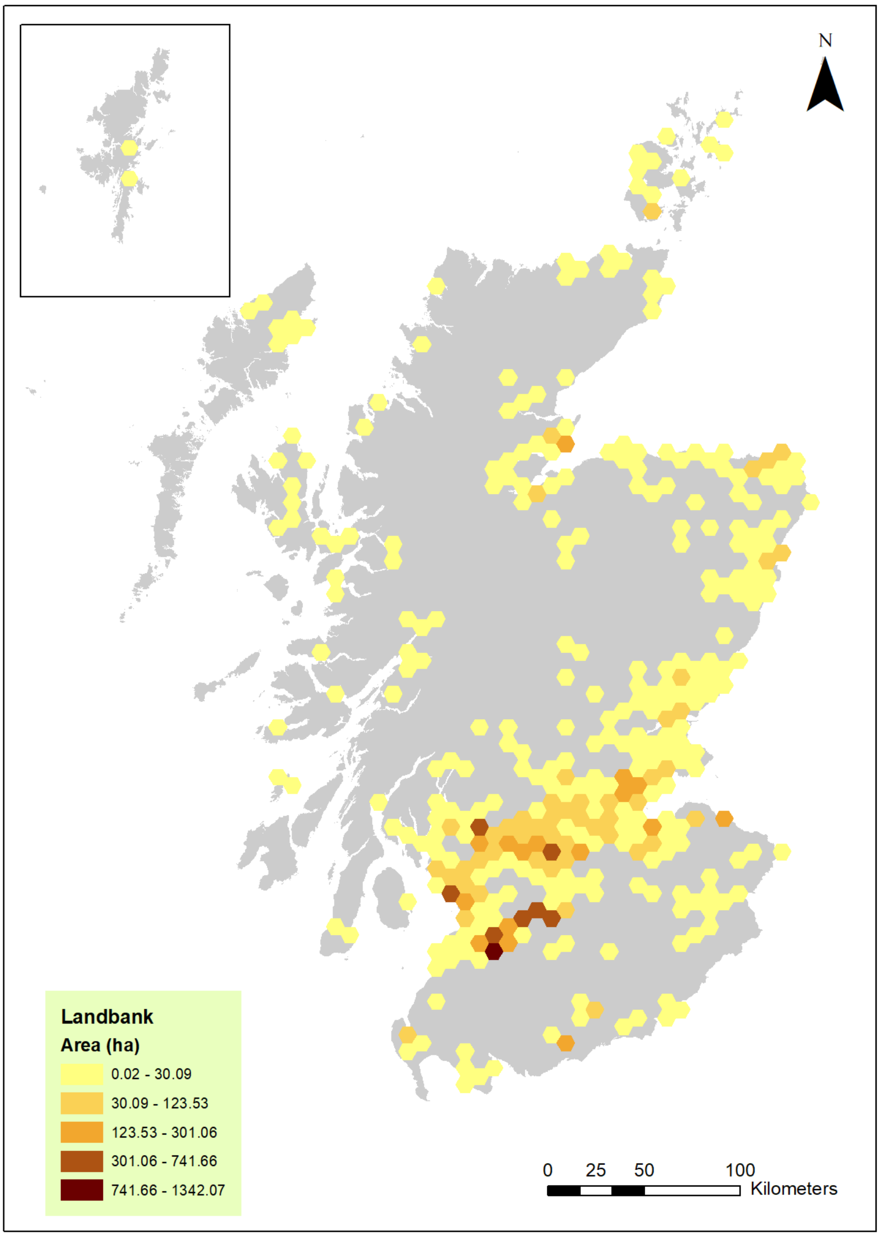
A.6 Metadata sheet for land resources included in theoretical landbank compiled 2014 - 2016

