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Evidence review: Perennial energy crops and their potential in Scotland

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1. Executive summary

If Scotland is to achieve its ambitious net-zero greenhouse gas emissions target by 2045, bioenergy crops present one option as an integral part of the energy supply system.

The Committee on Climate Change (CCC) has identified that under net zero emissions scenarios, bioenergy supplied in the UK could reach 200TWh (with 170TWh of this sourced from the UK) by 2050. The CCC considered that UK-produced energy crops could be an important source of bioenergy and assumed that around 700,000 ha could be planted in the UK to help achieve this target, although it did not consider where. If it were evenly spread across the arable area of the UK, Scotland's 'share' would be about 70,000 ha.

This report examines the potential for a sustainable expansion of perennial bioenergy crop production on low-grade agricultural land or underutilised land, focusing on short rotation coppice (SRC), miscanthus and short rotation forestry (SRF). The aim was to understand the potential implications of any expansion, as a basis for further discussion.

Key findings

The theoretically suitable total land area identified across all three crops and land types, which include grassland, is more than 900,000 ha; suggesting that Scotland could make a substantial contribution to the area of UK energy crops, and meet its 'share.' The **theoretically** suitable total land area is shown to decline when grassland areas are excluded.

In terms of total area, geospatial modelling shows a **theoretical** potential for each crop type in Scotland (based on current data) of:

- 912,600 ha of suitable land is currently available for planting of SRF
- 219,100 ha is available for SRC
- 51,800 ha is available for miscanthus

The areas can overlap and are therefore not mutually exclusive.

The majority of this **theoretically** available land is located in the east of Scotland and the lowlands. The availability of this land will be limited by a range of other factors, for example the need for land for other uses, such as fodder production, forestry (non-energy) etc.

The **theoretically** available land could provide the following energy yields:

- 30.50TWh/yr and 5.78Modt/yr for SRF
- 9.25TWh/yr and 1.75Modt/yr for SRC
- 2.59TWh/yr and 0.52Modt/yr for miscanthus

Overall constraints are more severe for miscanthus than for SRC or SRF. The following constraints have high impacts on potential production area:

- Winter hardiness of miscanthus is a major constraint for this crop in much of Scotland.
- Current varieties of miscanthus are constrained by climate to the south and south east of Scotland (Towers, 2013).
- Soil carbon loss is a constraint for SRC expansion. There is a large area of land in Scotland with high levels of soil organic carbon and this land is susceptible to loss of soil carbon when it is cultivated. For SRF this constraint is less relevant because there is less soil cultivation but planting of trees on blanket bog (peatland) should be avoided (as recommended in the UK Forestry Standard (Forestry Commission, 2017)) because of habitat loss and carbon loss as a consequence of drainage.

Using a UK Climate Projections 2009 (UKCP09) medium emissions scenario for a changing climate, we found that the expansion in suitable land is between:

- 22-25% of the current theoretically suitable land area out to 2030 and between 29-30% of the current suitable land area out to 2045 for SRC and miscanthus.
- However, the suitable land available for SRF is shown to decline by 3% by 2040.

Overall, the data show there are opportunities for energy crop expansion, both currently and under a changing climate.

Contents

2. Introduction

The aim of this project was to review and identify the potential constraints for a sustainable expansion of perennial bioenergy crop production on low-grade agricultural land or underutilised land. The crops considered were short rotation coppice (SRC), miscanthus and short rotation forestry (SRF). We also considered potential land use for reed canary grass, but it was not included in the analysis of constraints (Section 3) because of a lack of evidence.

SRC in the UK is usually a closely-planted stand of willow that is harvested at three-year intervals for up to 10 harvests. Poplar is grown in mainland Europe, with good growth rates and disease resistance advantages compared with willow.

Miscanthus is a genus of perennial grasses that grows woody canes like bamboo and is not native to the UK. Crops are produced using the sterile hybrid *Miscanthus* x *giganteus*, also known as elephant grass. Miscanthus species that are fertile have been used in trials.

SRF is the production of trees in a rotation of 15-20 years, and usually without the thinning that is practiced in typical long-rotation forestry. Species can be coniferous (e.g. Sitka spruce, Douglas fir) or broadleaved (e.g. silver birch, downy birch, sycamore).

The Climate Change (Scotland) Act 2009 details the statutory targets for greenhouse gas (GHG) emission reductions of 42% by 2020 and 80% by 2050. These targets have since been reviewed and new GHG reduction targets of 75% by 2030, 90% by 2040 and zero-net emissions by 2045 have been introduced following advice from the UK Committee on Climate Change (2019).

The Climate Change Plan (Scottish Government, 2018) contained a proposal to develop a Bioenergy Action Plan with the aim of considering further the role that bioenergy plays within the Scottish energy system. While bioenergy contributed around 4.8% of Scotland's primary energy supply in 2017[1], there is scope to increase this and to encourage a constructive role in contributing to Scotland's greenhouse gas reduction targets. However, current production of perennial energy crops in Scotland is very low. Only SRC is currently grown at commercial scale in Scotland, although areas are very small – about 250 ha. Miscanthus can be grown in some parts of Scotland, and will overwinter, but there are only pilot plots and no commercial production. Similarly, in the case of SRF, there are no commercial plantations, only trial plots established between 2010-2013 and which have yet to reach maturity. Understanding the technical and environmental constraints is key to a realistic assessment of future uptake levels as well as the design of policy

The research tasks completed were:

- an assessment of potential bioenergy feedstock demand;
- an analysis of the opportunities and constraints for increased bioenergy feedstock production, together with mitigation actions to overcome the constraints;
- the quantification of land that is agronomically suitable, in theory, for expansion of perennial energy crops; and
- an assessment of potential impacts of climate change on the effectiveness of perennial crops.

[1] Energy balance for Scotland from Energy Statistics Database, available at https://www2.gov.scot/Topics/Statistics/Browse/Business/Energy/Database, accessed 01/02/2020

3. Bioenergy feedstock production: availability and potential demand

3.1 Current production

Bioenergy already makes a contribution to Scotland's energy system: In 2018, 2.1 TWh of electricity (Defra, 2019) and 4.9 TWh of heat (Energy Saving Trust, 2019) were produced from bioenergy sources - about 4.5% of total electricity generation and about 5.9% of non-electrical heat demand. For electricity generation, just over half of bioenergy generating capacity is based on plant biomass (56%)[2] which is thought to be mainly wood – whether waste wood, sawmill residues or wood chips and pellets from forestry, both domestic and international. The remainder is based on wastes (e.g. sewage gas, landfill gas energy from waste, anaerobic digestion). In the case of heat, the majority of it came from solid biomass, predominantly wood chips and wood pellets. The contribution from perennial energy crops was negligible as their production in Scotland is currently very low. Only SRC is grown on a small commercial scale, with around 250 ha thought to be planted, yielding around 2,000 oven dried tonnes (odt) (0.01 TWh); this would be capable of producing about 0.0035 TWh of electricity or 0.0085 TWh of heat when combusted. Miscanthus and short rotation forestry are not currently produced commercially in Scotland, although there are some very small trial plots (Bates, The potential contribution of bioenergy to Scotland's energy system. Ricardo report for ClimateXChange, 2018).

3.2 Future demand

The Committee on Climate Change (CCC) has suggested that for the UK to reach 'net-zero' emissions by 2050, bioenergy will need to increase its contribution to energy supply (Committee on Climate Change, 2019). The CCC has also suggested that this will be necessary for Scotland to achieve its more ambitious GHG reduction targets of achieving net zero emissions by 2045. Studies, which have begun to assess how net zero emissions could be achieved, foresee an important role for bioenergy, principally in the form of bioenergy electricity generation plant with carbon capture and storage (BECCs). Here the carbon dioxide produced as the biomass is combusted is captured and sequestered, effectively meaning that there are negative carbon emissions. For example the CCC's net zero emissions scenario assumes that by 2050, bioenergy supplied in the UK could reach about 200 TWh (compared to about 145 TWh today) of which most (about 170 TWh) would be sourced from the UK. Of the total 200 TWh of bioenergy supply, the majority (173 TWh equivalent to about 35 million oven dried tonnes (odt) of wood[3]) could be used in BECCs plant providing removal of 51 Mt of CO_2, and providing 6% of power generation (Committee on Climate Change, 2019). It is likely that any BECCs plants which are built will be large (in the range of 300 to 500 MW) to allow economies of scale and higher efficiencies to be achieved. Such large plant would require large amounts of feedstock, e.g. a 500 MW BECCs plant might require 10 TWh (2 Modt) of fuel.