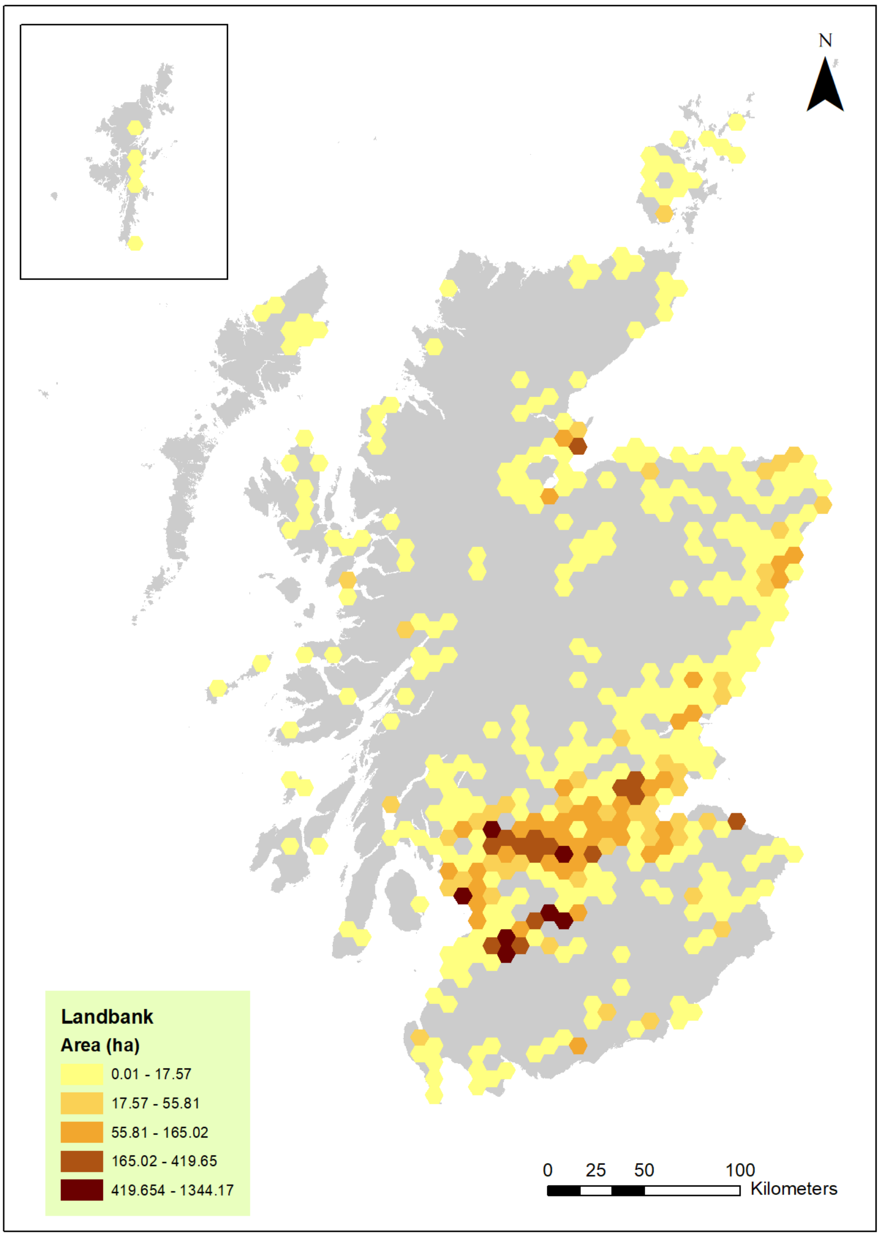
Resource	Authority	GIS data provided?	Data provider	Number of sites	Date received/digitised	Scale	Projected co-ordinate system	Datum
Brownfield land	Aberdeen City Council	Y	Grace Harrison, GrHarrison@aberdeencity.gov.uk	45	13/02/2014	1:3,000	British National Grid	OSGB 1936
	Aberdeenshire Council	Y	Mel Greig, mel.greig@aberdeenshire.gov.uk	60	29/07/2014	1:3,000	British National Grid	OSGB 1936
	Angus Council	N	n/a	52	13/01/2015	1:3,000	British National Grid	OSGB 1936
	Argyll and Bute Council	Y	Matthew Watkiss, matthew.watkiss@argyll-bute.gov.uk	44	23/07/2014	1:3,000	British National Grid	OSGB 1936
	City of Edinburgh	Y	Simon Antrobus, simon.antrobus@edinburgh.gov.uk	102	13/02/2014	1:3,000	British National Grid	OSGB 1936
	City of Glasgow Council	Y	Iain Wallace, iain.wallace@glasgow.gov.uk	855	20/08/2014	1:3,000	British National Grid	OSGB 1936
	Clackmannanshire Council	N	n/a	16	06/10/2014	1:3,000	British National Grid	OSGB 1936
	Dumfries and Galloway Council	N	n/a	51	13/01/2015	1:3,000	British National Grid	OSGB 1936
	Dundee City Council	Y	Alistair Hilton, alistair.hilton@dundeecity.gov.uk	195	17/02/2014	1:3,000	British National Grid	OSGB 1936
	East Ayrshire Council	Y	Antony McGuinness, antony.mcguinness@east-ayrshire.gov.uk	139	26/08/2014	1:3,000	British National Grid	OSGB 1936
	East Dunbartonshire Council	Y	Richard Todd, richard.todd@eastdunbarton.gov.uk	24	20/03/2014	1:3,000	British National Grid	OSGB 1936
	East Lothian Council	Y	Phil McLean, pmclean@eastlothian.gov.uk	34	13/02/2014	1:3,000	British National Grid	OSGB 1936
	East Renfrewshire Council	Y	Matt Greenen, matt.greenen@eastrenfrewshire.gov.uk	47	14/02/2014	1:3,000	British National Grid	OSGB 1936
	Falkirk Council	Y	Joyce Hartley, joyce.hartley@falkirk.gov.uk	83	17/03/2014	1:3,000	British National Grid	OSGB 1936
	Fife Council	Y	Ramsay Duff, ramsay.duff@fife.go.uk	201	25/02/2014	1:3,000	British National Grid	OSGB 1936
	Highland Council	Y	Hamish Thomson, hamish.thomson@highland.gov.uk	232	06/08/2014	1:3,000	British National Grid	OSGB 1936
	Inverclyde Council	Y	Fergus MacLeod, Fergus.MacLeod@inverclyde.gov.uk	129	25/02/2014	1:3,000	British National Grid	OSGB 1936
	Midlothian Council	Y	Stephen MacPhail, stephen.macphail@midlothian.gov.uk	92	20/03/2014	1:3,000	British National Grid	OSGB 1936
	Moray Council	Y	Kevin Belton, Kevin.Belton@moray.gov.uk	27	23/07/2014	1:3,000	British National Grid	OSGB 1936
	Na H-Eileanan an Iar	Y	Kenny MacIver, k.maciver@cne-siar.gov.uk	9	23/07/2014	1:3,000	British National Grid	OSGB 1936
	North Ayrshire Council	Y	Sandra Taylor, sandrataylor@north-ayrshire.gov.uk	275	06/08/2014	1:3,000	British National Grid	OSGB 1936

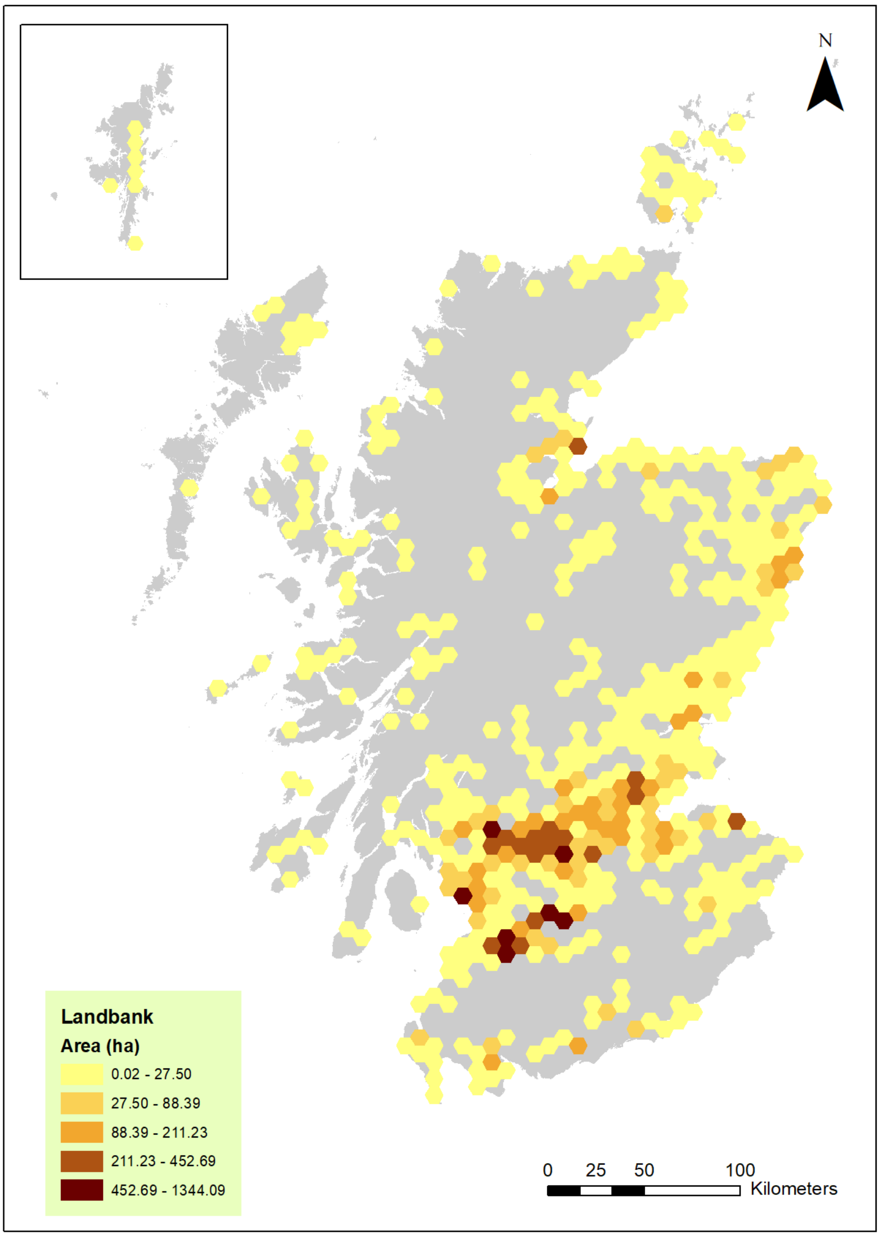
Resource	Authority	GIS data provided?	Data provider	Number of sites	Date received/digitised	Scale	Projected co-ordinate system	Datum
Brownfield land	North Lanarkshire Council	Y	Stevan Gilchrist, gilchrists@northlan.gov.uk	470	06/08/2014	1:3,000	British National Grid	OSGB 1936
	Orkney Islands Council	N	Luke Fraser, luke.fraser@orkney.gov.uk	15	19/01/2015	1:3,000	British National Grid	OSGB 1936
	Perth and Kinross Council	Y	Shelley McCann, SMcCann@pkc.gov.uk	41	24/07/2014	1:3,000	British National Grid	OSGB 1936
	Renfrewshire Council	Y	Iain Stewart, iain.stewart@renfrewshire.gov.uk	178	14/02/2014	1:3,000	British National Grid	OSGB 1936
	Scottish Borders	Y	Joanna Storer, joanna.storer@scotborders.gov.uk	93	25/02/2014	1:3,000	British National Grid	OSGB 1936
	Shetland Islands Council	N	n/a	10	19/01/2015	1:3,000	British National Grid	OSGB 1936
	South Ayrshire Council	Y	Andrew Monkhouse, Andrew.Monkhouse@south-ayrshire.gov.uk	54	23/07/2014	1:3,000	British National Grid	OSGB 1936
	South Lanarkshire Council	Y	Shiela Alderson, shiela.alderson@southlanarkshire.gov.uk	256	23/07/2014	1:3,000	British National Grid	OSGB 1936
	Stirling Council	N	n/a	71	19/01/2015	1:3,000	British National Grid	OSGB 1936
	West Dunbartonshire Council	Y	Moira Clark, moira.clark@west-dunbarton.gov.uk	84	26/02/2014	1:3,000	British National Grid	OSGB 1936
	West Lothian Council	N	n/a	79	19/01/2015	1:3,000	British National Grid	OSGB 1936
Authorised Landfill	SEPA	N	n/a	69	03/02/2015	1:3,000	British National Grid	OSGB 1936
Closed Landfill	SEPA	N	n/a	273	01/05/2015	1:3,000	British National Grid	OSGB 1936
Historic landfill	Aberdeen City Council	N	Grace Harrison, GrHarrison@aberdeencity.gov.uk	3	23/03/2016	1:3,000	British National Grid	OSGB 1936
	Aberdeenshire Council	Y	Mel Greig, mel.greig@aberdeenshire.gov.uk	173	27/10/2015	1:3,000	British National Grid	OSGB 1936
	Angus Council	Y	Alan Milne, MilneAJ@angus.gov.uk	160	19/11/2015	1:3,000	British National Grid	OSGB 1936
	Argyll and Bute Council	N	Matthew Watkiss, matthew.watkiss@argyll-bute.gov.uk	26	23/03/2016	1:3,000	British National Grid	OSGB 1936
	City of Edinburgh	N	n/a	0		1:3,000	British National Grid	OSGB 1936
	City of Glasgow Council	Y	Iain Wallace, iain.wallace@glasgow.gov.uk	10	30/10/2015	1:3,000	British National Grid	OSGB 1936
	Clackmannanshire Council	Y	Michael McNaughton, MMcNaughton@clacks.gov.uk	19	05/10/2015	1:3,000	British National Grid	OSGB 1936
	Dumfries and Galloway Council	Y	Gillian Flack,Flack, Gillian.Flack@dumgal.gov.uk	25	26/06/2015	1:3,000	British National Grid	OSGB 1936
	Dundee City Council	N	Freedom of Information request	7	23/03/2016	1:3,000	British National Grid	OSGB 1936
	East Ayrshire Council	N	Freedom of Information request	12	23/03/2016	1:3,000	British National Grid	OSGB 1936
	East Dunbartonshire Council	Y	Anne Prescott, Anne.Prescott@eastdunbarton.gov.uk	30	27/10/2015	1:3,000	British National Grid	OSGB 1936
	East Lothian Council	Y	Freedom of Information request	27	26/06/2015	1:3,000	British National Grid	OSGB 1936
	East Renfrewshire Council	N	Claire Reid, claire.reid@eastrenfrewshire.gov.uk	3	23/03/2016	1:3,000	British National Grid	OSGB 1936
	Falkirk Council	N	Freedom of Information request	15	23/03/2016	1:3,000	British National Grid	OSGB 1936
	Fife Council	Y	Donald Payne, Donald.Payne@fife.gov.uk	129	05/05/2015	1:3,000	British National Grid	OSGB 1936
	Highland Council	Y	Scott Barclay, Scott.Barclay@highland.gov.uk	83	05/06/2015	1:3,000	British National Grid	OSGB 1936
	Inverclyde Council	Y	Roslyn McIntosh, roslyn.mcintosh@inverclyde.gov.uk	11	04/09/2015	1:3,000	British National Grid	OSGB 1936
	Midlothian Council	N	Freedom of Information request	13	23/03/2016	1:3,000	British National Grid	OSGB 1936
	Moray Council	N	Freedom of Information request	23	23/03/2016	1:3,000	British National Grid	OSGB 1936
	Na H-Eileanan an Iar	N	n/a	0		1:3,000	British National Grid	OSGB 1936
	North Ayrshire Council	N	n/a	0		1:3,000	British National Grid	OSGB 1936