The CCC also examines other scenarios for biomass supply, considering options where the UK share of global biomass resources was greater. Around an additional 100-300 TWh (20 to 60 M odt of wood), could be available to the UK depending on land availability and governance arrangements internationally. If the biomass resource were at the upper end of this range and

[2] Based on data from Energy Trends, Table 6.1 of Renewable electricity capacity and generation available at https://www.gov.uk/government/statistics/energy-trends-section-6-renewables

[3] Assuming a lower heating value of 18 GJ per oven dried tonne (odt)

all of this extra resource were to be used for BECCs, this would provide an extra 32 Mt of CO_2 of removals (Committee on Climate Change, 2019). To set this in context, in 2018 the UK imported 36.7 TWh of wood pellets (7,837 ktonnes) for use in power generation and heating; these come mainly from the US (62%), Canada (19%) and the EU (16%) (BEIS, 2019).

The National Grid has developed Future Energy Scenarios, reflecting differing degrees of ambition regarding decarbonisation of the economy, and the level of decentralisation of renewables, including a net zero scenario[4]. Electricity generation from bioenergy reaches about 9GW in the more ambitious decarbonisation scenarios (e.g. Community Renewables) and a further 7GW of BECCs is forecast to be necessary in the Net Zero scenario. This amount of generation would require about 340 TWh of biomass feedstocks, and given estimates of quantities of domestic bioenergy resources made by the CCC could require substantial imports of biomass.

The CCC scenario assumption that 170 TWh of domestically sourced biomass feedstocks could be available in the UK is based on analysis done in earlier work on the role of biomass in a low carbon economy (Committee on Climate Change, 2018a), and on the role of land use in reducing emissions and preparing for climate change (Committee on Climate Change, 2018b). The scenario (multi-functional land use) after allowing for other competing demands for land, considers that afforestation rates could reach 30,000 ha/year and that by 2050, 0.7 Mha of perennial energy crops can be planted, including SRC and miscanthus, and from 2030, short rotation forestry. Afforestation refers to more conventional types of forestry, where trees are grown principally for lumber, and to help increase carbon stocks. Although some wood may be removed from such forests and used for bioenergy (e.g. thinnings or residues created at harvesting of wood for lumber), such afforestation is not done with the main aim of producing wood for energy purposes. The areas which become available for energy crops and forestry arise from an assumed reduction in use of land for food and fodder crops. This assumed reduction is due to increases in agricultural productivity, reductions in both on-farm and consumer food wastage, and changes in food consumption patterns.

The areas represents substantial increases on current practice. Current targets for afforestation in the UK are 20,000 ha/year afforestation rates, due to increase to 27,000 ha/year by 2025 (Committee on Climate Change, 2019). However, estimated new plantings in 2018/19 were only 13,400 ha (Forest Research, 2019a). In Scotland, the Climate Change Plan (Scottish Government, 2018) sets a target for new afforestation of 12,000 ha per year for 2020 to 2021, rising to 15,000 ha per year in 2024-2025. New planting in 2018/2019 in Scotland was 11,210 ha (Forest Research, 2019a).

In the case of energy crops, the UK currently has around 10,000 ha (0.01 Mha) of miscanthus and SRC (Defra, 2019), mainly located in England. This area is assumed to expand to 700,000 ha (0.7 Mha) in the CCC's net-zero scenario, an area equivalent to 11.7% of the UK's arable area and 4% of its total utilisable agricultural area (i.e. including temporary and permanent grass land) (Committee on Climate Change, 2019). Scotland has a relatively small percentage (about 10%) of the UK's arable area, so if energy crop production were evenly spread across the arable area of the UK, Scotland's 'share' of energy crop cultivation, to help meet future demand for bioenergy in a low-carbon future, would be about 70,000 ha. However, Scotland has higher proportions of grassland and rough grazing compared with the UK as a whole, and accounts for just over a third of the total agricultural area in the UK. If some of the grassland areas were considered to be suitable for energy crops, then the Scotland 'share' of the future UK energy crops area could be much higher – about 250,000 ha.

[4] See http://fes.nationalgrid.com/

The remaining sections of the report look at what areas of land in Scotland might be suitable for growing perennial energy crops, in order to allow comparison with these potential levels of future demand.

4. Constraints to increased bioenergy feedstock production

4.1 Methods

We have reviewed opportunities and constraints for increased bioenergy feedstock production, together with mitigation actions to overcome the constraints. Our review and analysis considered the current situation and forwards to 2045.

The review of biodiversity and ecosystem effects of perennial energy crops was not exhaustive but provides an overview of the potential key effects to inform the constraints and exclusion criteria.

The main sources used in the review were:

- Unpublished Ricardo report, 2019[5]
- Expertise of the project team based on industry experience
- Bioenergy: Environmental Impact and Best Practice (Land Use Consultants, 2007)
- The potential contribution of bioenergy to Scotland's energy system (Bates, The potential contribution of bioenergy to Scotland's energy system. Ricardo report for ClimateXChange, 2018)
- Establishment and Management of Short Rotation Coppice (Tubby & Armstrong, 2002)
- Short Rotation Forestry: review of growth and environmental impacts (McKay, 2011)
- Domestic energy crops; potential and constraints review (Aylott & McDermott, 2012)
- A synthesis of the ecosystem services impact of second generation bioenergy crop production (Holland, et al., 2015)
- Biodiversity in short-rotation coppice (Vanbeverena & Ceulemansa, 2019)
- Space for energy crops – assessing the potential contribution to Europe's energy future (Allen, et al., 2014)

The full list of sources can be found in the reference list at the end of the report.

The review produced a long list of opportunities, constraints and mitigation actions, these were organised using a PESTEL table (Political, Economic, Social, Technical, Environmental, Legal), and by crop type (SRC, miscanthus and SRF). Reed canary grass was not included because of a lack of evidence. We then shortened the long list to produce a shortlist using the following criteria:

- The shortlist is for constraints only (not opportunities and mitigations – please refer to the long list for these);
- Technical and/or environmental constraints were included, but other PESTEL categories were excluded (political, economic, social, legal); this was because political,

[5] This study is quoted several times in this report, but is not yet published. Publication is expected in 2020, and this report will be updated when the ful reference is available.

economic, social and legal constraints were out of project scope for subsequent analysis, but their inclusion in the long list ensures awareness of wider issues and highlights the need to consider them in any further analysis of the potential uptake of energy crops;

- Relevant to the analysis timeframe (present to 2045); and
- Expected to limit production of bioenergy feedstock by at least 10% of the potential, largely based on expert judgement.

4.2 Results

A long list of opportunities, constraints and mitigation actions is given in Appendix 1. The focus of the project is on technical and environmental constraints to bioenergy feedstock production, including (for example) agronomic constraints, biodiversity impacts, climate effects and physical constraints. We considered a wider group of opportunities and constraints to ensure an awareness of the wider context, although they are not within scope for further analysis. Some of the constraints in the PESTEL categories that were excluded from the short list (political, economic, social, legal) are, in the views of the project team, important constraints, and include the following:

- Lack of long-term policy support or targets;
- There is no market pull and uncertainty over the stability of a long-term market; A limited market is perceived as a risk, currently limited to few combustion plants (Unpublished Ricardo report, 2019);
- Poor cash flow: large initial investment but no income for 2-3 years (miscanthus), 4-5 years (SRC), (10-20 years) SRF; and
- An Environmental Impact Assessment is required to convert agricultural land to forestry.

A shortlist of technological and environmental constraints is given in Table 1, presented in groups with relevance to all crops or particular crop types. This list was developed from the long list in Appendix 1, where more detail can be found.

Table 1: Shortlist of constraints showing relevance to crop types

Constraint number	Short name	Description
Relevant to SRC, miscanthus and SRF		
1	Access constraints	Need for adequate access for planting and harvesting machinery. Machines are often large and can be restricted by risks to soil, access to the public road network, and slope. Difficult or slow access can increase costs by, for example, requiring the use of tracked vehicles.