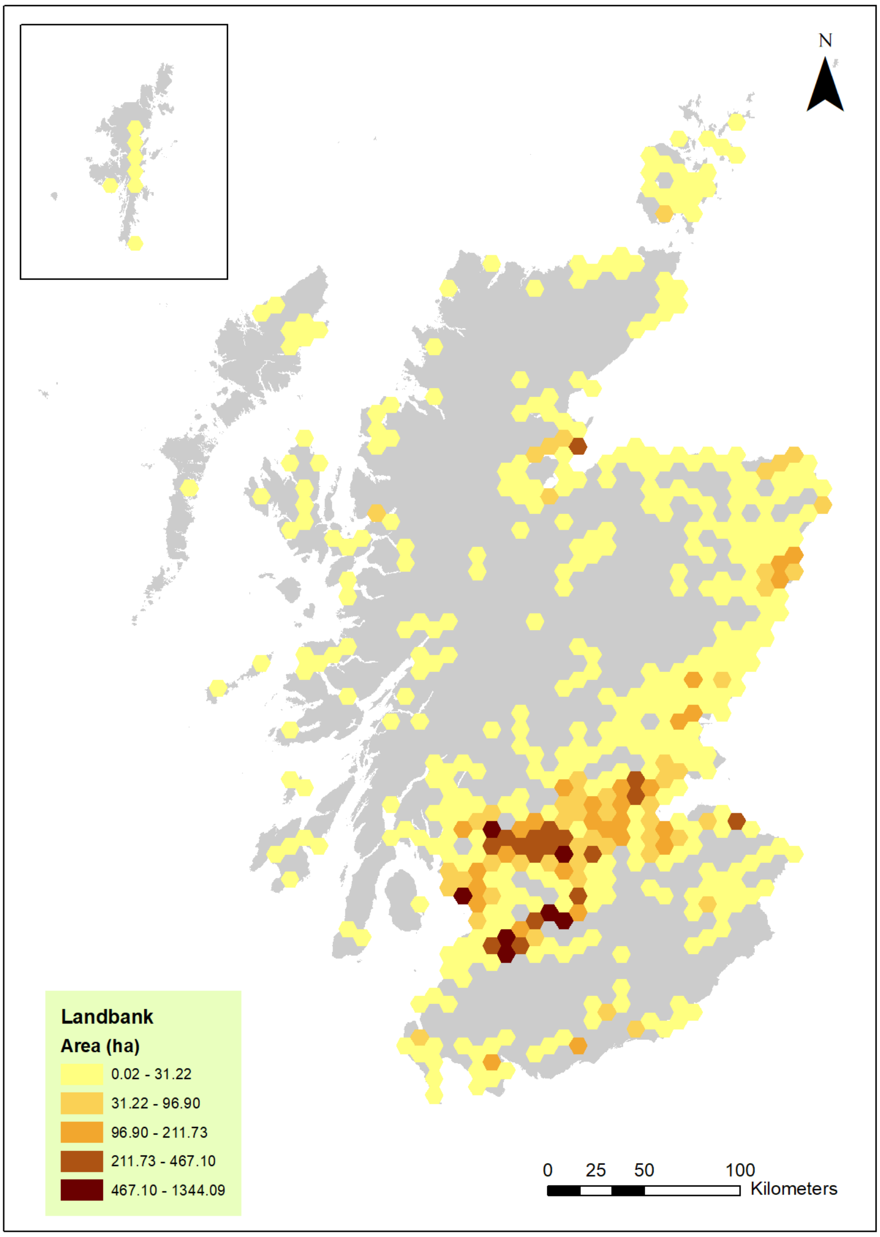
Resource	Authority	GIS data provided?	Data provider	Number of sites	Date received/digitised	Scale	Projected co-ordinate system	Datum
Historic landfill	North Lanarkshire Council	N	Freedom of Information request	36	23/03/2016	1:3,000	British National Grid	OSGB 1936
	Orkney Islands Council	N	Freedom of Information request	17	23/03/2016	1:3,000	British National Grid	OSGB 1936
	Perth and Kinross Council	Y	Louise Jardine, LJardine@pkc.gov.uk	19	14/09/2015	1:3,000	British National Grid	OSGB 1936
	Renfrewshire Council	Y	Gerard Mcgarrity, gerard.mcgarrity@renfrewshire.gov.uk	43	09/09/2015	1:3,000	British National Grid	OSGB 1936
	Scottish Borders	N	Freedom of Information request	13	23/03/2016	1:3,000	British National Grid	OSGB 1936
	Shetland Islands Council	N	n/a	0		1:3,000	British National Grid	OSGB 1936
	South Ayrshire Council	Y	http://maps.south-ayrshire.opendata.arcgis.com	14	31/08/2015	1:3,000	British National Grid	OSGB 1936
	South Lanarkshire Council	Y	Kirstie Ogilvie, Kirstie.Ogilvie@southlanarkshire.gcsx.gov.uk	23	26/06/2015	1:3,000	British National Grid	OSGB 1936
	Stirling Council	N	Freedom of Information request	18	23/03/2016	1:3,000	British National Grid	OSGB 1936
	West Dunbartonshire Council	N	Freedom of Information request	14	23/03/2016	1:3,000	British National Grid	OSGB 1936
	West Lothian Council	N	Freedom of Information request	2	23/03/2016	1:3,000	British National Grid	OSGB 1936
Abandoned Mine land	East Ayrshire Council	N	Marc Miller, Marc.Miller@east-ayrshire.gov.uk	10	12/09/2016	1:3,000	British National Grid	OSGB 1936
	Fife Council	N	Declan Semple, declan.semple@fife.gov.uk	3	22/08/2016	1:3,000	British National Grid	OSGB 1936
	South Lanarkshire Council	N	James Wright Wright, James.Wright@southlanarkshire.gcsx.gov.uk	2	23/08/2016	1:3,000	British National Grid	OSGB 1936

A.7 Mapped output from sensitivity analysis conducted on distance from road - 50m, 250m, 750m and 1000m - created using Ordnance survey Open Roads reports in 2015




N
Landbank
Area (ha)
0.01 - 17.57
17.57 - 55.81
55.81 - 165.02
165.02 - 419.65
419.654 - 1344.17
0 25 50 100
Kilometers