Constraint number	Short name	Description
2	Lack of agronomic advice	Lack of updated and unbiased technical advice and information for farmers and land owners; lack of trained agronomists specialising in energy crops (Unpublished Ricardo report, 2019); poor knowledge of management techniques (Unpublished Ricardo report, 2019).
3	Pesticide approvals	Limited pesticides approved for use on energy crops, including herbicides (Unpublished Ricardo report, 2019). Pesticides must be approved for use on specific crops and for specific purposes, under EU regulation[6] (currently in force in the UK). Approvals for use on energy crops are limited because it is not economically viable for agrochemical companies to apply for approvals for crops that have a small production area. In some cases there are no approved pest control methods at key steps in the establishment process. For example, soil pest insects are a high risk after conversion from grassland to energy crops and there are no approved insecticides for control of some of these pests (Unpublished Ricardo report, 2019).
4	Land availability	• Potential competition with food and fodder production if grown on arable land; can be grown on permanent grassland but conversion for energy crops should be limited to 5% to ensure compliance with greening requirement (Scotland specific national requirement).[7]Existing forest and existing energy crops should be excluded. • Should not be planted on land with a high conservation value (Land Use Consultants, 2007), including peat bogs. • Should not be grown on land with designated area exclusions (National Park, National Scenic Areas, Open Access land, SSSI, SAC, SPA, Ramsar, non-statutory sites), or areas of historical significance.

[6] Regulation (EC) No 1107/2009

[7] https://www.ruralpayments.org/publicsite/futures/topics/all-schemes/basic-payment-scheme/basic-payment-scheme-full-guidance/greening-guidance-2018/greening---permanent-grassland/

Constraint number	Short name	Description
5	Biodiversity	Change in land use to bioenergy feedstock production can have positive and/or negative effects on biodiversity, depending on many factors including: • Previous land use (e.g. effects more likely to be negative when the previous land use is grass, compared with arable), • The extent of new planting, influencing landscape diversity and habitat connectivity, • The species planted (e.g. alien species such as eucalyptus support low levels of biodiversity).
6	Soil type	Exclude: high organic matter/peat, marine clay, shallow excessively stony/chalky soils.
Relevant to SRC		
7	Waterlogged soils	This crop cannot be planted on land with soils that are water-logged for most of the time, because the crop does not perform well under these conditions.
7	Steep slopes >15º	Land with steep slopes (any land with a slope greater than 15º) is not suitable (Tubby & Armstrong, 2002) because of machinery limitations.
9	Soil carbon loss	Establishment on high organic/peaty soils potentially detrimental to soil carbon levels. Such soils in Scotland are found mainly in upland areas: for example, in north east Sutherland (the Flow Country) and in many areas across the Highlands and Islands.
10	Soil physical characteristics	On peat/high organic matter soils, likely to be challenging to harvest as soil capability in terms of supporting heavy machinery is poor, leading to soil damage and erosion.
Relevant to miscanthus		
11	Steep slopes >15º	Land with steep slopes (any land with a slope greater than 15º) is not suitable because of machinery limitations.

Constraint number	Short name	Description
12	Labour for planting	Rhizomes not suited to automated planting systems (Unpublished Ricardo report, 2019) so require hand planting like vegetable crops.
13	Winter hardiness	Hard wintry conditions for long periods of time, frozen ground and early spring and early autumn frosts, can halt growth, causing diminished achievable yield; in severe conditions plant loss can occur.
14	Climate	Lower overall day degrees in some parts of Scotland likely to cause reduced yields with current UK varieties.
Relevant to SRF		
15	Machinery limitations	Limited specialist machinery for SRF management (Unpublished Ricardo report, 2019).
16	Irreversible land conversion	Conversion of agricultural land to SRF is irreversible (Unpublished Ricardo report, 2019).
17	Steep slopes >20º	Economics of harvesting probably means that slopes >20º (approximately) will not be economic with current equipment.

The constraints in the shortlist can be reflected to some extent in a ruleset for quantifying the area of land that is agronomically suitable for the sustainable expansion of perennial energy crops. Some of the constraints can be used in an analysis of spatial data, such as climate, soil type and topography (gradient). Other constraints cannot be used in an analysis of the spatial data, such as lack of advice, limited availability of pesticides and machinery limitations; these do not influence the area of agronomically suitable land but will modify the extent of conversion to energy crops.

In Table 2, the short-listed constraints are given alongside assessments of evidence strength, potential effect of the constraints on planted area and yield.

Table 2: Assessment of the strength of constraints to sustainable expansion in production of perennial bioenergy crop feedstocks on currently under-utilised or low-grade agricultural land. The table shows scores for evidence strength and effects on area and yield, presented as high (H), medium (M) or low (L) and a score for effect on production that is the sum of scores in the previous two columns, where L = 1, M = 2 and H = 3; possible scores range from 2 to 6. The final column indicates whether or not the evidence for each constraint can be supported by spatial data sets.

Constraint	Evidence strength	Effect on area	Effect on yield	Spatial data sets available?
Relevant to SRC, miscanthus and SRF				
• Access constraints	H	M	L	No
• Lack of agronomic advice	M	M	M	No
• Pesticide approvals	M	L	M	No
• Land availability	L	M	L	No
• Biodiversity	M	M	L	No
• Soil type	H	M	M	Yes
Relevant to SRC				
• Waterlogged soils	H	M	H	No
• Steep slopes >15º	H	M	L	Yes
• Soil carbon loss	M	H	L	No
• Soil structure	M	L	M	No
Relevant to miscanthus				
• Steep slopes >15º	H	M	L	Yes
• Labour for planting	H	M	L	No
• Winter hardiness	H	H	H	No
• Climate	H	H	H	Yes
Relevant to SRF				
• Machinery limitations	H	M	L	No
• Irreversible land conversion	H	M	L	No
• Steep slopes >20º	H	L	L	Yes

Strength of evidence is high for most constraints. It was identified as low only for land availability, principally because of uncertainty about the impacts of potential competition with food and fodder production if bioenergy feedstocks are grown on arable land. Indirect impacts include the international market for food leads to impacts elsewhere in response to the displacement of food production by bioenergy crops, but these indirect impacts are difficult to quantify. Furthermore, there is uncertainty about the development of policy to limit indirect impacts by limiting food crop displacement.

There are three constraints given a high rating for impact on production area:

- Soil carbon loss as a constraint for SRC expansion.
  This is a high constraint because there is a large area of land in Scotland with high levels of soil organic carbon, and this land is susceptible to loss of soil carbon when it is cultivated.
  This constraint does not apply to miscanthus because in most areas where there are soils with high soil organic carbon, miscanthus would not be planted because of climate constraints.
  For SRF this constraint is less relevant because there is less soil cultivation, but planting of trees on blanket bog (peatland) should be avoided because of habitat loss and carbon loss as a consequence of drainage. This is reflected in the UK Forestry Standard which states that new forests should not be established on deep peat (where the peat layer is deeper than 50 cm), or on sites where planting would compromise the hydrology of adjacent bog or wetland habitats (Forestry Commission, 2017).
- Winterhardiness of miscanthus is a major constraint for this crop in much of Scotland.
- Climate constraint for miscanthus is linked to both the winterhardiness of the crop and to effects of temperature on growth.
  Current varieties of miscanthus are constrained by climate to the south and south east of Scotland (Towers, 2013).

Overall, constraints are more severe for miscanthus than for SRC or SRF.