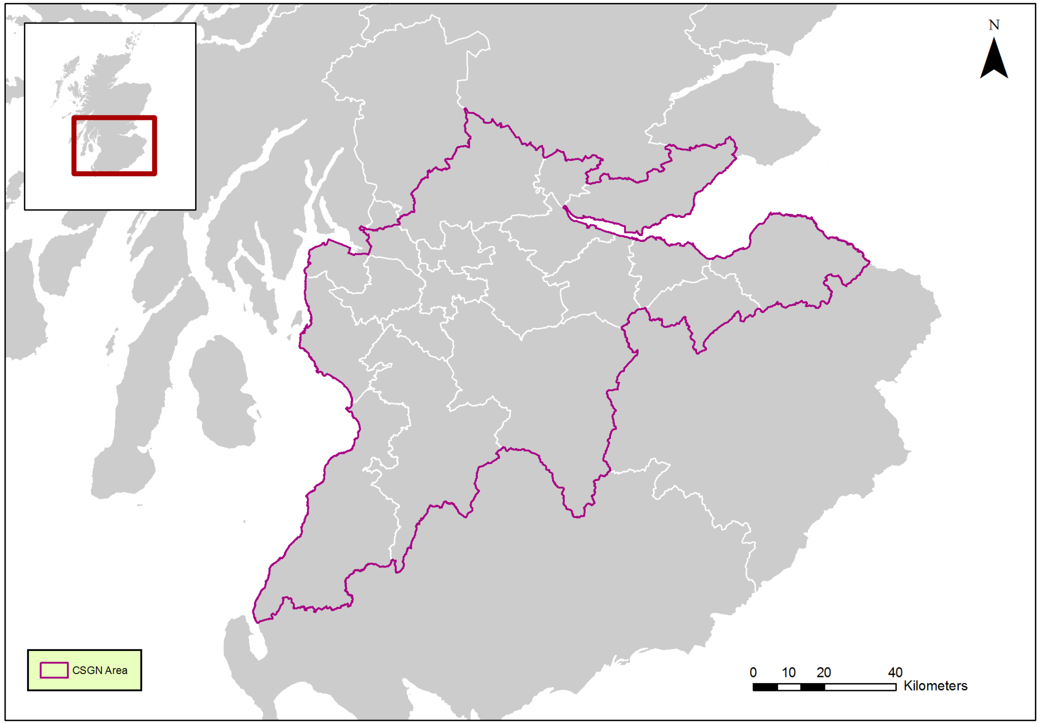

N
Landbank
Area (ha)
0.02 - 27.50
27.50 - 88.39
88.39 - 211.23
211.23 - 452.69
452.69 - 1344.09
0 25 50 100
Kilometers


N
Landbank
Area (ha)
0.02 - 31.22
31.22 - 96.90
96.90 - 211.73
211.73 - 467.10
467.10 - 1344.09
0 25 50 100
Kilometers

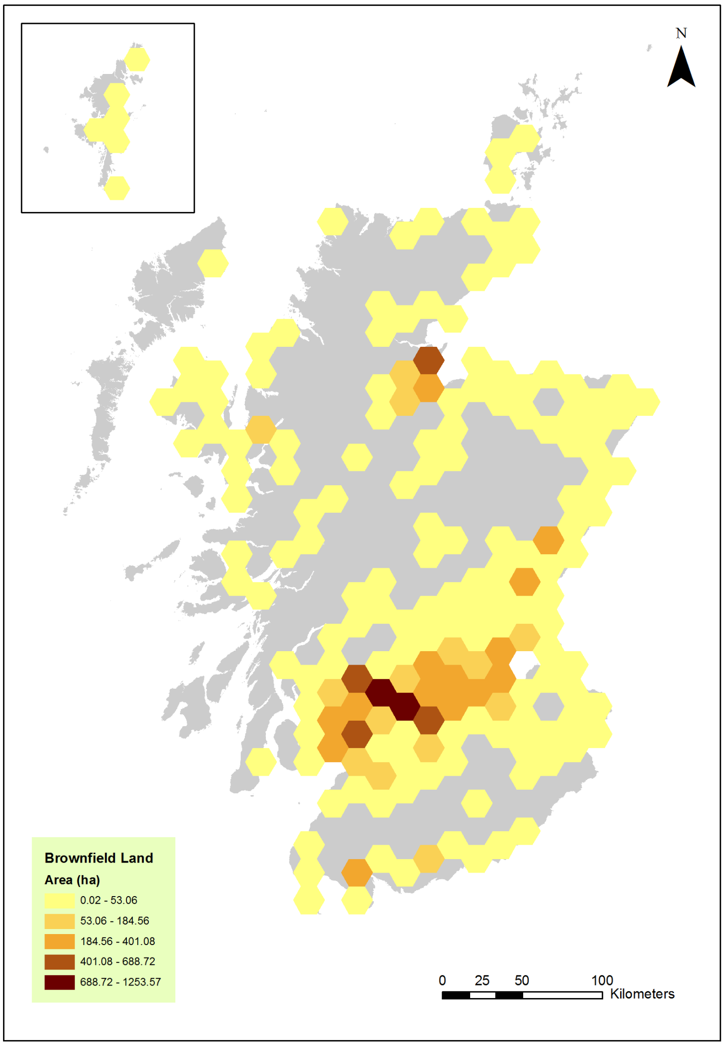
A.8 Total brownfield land area in each local authority - based on spatial database created in 2015 using the 2013 Scottish Vacant and Derelict Land Survey

Local authority	Sum of brownfield land area (ha)
Aberdeen City	52
Aberdeenshire	305
Angus	123
Argyll and Bute	48
City of Edinburgh	238
Clackmannanshire	22
Dumfries and Galloway	464
Dundee City	197
East Ayrshire	355
East Dunbartonshire	64
East Lothian	44
East Renfrewshire	60
Falkirk	157
Fife	841
Glasgow City	1193
Highland	1325
Inverclyde	149
Midlothian	272
Moray	27
Na H-Eileanan an Iar	11
North Ayrshire	1363
North Lanarkshire	1310
Orkney Islands	43
Perth and Kinross	44
Renfrewshire	958
Scottish Borders	91
Shetland Islands	8
South Ayrshire	103
South Lanarkshire	490
Stirling	179
West Dunbartonshire	190
West Lothian	626

A.9 Central Scotland Green Network Boundary (CSGN, 2017)