Biodiversity and ecosystem effects of perennial energy crops

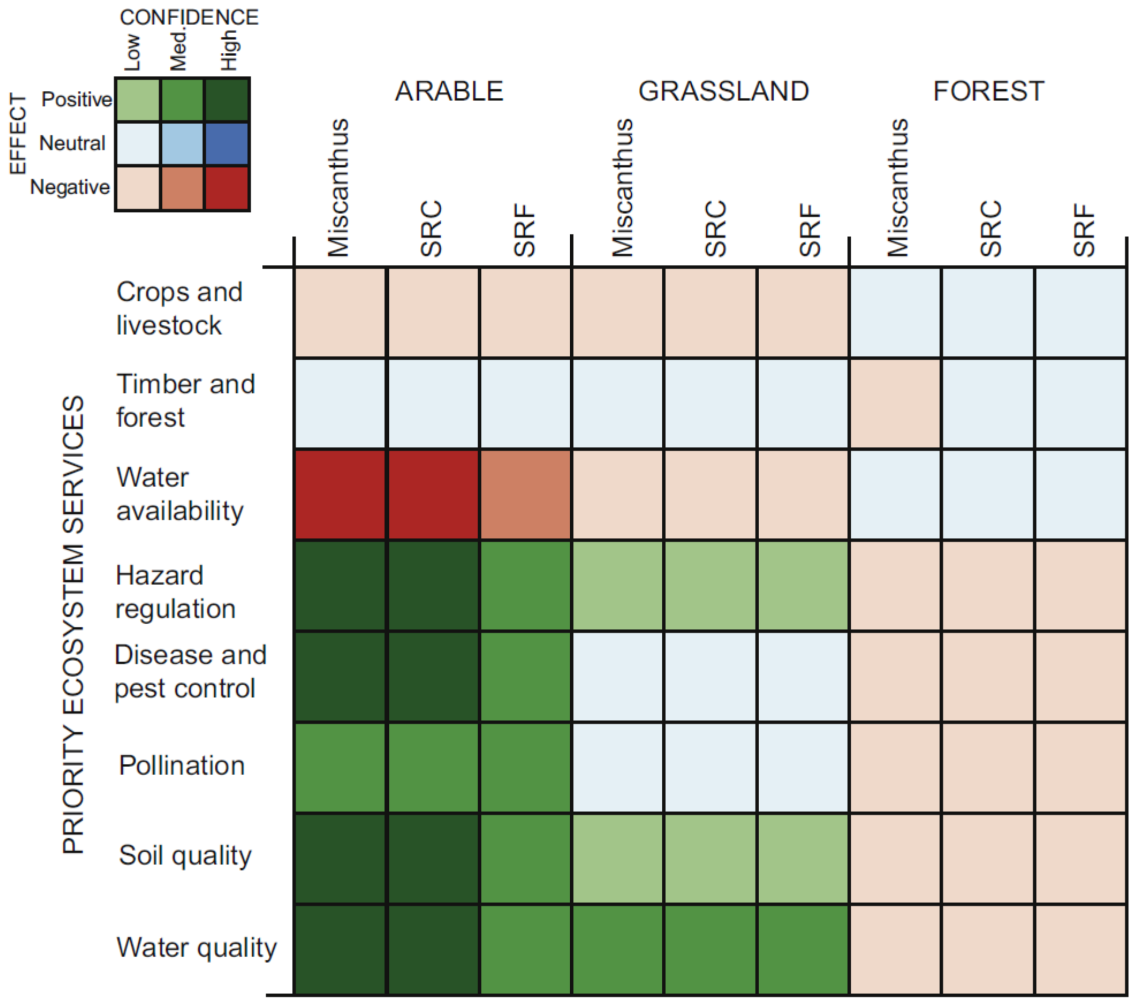
Biodiversity and ecosystem effects

The effects of converting land to produce energy crops on biodiversity and ecosystem function is likely to be highly varied due to influences from crop type (perennial grasses, SRC, SRF), species used, previous land use, extent of planting, management, and location. The methodology in this report used to identify land for planting bioenergy crops excluded priority and important habitats for wildlife (see section 5).

The current research on biodiversity impacts associated with growing bioenergy crops is primarily focused on field scale changes and/or establishment of bioenergy crops on areas with existing arable land with annual crops (miscanthus, SRC) or woodland (SRF and SRC). There is also contradictory evidence in the literature on the effects of converting land to produce energy crops depending on the existing habitats, energy crop type, and species used. Therefore, extrapolation of potential biodiversity effects from conversion of marginal land have low confidence (Holland, et al., 2015) (Vanbeverena & Ceulemansa, 2019).

Holland et al. (2015) identified that for transitions from arable land to bioenergy crops significant benefits may arise for a number of ecosystem services, including hazard regulation, disease and pest control, water, and soil quality. The study also indicated that the conversion of marginal land to bioenergy crops will likely deliver benefits for some services while remaining broadly neutral for others. Whereas, conversion of forest to energy crops will likely reduce the provision of a range of services due to increased disturbance associated with shortening of the management cycle. The potential ecosystem effects from conversion of arable, grasslands, and forest to bioenergy crops (SRC, SRF and miscanthus) are summarised in Figure 1 taken from Holland et al. (2015).

Figure 1: taken from Holland et al (2015), a synthesis of the ecosystem services impact of second-generation bioenergy crop production. Impact matrix of effects on priority ecosystem services of land use transitions to bioenergy crops (SRC, SRF and miscanthus). Impacts are scored positive where there is an increase in the service, negative with a decrease, and neutral where there is no significant effect reported. Confidence is assigned based on the weight of evidence as described in the main text of Holland et al. (2015).



Wide scale monoculture of energy crops of all types is likely to result in a reduction in biodiversity and ecosystem function due to loss of habitat variation.

Biodiversity impacts from SRC, SRF and miscanthus vary significantly with location of crop plantations, previous land use and crop type and management (e.g. cultivations, levels of pesticide and fertiliser inputs used); these are amongst the key drivers in the biodiversity impacts observed. The introduction of non-native species that support extremely low levels of biodiversity (Allen, et al., 2014) (Forsyth, Richardson, Brown, & Van Wilgen, 2004) (Searle & Malins, 2014) is a potential concern; particularly for species such as eucalyptus which is currently being used in SRF trials in Scotland, (Parrat, 2018). A particular concern arises when energy crops are cultivated on less productive land, where most high-nature-value agriculture (i.e. agriculture which is characterised by a high proportion of semi-natural vegetation and low intensity agriculture which supports rare species of European wildlife (Baldock, Beaufoy, Benne, & Clark, 1993)) is concentrated. There is a potential loss of semi-natural habitats (grassland, calcareous grassland and heathlands) in the case of abandoned land (Allen, et al., 2014). Current research provides contradictory evidence as to the biodiversity impacts relating to planting of bioenergy crops depending on the organisms included in the assessments and the factors identified above. The replacement of any semi-natural habitat (especially those listed under Annex I of the Habitats Directive) by a dedicated bioenergy crop would result in significant biodiversity losses.

The miscanthus crops grown in the UK are *Miscanthus* × *giganteus*, a sterile hybrid of the species *Miscanthus sinensis* and *Miscanthus sacchariflorus*. Being sterile, this hybrid is not invasive, but seed-grown hybrids that are fertile have been developed and are being trialled. This raises concerns about invasiveness and consequential impacts on biodiversity. Functional sterility has been identified as potential control for invasiveness. Where late flowering genotypes are planted in northern latitudes allowing little or no time for seed maturation prior to the onset of winter (Matlaga & Davis, 2013) (Quinn, Allen, & Stewart, 2010). Further research is required to determine the suitability of the climate throughout the UK to support seed development in *Miscanthus* sp. However, as the climate warms this risk may increase due a change in availability of suitable habitats and climatic conditions.

Pollination

As with overall biodiversity, transitions from arable land to bioenergy crops have potential to lead to benefits for pollinating species due to more stable environment from longer rotation periods (3-7 years). The key factors increasing suitability for pollinators are: reduced ground disturbance, increased diversity of nectar and pollen sources, and potential over wintering sites (Holland, et al., 2015) (Stanley & Stout, 2013) (Rowe, et al., 2011). However, the effect of large scale monocultures of bioenergy crops is likely to be detrimental to pollinator species as landscape homogenisation is widely accepted to be a driver for the current loss of pollinating species.

SRC, SRF and to a lesser extent miscanthus, have greater potential to benefit pollinating species when used to provide heterogeneity in an agriculture-dominated landscape than as large-scale plantations. Variation in age, species, density, and rotation length within a landscape facilitates benefits for wild pollinating species.

Wildlife corridors

Large scale planting of SRC, SRF and miscanthus has the potential to provide wildlife corridors. Evidence suggests facilitation of movement of animals across open agricultural landscapes (Tullus, Rytter, Tullus, & Weih, 2012) (Allen, et al., 2014), due to increased cover provided by established crops and lower disturbance compared to arable land and improved grasslands.