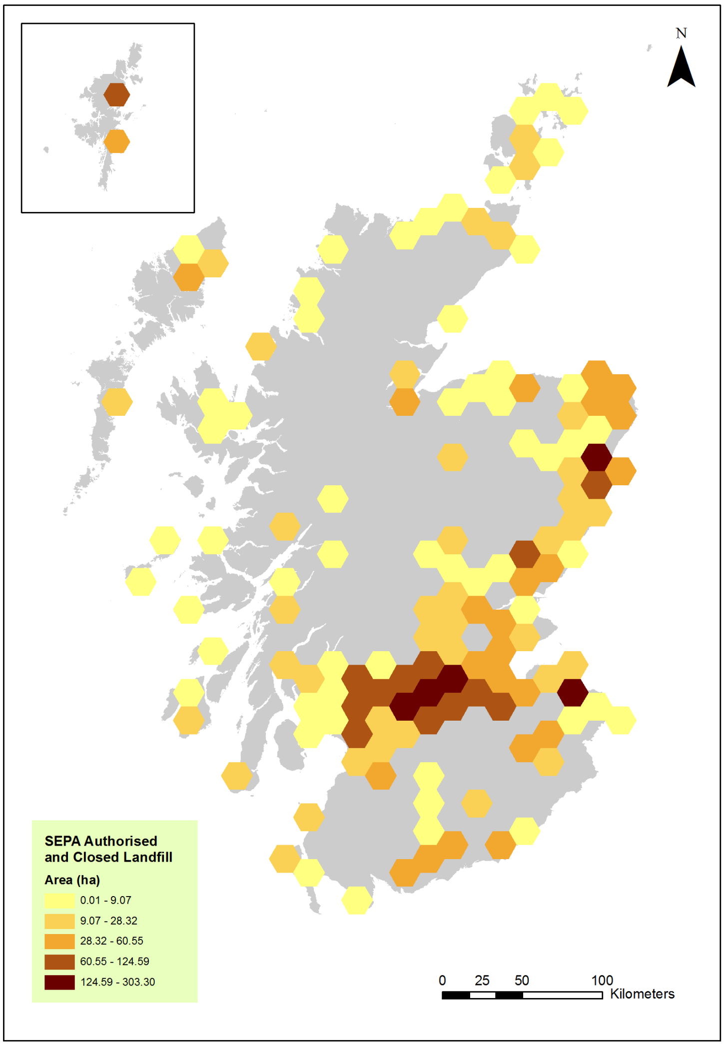
A.10 Total area of brownfield land in Scotland aggregated into a hexagonal grid with 10 km length sides - based on spatial database created in 2015 using the 2013 Scottish Vacant and Derelict Land Survey



A.11 Total SEPA licensed landfill area in each local authority - based on spatial database created in 2015 using SEPA report published in 2012

Local authority	Sum of SEPA licensed landfill area (ha)
Aberdeen City	134
Aberdeenshire	517
Angus	186
Argyll and Bute	101
City of Edinburgh	25
Clackmannanshire	9
Dumfries and Galloway	215
Dundee City	3
East Ayrshire	50
East Dunbartonshire	115
East Lothian	426
East Renfrewshire	16
Falkirk	173
Fife	356
Glasgow City	95
Highland	177
Inverclyde	7
Midlothian	127
Moray	55
Na H-Eileanan an Iar	60
North Ayrshire	208
North Lanarkshire	317
Orkney Islands	31
Perth and Kinross	108
Renfrewshire	67
Scottish Borders	110
Shetland Islands	117
South Ayrshire	35
South Lanarkshire	165
Stirling	78
West Dunbartonshire	61
West Lothian	151

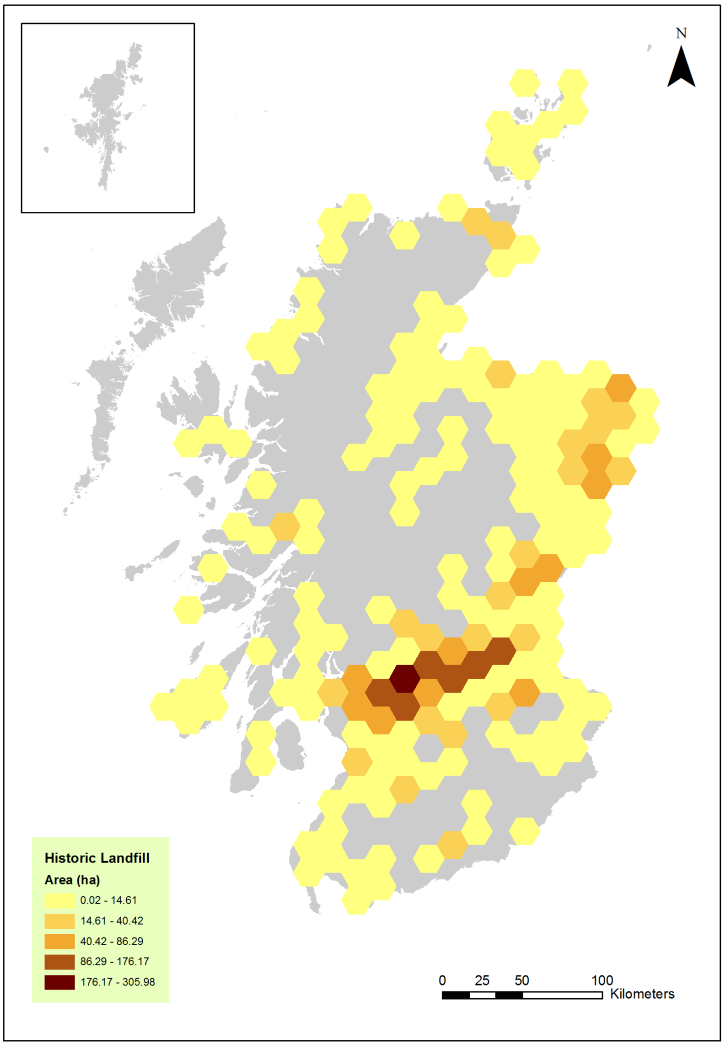
A.12 Total area of SEPA authorised and closed landfill in Scotland aggregated into a hexagonal grid with 10 km length sides - based on spatial database created in 2015 using SEPA report published in 2012