The effect of SRF plantations on biodiversity is highly dependent on location within the wider landscape. Positioning SRF and SRC plantations adjacent to native/established woodlands native can facilitate the migration of birds, insects and plants and thus increase the biodiversity benefits (Tullus, Rytter, Tullus, & Weih, 2012) (Allen, et al., 2014). On the other hand, overall biodiversity, homogenisation of the landscape from large scale biodiversity planting could also result in habitat fragmentation if large scale monocultures are positioned unsympathetically within the landscape between connected habitats.

Pests

The literature review by Dauber et al. (2010) indicates that a transition from arable land and improved grasslands to bioenergy crops (SRC and miscanthus) can increase diversity and abundance of groups that contribute to natural pest control. Holland et al. (2015) suggests that the relationship between biodiversity in bioenergy crops and natural pest control benefits are unclear. Although there is potential for bioenergy crops (SRC, SRF and miscanthus) within an agricultural landscape to provide reservoirs of beneficial species for recolonisation of food crops following disturbance of adjacent land from harvesting agricultural crops or application of pesticides (Holland, et al., 2015) (Thomson & Hoffmann, 2011). The lower levels of soil disturbance in SRC favours biological control species of pests present in cereal food crops (Verheyen, et al., 2014) (Langer, 2001). These conclusions raise the possibility that the reverse may also be true with bioenergy crops providing a refuge for pest species of food crops.

A review of biodiversity in SRC by Vanberveren and Ceulemans (2019) identified that pesticides required to control leaf beetles which can damage SRC crops are typically non-selective and hence will lower overall biodiversity reducing the benefits to adjacent crops as identified above. In addition, the review identified that biological control of leaf beetles in SRC was disrupted by coppicing (Björkman, Bommarco, & Höglund, 2004). This indicates that, as identified above, rotation length is highly influential on the ecosystem effects of bioenergy crops in agricultural landscapes.

5. Potential for sustainable expansion of perennial energy crops

5.1 Methods

Upper estimates of areas **theoretically** suitable for bioenergy crop production were calculated using a simple exclusion-based approach within GIS (similar to Andersen et. al. (2005) and Lovett et. al. (2014). This approach was applied to the three main crop types: SRF, SRC and miscanthus. The excluded areas were deemed to be unsuitable based on expert judgement on growing conditions, the need not to utilise land currently used for agriculture or forestry and to exclude any designated sites of scientific or cultural significance. In addition, land acknowledged as having biodiversity value and importance, such as designated sites, peat land etc. was excluded to further protect biodiversity. These excluded areas were used to create a series of rulesets which were used in the GIS to create the final land suitability layer for each of the three crop types. Data covering the entirety of Scotland, including all islands, were used. Details of the datasets and the rulesets are provided in Table 3 and Table 4 respectively.

Table 3: Datasets

Dataset name and data source	Ruleset applied to data
James Hutton Institute: Land Capability for Agriculture, 1:250,000 – http://nar.hutton.ac.uk/dataset/land-capability-maps	Land capability – agriculture
James Hutton Institute: Land Capability for Forestry, 1:250,000 – http://nar.hutton.ac.uk/dataset/land-capability-maps	Land capability - forestry
Ordnance Survey: Terrain 50 50m resolution digital elevation model (DEM) – https://www.ordnancesurvey.co.uk/opendatadownload/products.html	Elevation and slope angle
Centre for Ecology and Hydrology (CEH): Gridded Estimates of Areal Rainfall (GEAR) – https://doi.org/10.5285/ee9ab43d-a4fe-4e73-afd5-cd4fc4c82556	Rainfall
CEH: Climate Hydrology and Ecology research Support System (CHESS) – https://doi.org/10.5285/c76096d6-45d4-4a69-a310-4c67f8dcf096	Temperature

Dataset name and data source	Ruleset applied to data
Forestry Commission, Ecological Site Classification (ESC)	Elevation, Rainfall and Temperature
James Hutton Institute: National Soils of Scotland, 1:250,000 – http://nar.hutton.ac.uk/dataset/national-soils-of-scotland	Soil type
Scottish Natural Heritage: Carbon and Peatland Map 2016 – https://gateway.snh.gov.uk/natural-spaces/	Peat land
Forestry Commission: National Forestry Inventory Woodland Scotland 2017 – http://data-forestry.opendata.arcgis.com	Forestry
European Space Agency: CORINE 2018 – https://land.copernicus.eu/pan-european/corine-land-cover	Other land cover
Ordnance Survey: Open Zoomstack – https://www.ordnancesurvey.co.uk/opendatadownload/products.html	Waterbodies
Scottish Natural Heritage: National Parks, National Scenic Areas, Country Parks etc. – https://gateway.snh.gov.uk/natural-spaces/	Landscape designations
Scottish Natural Heritage: World Heritage Sites, Battlefields, Conservation Areas etc. – https://gateway.snh.gov.uk/natural-spaces/	Cultural designations
Scottish Natural Heritage: Ramsar, SAC, SPA, SSSI etc. – https://gateway.snh.gov.uk/natural-spaces/	Scientific designations

Specific attributions to their use are required by these datasets. In order to fulfil this requirement, and acknowledge their use, a full list of data attributions is provided in Table 11 (Appendix 2).

Table 4: Rulesets used to define land suitability

	Exclusion criteria		
Ruleset	**SRF**	**SRC**	**Miscanthus**
Land capability – agriculture	---	Classes 1, 2, 3.1, 3.2, 6.2, 6.3, 7, 888,999 and 9500	Classes 1, 2, 3.1, 3.2, 6.1, 6.2, 6.3, 7, 888,999 and 9500
Land capability - forestry	Classes F6, F7, F8 and F9	---	
Elevation	---	>300m	>100m for >55° latitude >300m for ≤55° latitude
	ESC: DAMS > 18	---	
Slope angle	>20°	>15°	
Rainfall	---	>650mm per year during April - October	

	Exclusion criteria		
	ESC: Very Dry, Dry and Very Wet.	---	
Temperature	---	<10 - >25°C	<3 - >28°C between May to September.
	ESC: Alpine, Sub-alpine and Warm Dry	---	
Soil type	Bare rock, peat and saline soils omitted.		
Peat land	Defined peat bogs.		
Forestry	All woodland where ID was certain.		
Other land cover	Urban land, permanent grassland and pasture, estuarine and littoral land cover.		
Waterbodies	Lakes and larger watercourses.		
Landscape designations	National Parks, Country Parks, National Scenic Areas and Council of Europe Diploma sites.		
Cultural designations	Battlefields, Conservation areas, Gardens and designated landscapes, Historic marine protection areas, Listed buildings, Scheduled monuments and World Heritage Sites.		
Scientific designations	Ancient woodland, Biogenetic reserve, Biosphere reserve, Geological Conservation Review sites, Local Nature Reserves, National Nature Reserves, Nature Reserves, Ramsar, SAC, SPA and SSSI.		

Complete details of the datasets, the specific features excluded from each dataset, assumptions used and specifics on the processing of each dataset are found in Appendix 2 and in Table 8 (Appendix 2).

Datasets were processed within QGIS (QGIS Development Team, 2019), SAGA GIS (Conrad, et al., 2015) and GRASS GIS (GRASS GIS Development Team, 2019). The rulesets (**Error! Reference source not found.** and **Error! Reference source not found.**) were applied in a step by step fashion to the datasets using geoprocessing difference calculations within QGIS and SAGA GIS.

This generated three different datasets for each of the three crop types. The methodology applied is outlined below:

- **Step 1a –** Generate topographic exclusion datasets for elevation and slope angle based on the critical threshold parameters (**Error! Reference source not found.**) from a 50m digital elevation model of Scotland and Ecological Site Classification (for forestry).
- **Step 1b –** Generate rainfall and temperature exclusion datasets based on the critical threshold parameters (**Error! Reference source not found.**) using the CEH GEAR and CHESS datasets.
- **Step 2a –** Remove excluded land classifications from Land Capability for Agriculture (LCA) layer. The output formed the *LCA base layer* from which all other exclusions are based. **This layer is used for SRC and miscanthus only.**

- **Step 2b –** Remove excluded land classifications from Land Capability for Forestry (LCF) layer. The output formed the *LCF base layer* from which all other exclusions are based. **This layer is used for SRF only.**
- **Step 3a –** Remove CORINE dataset excluded land cover types from the relevant *base layer* (the output from Step 2).
- **Step 3b –** Remove the National Forestry Inventory Woodland areas from the relevant *base layer* (the output from Step 3a).
- **Step 3c –** Remove peat bog land areas (using the Carbon and Peatland Map dataset) from the relevant *base layer* (output from Step 3b).
- **Step 4a –** Remove all landscape designation areas from the relevant *base layer* (output from Step 3c).
- **Step 4b –** Remove all cultural designation areas from the relevant *base layer* (output from Step 4a).
- **Step 4c –** Remove all scientific designation areas from the relevant *base layer* (output from Step 4b).
- **Step 5 –** Exclude the areas in the relevant *base layer* (output from Step 4c) which fall outside the topographic exclusion datasets created in Step 1a.
- **Step 6 –** Exclude the areas in relevant *base layer* (output from Step 5) which fall outside the rainfall and temperature created in Step 1b and also the ESC data.
- **Step 7 –** Calculate the area of the remaining land (using the output from Step 6) to calculate the suitable land available for growing each of the three bioenergy crop types.