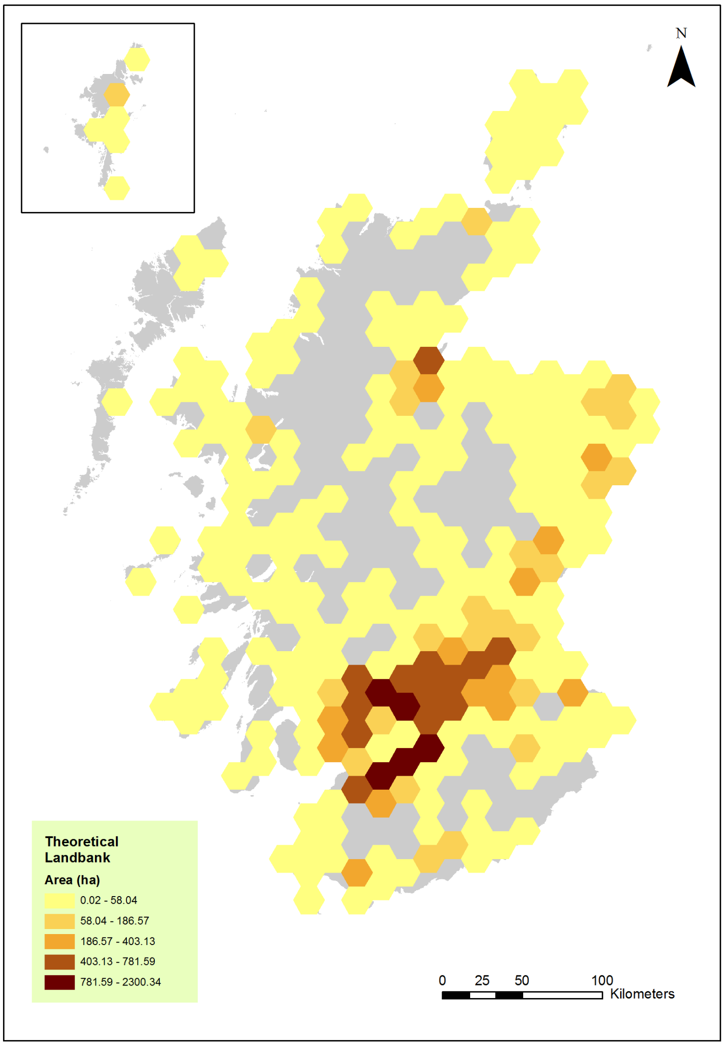
A.13 Total historic landfill area in each local authority - based on spatial database created in 2016 using data collected 2015 - 2016

Local authority	Sum of historic landfill area (ha)
Aberdeen City	47
Aberdeenshire	434
Angus	233
Argyll and Bute	32
City of Edinburgh	0
Clackmannanshire	89
Dumfries and Galloway	81
Dundee City	10
East Ayrshire	41
East Dunbartonshire	153
East Lothian	57
East Renfrewshire	26
Falkirk	87
Fife	461
Glasgow City	76
Highland	139
Inverclyde	52
Midlothian	48
Moray	51
Na H-Eileanan an Iar	0
North Ayrshire	0
North Lanarkshire	263
Orkney Islands	12
Perth and Kinross	31
Renfrewshire	192
Scottish Borders	10
Shetland Islands	0
South Ayrshire	50
South Lanarkshire	86
Stirling	54
West Dunbartonshire	31
West Lothian	11

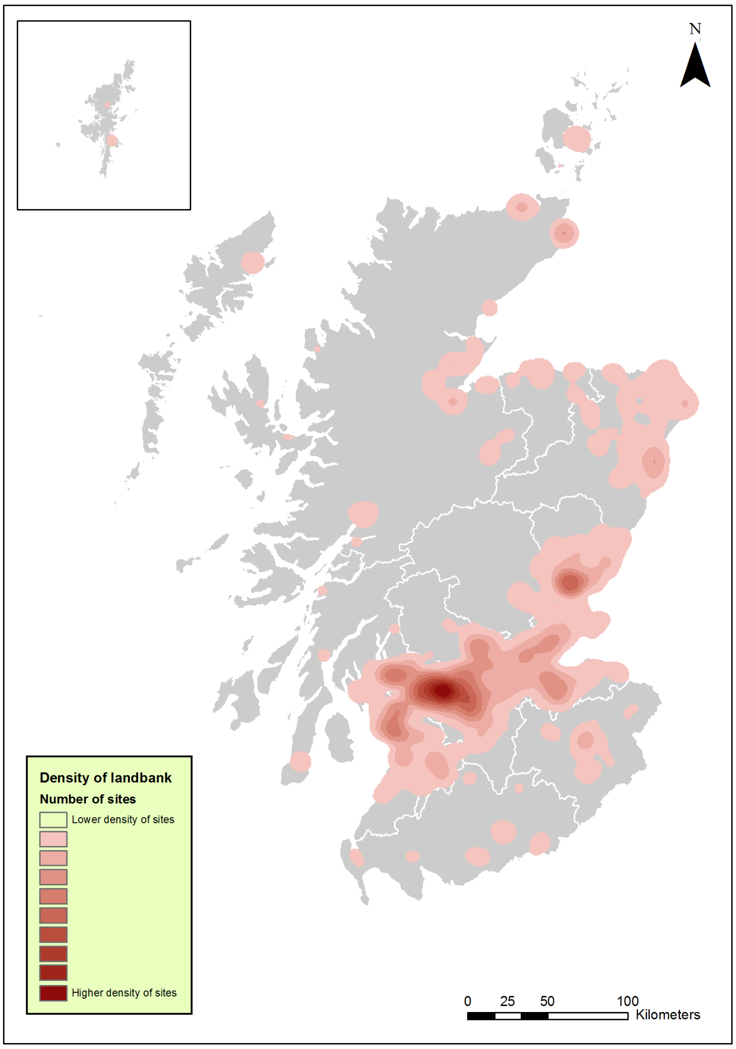
A.14 Total area of historic landfill aggregated into a hexagonal grid with 10 km length sides - based on spatial database created in 2016 using data collected 2015 - 2016