Maps of the resulting land suitability areas are provided in Appendix 2. The calculations of areas of suitable land are detailed in Table 5 below.

5.2 Results

The resulting areas of suitable land **theoretically** available for bioenergy crop cultivation are presented in Table 5 (upper estimates). Calculations to derive these areas only consider the constraints in Table 2 where spatial data was available (e.g. soil type, slope angle and climate) and the resulting areas for each bioenergy crop can overlap and are therefore not mutually exclusive. Errors on each area are taken to be ±5% (see Appendix 2) and are quoted in Table 5.

Table 5 also presents the potential bioenergy crop yield estimates for these areas in both TWh/year and Modt/year. Yield conversion values for SRF are derived from Unpublished Ricardo Report (2019) and values for SRC and Miscanthus are from *Crops Grown For Bioenergy in the UK* (Defra, 2019).

Table 5: Areas of land suitable for bioenergy crop cultivation and associated potential yield estimates

Crop type	Area of suitable land (ha)				
	Theoretically suitable total land area	Suitable land area excluding LCA 5.1	Suitable land area excluding LCA 5.2	Suitable land area excluding LCA 5.3	Suitable land area excluding sum of LCA 5.1, 5.2 and 5.3
Short Rotation Forestry	912,600 ±45,600	---	---	---	---
Short Rotation Coppice	219,100 ±11,000	206,464 ±10,323 (-6%)	178,142 ±8,907 (-19%)	151,652 ±7,583 (-31%)	98,058 ±4903 (-55%)

Miscanthus	51,800 ±2,600	49,851 ±2,493 (-4%)	41,487 ±2,074 (-20%)	38,436 ±1,922 (-26%)	26,173 ±1309 (-49%)
	Potential yield estimates in TWh/year per suitable land area				
Short Rotation Forestry	30.50 ±1.52	---	---	---	---
Short Rotation Coppice	9.25 ±0.46	8.72 ±0.44	7.52 ±0.38	6.40 ±0.32	4.14 ±0.21
Miscanthus	2.59 ±0.13	2.49 ±0.12	2.07 ±0.10	1.92 ±0.10	1.31 ±0.07
	Potential yield estimates in Modt/year per suitable land area				
Short Rotation Forestry	5.78 ±0.29	---	---	---	---
Short Rotation Coppice	1.75 ±0.09	1.65 ±0.08	1.43 ±0.07	1.21 ±0.06	0.78 ±0.04
Miscanthus	0.52 ±0.03	0.50 ±0.02	0.41 ±0.02	0.38 ±0.02	0.26 ±0.01

The analysis shows there currently exists a large area of land which is **theoretically** suitable for SRF and SRC. Generally the most suitable land lies in the east of Scotland and the lowlands. However, the mapping shows that there are currently opportunities in the west and north of Scotland, particularly for SRF. Miscanthus is limited, specifically due to the elevation constraints imposed on the species, although there is scope for expansion in lower land areas fringing the Scottish coastline and also on Orkney and Shetland. The availability of this land will be limited by a range of other factors, for example the constraints not covered by spatial data (Table 2) and the need for land for other uses, such as fodder production, forestry (non-energy) etc.

As noted, the land areas represent a **theoretical** upper limit of what is available. In order to understand how this suitable land area for SRC and miscanthus changes as grassland of varying quality is excluded from it the area of each of the LCA grassland classes (LCA class 5.1, 5.2 and 5.3, Table 9) were individually removed from the theoretically suitable total land area. In addition, the sum of the LCA grassland classes were also removed (Table 5). Percentage changes for each of these areas against the **theoretically** suitable total land area are also presented in brackets in Table 5.

The LCF data does not contain grassland classes so this calculation cannot be performed for SRF. The data show a 6-31% reduction in theoretically suitable land area for SRC and a 4-26% reduction in **theoretically** suitable land area for miscanthus when the LCA grassland classes are excluded individually. When all LCA grassland classes are excluded this results in a 55% and 49% reduction in theoretically suitable total land area for SRC and miscanthus respectively.

For potential yields for the **theoretically** available land for each of the bioenergy crop cultivation, SRF indicates the greatest yield of all three crops, estimated at 30.50TWh/yr and 5.78Modt/yr. For SRC, a yield of 9.25TWh/yr and 1.75Modt/yr is predicted for the total **theoretically** suitable land area, declining to 4.14TWh/yr and 0.78Modt/year when all LCA classes are excluded. For miscanthus, a yield of 2.59TWh/yr and 0.52Modt/yr is predicted for the total **theoretically** suitable land area, declining to 1.31TWh/yr and 0.26Modt/yr when all LCA classes are excluded.

6. Impact of changing climate on perennial energy crops

6.1 Methods

The study requires an understanding of the availability of suitable land for bioenergy crops out to 2030 and 2045 due to climate change. For the purposes of this project it was decided to use the UK Climate Projections 2009 (UKCP09) (Jenkins, et al., 2009) predictions rather than the UK Climate Projections 2018 (UKCP18) predictions for pragmatic reasons. The medium emissions scenario, 50% probability summer predictions for the Eastern Scotland area were used as this area covered the majority of the land predicted to be suitable for bioenergy crop production. The forward climate predictions from UKCP09 were provided for the 2020s, 2050s and 2080s and these were scaled to 2030 and 2045 to derive the changes in rainfall and temperature used in the analysis. These scaled predictions are presented in Table 6.

Table 6: UKCP09 predictions for changing mean summer rainfall and mean summer temperature for Eastern Scotland for medium emissions scenario at 50% probability scaled to 2030 and 2045

	Time period of scenario	
Climate variable	**2030**	**2045**
Mean summer temperature (°C)	1.7	2.1
Mean summer precipitation change (%)	-9	-12

The climate predictions for mean summer rainfall and temperature for 2030 and 2045 (Table 6: UKCP09 predictions for changing mean summer rainfall and mean summer temperature for Eastern Scotland for medium emissions scenario at 50% probability scaled to 2030 and 2045Table 6) were applied to the processed 1990 baseline rainfall (CEH GEAR, Table 3) and temperature datasets (CEH CHESS, Table 3) downloaded from CEH. The resulting datasets were thresholded using the critical temperature and rainfall thresholds detailed in Table 4. These thresholded datasets were subsequently used to exclude areas of land outside the suitable climatic ranges from the baseline suitable land areas created in Step 6 (see section 5) for the SRC and miscanthus. These actions generated datasets of suitable land areas under climate change projections for the dates 2030 and 2045. The ESC datasets have only been forward predicted to 2040 and therefore suitable land changes for SRF are only provided for this date.

Full details of the UKCP09 and the selected climate change scenarios and a more detailed methodology are presented in the Appendix 3.

6.2 Results

The resulting areas of suitable land available for each bioenergy crop in the future (with respect to climate change) are presented in Table 7 along with percentage change in land area against the baseline areas calculated in Table 5. Errors on each area are taken to be ±5% (Appendix 3). It has not been attempted to provide any additional error associated with climate change uncertainty in these predictions.

Table 7: Predicted areas of suitable land for each bioenergy crop in 2030, 2040 and 2045

	Area of suitable land (ha)					
Crop type	**2030**	**Change against baseline**	**2040**	**Change against baseline**	**2045**	**Change against baseline**
Short Rotation Forestry	---	---	888,500 ±44,400	~-3%	---	---
Short Rotation Coppice	274,500 ±13,700	~+25%	---	---	285,400 ±14,300	~+30%
Miscanthus	63,000 ±3,200	~+22%	---	---	66,600 ±3,300	~+29%

The analysis shows that under the UKCP09 climate predictions for Scotland areas of **theoretically** suitable land for SRC and miscanthus will increase. Most of the expansion for miscanthus occurs in the south of Scotland. The largest percentage increase in suitable land under climate change is for SRC, although miscanthus shows a very similar percentage increase in suitable land area in both 2030 and 2045. SRF on the other hand shows a decline in area of around 3%. This is most likely due to increased soil wetness predicted by the ESC datasets in the north of Scotland due to increased rainfall. It should also be noted that the SRF data indicate an expansion of suitable land in the Scottish lowlands.

7. Conclusions

Production of energy crops in Scotland is currently very low, only SRC is grown on a small commercial scale of approximately 250 ha, yielding around 2000 oven dried tonnes (odt).

If Scotland is to achieve its ambitious net zero GHG emissions target by 2045, bioenergy crops present one option as an integral part of the energy supply system.

The Committee for Climate Change has identified that under net zero emissions scenarios, bioenergy supplied in the UK could reach 200TWh (with 170TWh of this sourced from the UK) by 2050. The CCC considered that UK produced energy crops could be an important source of bioenergy and assumed that around 700,000 ha could be planted in the UK to help achieve this target. Decarbonisation scenarios in National Grid studies also show substantial contributions from bioenergy, indicating 9GW of bioenergy generation, followed by an addition 7GW from bioenergy in net zero scenarios (requiring 340TWh of biomass feedstocks, much of which could require importing).

There are a number of technical and environmental constraints to land use for bioenergy feedstock supply; those with medium or high effects on crop area, include:

- soil carbon loss (preventing conversion on land with high carbon stock)
- winter hardiness of miscanthus
- climate (for miscanthus)
- access for machinery
- machinery limitations (SRF)

- land availability
- irreversible land conversion (SRF)
- effects on biodiversity (especially for conversion of pasture to bioenergy)
- soil type
- waterlogged soils
- steep slopes
- labour for planting miscanthus
- lack of technical advice

The analysis highlights that most of the **theoretically** suitable land is located on the eastern side of Scotland. Area coverage shows that SRF and SRC currently have the largest amount of suitable land available for their production. Miscanthus is shown to have only a limited area of suitable land, mostly due to the altitude constraint on the crop. Much of the suitable land for miscanthus is found around the coast of Scotland and on Orkney and Shetland. The **theoretically** suitable total land area is shown to decline when grassland areas are excluded from these.

The CCC did not indicate how the 700,000 Mha of UK energy crops it considered could be planted would be spread across the UK. If it were evenly spread across the arable area of the UK, Scotland's 'share' would be about 70,000 ha. However, if some of the grassland areas were considered to be suitable for energy crops, then the Scotland 'share' could be much higher – about 250,000 ha. The theoretically suitable total land area identified across all three crops and land types which include grassland, is more than 900,000 ha suggesting that Scotland could theoretically make a substantial contribution to the area of energy crops, and meet its 'share'. If planting on grassland was not considered then the theoretically suitable area for miscanthus and SRC would be around 100,000 ha; suggesting that Scotland could theoretically meet its share on this basis too, especially as there could be potential additional areas of SRF[8]. In practice, the availability of land will also be limited by a range of other factors, which were not possible to model in this study e.g. non-spatial constraints and the need for land for other uses, such as fodder production, forestry (non-energy) etc. and these would need to be taken account if a full evaluation of the areas of energy crops which could actually be planted by 2050 in Scotland is required.

Under the climate change scenario considered (medium emissions, 50% probability) SRC and miscanthus show relatively large increases in **theoretically** available suitable land area. SRC shows the largest increase, with miscanthus showing only slightly lower percentage increases (mostly in the south of Scotland). For miscanthus these increases are likely to decline past 2045 given the elevation constraint on this crop. In contrast, SRF shows a 3% decline out to 2040 as growing conditions for trees become less favourable. Overall, the data do show that there are opportunities for energy crop expansion both currently and under a changing climate.

[8] The theroretically suitable area of SRF if planting on grassland was not considered could not be determined in this study due to a lack of data.

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9. Appendices

Appendix 1: Long list of opportunities, constraints and mitigation measures for growing SRC, miscanthus and SRF

General, applicable to energy crops and short rotation forestry (SRF)

Type	Opportunities	Constraints	Potential mitigation measures
Political	• Energy crops sequester significant CO_2 each year, which could be used to reduce overall CO_2 target levels	• Lack of long-term policy support or targets • No market pull and uncertainty over stability of long term market • Impact of the UK leaving the EU – and requirements for devolved agricultural and energy policy – significant uncertainty	

Type	Opportunities	Constraints	Potential mitigation measures
Economic	• Crowd funding opportunities for local rural businesses, schools, to use local supply of biomass to heat buildings	• Poor cash flow • Large initial investment but no income for 2-3 years (miscanthus), 4-5 years (SRC), (10-20 years) SRF • Limited market perceived as risk • Currently limited to few combustion plants (Unpublished Ricardo report, 2019) • Bulky nature of material means cost of storage and transport can limit market to areas within limited radius of where crop grown (Unpublished Ricardo report, 2019). • Limited land availability • Uncertain profitability in comparison to land-uses that are better known • Existing forest and existing energy crops should be excluded	• Grant/support to help cover initial period of no financial return. (Aylott & McDermott, 2012) • If close initial spacing is used, possible to generate income by thinning at mid-rotation, e.g. after 7-8 years • Encourage local, medium-scale markets • Encourage larger and more diverse market • Alternative business models such as contract growing • Pelleting to reduce cost of storing SRC and miscanthus, (Sahoo, Blek, & Mani, 2018) • SRF can be dried on site • Chip can be ‘packed’ at higher density for transportation

Type	Opportunities	Constraints	Potential mitigation measures
Social		• Permanency of crop • Long term nature of crop removes flexibility to respond to changes in market conditions • Reversion to farming use may not be allowed once SRF is planted as deemed change of use • Planning and preparation to make land suitable for energy crops may deter farmers due to time required for reversion at end of plantation life (Land Use Consultants, 2007) • Negative publicity regarding the benefits of energy crops (Unpublished Ricardo report, 2019) • Objections to planning applications for biomass power stations leads to limited feedstock market and demand (BioFuelWatch, 2019)	• Change to Forestry Act • Campaign to explain rationale for burning *sustainably grown* biomass instead of fossil fuels. Campaign to emphasise wider environmental benefits that are possible with good design and management

Type	Opportunities	Constraints	Potential mitigation measures
Technological (including agronomic)	• Can be grown on land not suitable for arable or grassland crops (Wang, et al., 2014) (Bourgeois, Dequiedt, & Lelièvre, 2015)	• Access • Need for adequate access for planting and harvesting machinery • Should not be grown on slopes>15 degrees (energy crops) or 20 degrees (SRF) • Lack of updated and unbiased advice and information for farmers and land owners: • Lack of trained agronomists specialising in energy crops (Unpublished Ricardo report, 2019) • Poor knowledge of management techniques (Unpublished Ricardo report, 2019) • Limited pesticides approved for use on energy crops (Unpublished Ricardo report, 2019) • Growing as a monoculture increases risk of disease and pest outbreak (Unpublished Ricardo report, 2019) • Exclude: high organic matter/peat, marine clay, shallow excessively stony/chalky soils	• Browsing (deer, sheep, rabbits, hares, boar) must be controlled by reduction in number of animals and/or provision of protection • Use drones for disease identification and growth monitoring (Ahamed, Tian, Zhang, & Ting, 2011) • Grow as a species mix to decrease risk of disease/pest outbreaks (Unpublished Ricardo report, 2019)