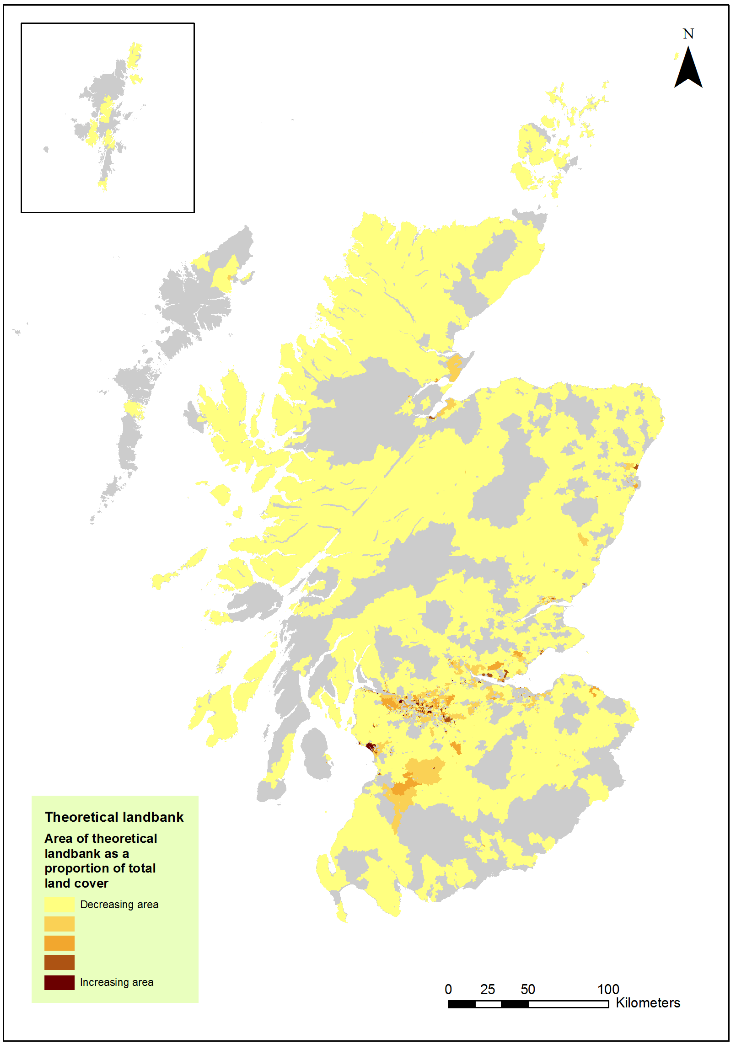
A.15 Total area of theoretical landbank in Scotland aggregated into a hexagonal grid with 10 km length sides - using spatial database containing data from 2013 - 2016 compiled in 2016



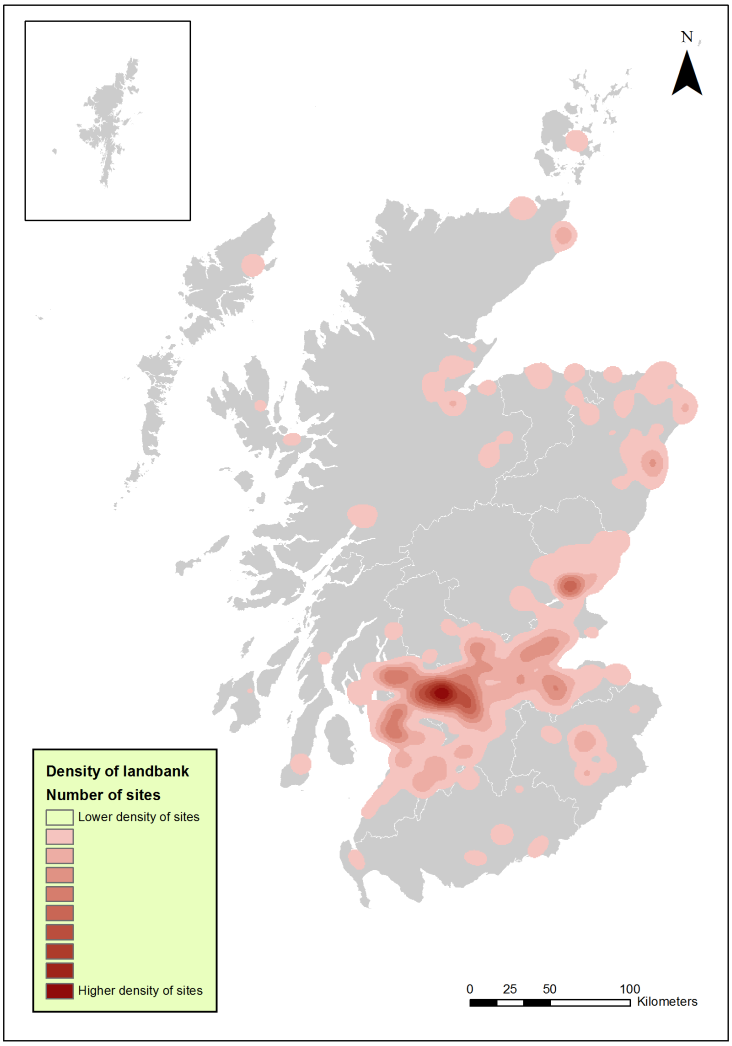
A.16 Kernel density estimation representing the density of the theoretical landbank in Scotland created using site points only - using spatial database containing data from 2013 - 2016 compiled in 2016



A.17 Area of theoretical landbank as a proportion of total land cover in each datazone - using spatial database containing data from 2013 - 2016 compiled in 2016



A.18 Kernel density estimation representing the density of the technical landbank in Scotland created using site points only - based on spatial database created in 2017



A.19 Area of landbank within each cluster (ha) compared with the sum of the heat demand within a 40 km radius (GWh/yr) - based on spatial database created in 2017 and heat demand data provided in 2017

Cluster ID	Sum of heat demand within 40km radius (GWh/yr)	Area landbank within cluster (ha)
1	2957	386
2	28832	876
3	4316	279
4	29505	155
5	21644	123
6	38917	200
7	40398	4037
8	24951	943
9	25908	4454

A.20 Sum of heat demand (GWh/yr) within each cluster compared to the sum of the technical landbank (ha) within a 40 km radius - based on spatial database created in 2017 and heat demand data provided in 2017

Cluster ID	Sum of heat demand within cluster proxy (GWh/yr)	Area of landbank within 40km radius (ha)
1	7034	8701
2	1360	1241
3	5808	3550
4	47	2724
5	293	4374
6	403	6141
7	153	5098
8	29	527
9	12	2790
10	6	6092
11	49	634
12	30	1651
13	42	8652

A.21 Landbank density, heat density and sum of landbank within 40km radius of the selected case study datazones - based on spatial database created in 2017 and heat demand data provided in 2017

Datazone	Heat Density (GWh/yr)	Landbank Density (ha)	Sum heat demand (GWh/yr)	Sum heat demand (GWh/yr)	Landbank within 40km (ha)
Parkhead West and Barrowfield	306.64	0.11	80254511.21	80	7275
Gallowgate North	424.79	0.2	45508090.42	46	6999
Possil Park	550.93	0.22	89735136.58	90	6230
Paisley North	261.07	0.29	56253069.55	56	6043