Environmental	• Improved water quality due to reduced use of herbicides, pesticides and fertilisers compared to other crops (Christen & Dalgaard, 2013) • Improved soil health (Bourgeois, Dequiedt, & Lelièvre, 2015) (Holder, McCalmont, McNamara, Rowe, & Donnison, 2018) (Rowe, Street, & Taylor, 2009) • Improved environment for wildlife (Dauber, et al., 2015) (Wu, et al., 2018) • High water uptake means SRC has flood mitigation qualities (Christen & Dalgaard, 2013) (Holder, McCalmont, McNamara, Rowe, & Donnison, 2018) (Environment Agency, 2015) • Carbon sequestration benefits, which could be a valuable way of locking up CO_2 under NET Zero campaign • Provision of shelter for crops and/or animals • Visual screening • Removal of pollutants from intensive poultry units	• Availability of suitable land • Potential competition with food and fodder production if grown on arable land • Can be grown on permanent grassland but conversion for energy crops limited to 10% (no limit for SRF) • Visual landscape changes (Land Use Consultants, 2007) • Large areas grown as monoblocs could significantly change landscape • Lasting impacts on soil quality due to compaction while harvesting. • Climate conditions will affect the development of crops and how well they yield, conditions in Scotland are generally cold so this may reduce overall yield. • Greater water demand in comparison with arable or grassland (Bates, The potential contribution of bioenergy to Scotland's energy system. Ricardo report for ClimateXChange, 2018) • Should not be planted nearby sensitive wetland habitats due to high water use (Land Use Consultants, 2007) • Biodiversity: change in land use to bioenergy feedstock production can have positive and/or negative effects on biodiversity, depending on many factors including: 　○ Previous land use (e.g. effects more likely to be negative when the previous land use is grass, compared with arable),	• Use less productive areas of farm for energy crops, and focus food production on more productive areas • Use mixed species to mitigate visual landscape concerns

Type	Opportunities	Constraints	Potential mitigation measures
		○ The extent of new planting, influencing landscape diversity and habitat connectivity, ○ Species: alien species such as eucalyptus support low levels of biodiversity. • Should not be grown on land with designated area exclusions (National Park, National Scenic Areas, Open Access land, SSSI, SAC, SPA, Ramsar, non-statutory sites), or land areas of historical significance.	
Legal/Regulatory	• Increased awareness of climate change may encourage a rapid uptake	• Restrictions in CAP on conversion of permanent grassland	• Future policy post EU exit • Opportunity for enabling regulations

Short rotation coppice (SRC)

Type	Opportunities	Constraints	Mitigation measures
Social	• Harvest provides job opportunities in winter	• 5m+ high plantations which grow rapidly can have social impacts on rural views and footpath/bridle path access if plantations are not planned effectively • Roots can impact on archaeological aspects • Rural visual impact	• Information, communication

Type	Opportunities	Constraints	Mitigation measures
Economic	• Market opportunities for businesses to use biomass resource, to provide RHI supported fuel to produce local heat and CHP systems	• Currently there is limited end use demand for produced biomass in region • Cash flow implications (3-4 year from establishment, so 5-6 year potential cash flow problem) • Variable yield and uncertainty of total life cycle • Access to locally available harvesting and other management equipment, to ensure costs can be kept to a minimum • Bulk density of harvested material requires local end use (less than 100km) ETI report 2016	• Put in place policy and information to support and encourage growth in market sector • Develop consistent and yield resilient varieties • Develop local end use markets

Type	Opportunities	Constraints	Mitigation measures
Technological (including agronomic)	• Once established SRC can be very productive on soils with a high clay content (Defra, 2004) • Crop can be used to dispose of dirty waters, sewage sludge, anaerobic digestate, animal manures • New varieties are being researched which are able to be used for new end uses (biochemical, bio composite, biofuels)	• Limited number of contractor 'Step' planters available (Unpublished Ricardo report, 2019) • Planting systems need efficiency improvements (Lowthe-Thomas, Slater, & Randerson, 2010) (McCracken, Moore, Walsh, & Lynch, 2010) • Harvesting systems need efficiency improvements (Unpublished Ricardo report, 2019) • Cannot be planted on land with water-logged soils most of the time, or with steep slopes (Tubby & Armstrong, 2002) • Winter harvest means a higher risk of damage to soils (Land Use Consultants, 2007) • Changes in land management needed • Insufficient cold storage for cuttings in the winter months, if significant and rapid planting expansion is required (Croxton, 2014) • Newer varieties are better, but some varieties can grow in to field drains and block them up over time • Mixed plantings required, otherwise disease infections can significantly impact on achievable yield (Iggesund publication 2019) • Diminishing list of available agrochemical products for controlling competitive weeds	• Extending the planting window by planting at different times of the year would mitigate issues with limited machinery and soil moisture. (Unpublished Ricardo report, 2019)

Type	Opportunities	Constraints	Mitigation measures
Environmental	• Positive impact habitat development (Bates, The potential contribution of bioenergy to Scotland's energy system. Ricardo report for ClimateXChange, 2018) (Land Use Consultants, 2007) (Tubby & Armstrong, 2002) • Opportunity to provide wildlife corridors (Land Use Consultants, 2007) • Reduced diffuse pollution when planted as a buffer between agricultural crops and water sources (Land Use Consultants, 2007) • Reduction of soil erosion • Increased level of biodiversity over annual arable crops • Better carbon sequestration than arable and grass crops	• Intolerant of weeds (Tubby & Armstrong, 2002) • Small parcels of land (I.e. buffer strips) are challenging to establish, and manage, and often lower yielding • Establishment on high organic/peaty soils potentially detrimental to soil carbon levels • High quantity of peat/high OM soils across all regions of Scotland, which apart from release of soil carbon/nitrogen, likely to be challenging to harvest as soil structure is often poor, in terms of supporting heavy farm machinery, causing soil damage and soil erosion	• Encouraging small animals into SRC plantations will provide pest control (Land Use Consultants, 2007)
Legal/Regulatory		• Short term farm tenancy agreements can restrict access to long term plantings • Restrictions on land access for establishing energy crops on archaeological sites, SSIs, and non-registered CAP land	• Ensure land has long term access provision and clear definition of where supportive planting exists

Miscanthus

	Opportunities	Constraints	Mitigation measures
Political		• Lack of long term government policy support or targets • Food versus fuel challenge	• Supportive policy with clear target and requirement • Put CO_2 sequestration value on the political agenda
Economic	• High return per hectare	• Yield and sale price are biggest contributing factors to achieving good economics • No, or little, current market sector opportunity • Uncertainty over stability of long term market	• End use contracts required, with longevity, indexation and opt out clauses
Social	• Once established annual harvesting will require supportive contractor and other local employment services	• 3m+ high plantations which grow rapidly can have social impacts on rural views and footpath/bridle path access if plantations are not planned effectively • Roots can impact on archaeological aspects • Rural visual impact – green in the summer and yellow/brown over winter, which is opposite to all other farm crops	• Knowledge dissemination and communication

	Opportunities	**Constraints**	**Mitigation measures**
Technological (including agronomic)	• At end of crop, easy to remove (Land Use Consultants, 2007) • Low maintenance crop, little need for fertiliser • Currently no known disease risk • Very few pest problems once established • New varieties are being researched which are able to be used for new end uses in the production of (biochemical, biocomposite, biofuels)	• Rhizomes not suited to automated planting systems (Unpublished Ricardo report, 2019) so require hand planting like vegetable crops • Low availability of miscanthus rhizome planting material • Diminishing list of available agrochemical product for controlling competitive weeds	• Rhizome multiplication can be ramped up reasonably quickly to provide planting area, if supported and clear targets provided • Seed based planting is being trialled but needs further research (Unpublished Ricardo report, 2019) • *Miscanthus giganteus* is a sterile triploid hybrid, limiting invasiveness
Environmental	• Miscanthus generates a good environment for small species such as earthworms and spiders in comparison with arable crops (Aylott & McDermott, 2012) • Carbon sequestration benefits, plant sequesters carbon in to the soil on an annual basis	• Regular use of machinery over the same area of crop causes compaction pans, limiting yield (Unpublished Ricardo report, 2019) • Hard wintry conditions for long periods of time. Frozen ground and early spring and early autumn frosts can halt growth, causing diminished achievable yield, in severe conditions plant loss can occur • Lower overall day degrees in some parts of Scotland likely to cause reduced yields with current UK varieties	• More winter hardy varieties should be trialled from USA/Canada as well as varieties tolerant to lower light intensity for periods of growing season

	Opportunities	Constraints	Mitigation measures
Legal/Regulatory		• Tenanted farms often not able to commit to long term crop commitments • Restrictions on land access for establishing energy crops on archaeological sites, SSIs, and non-registered CAP land	• Ensure land has long term access provision • Enable better/clearer understanding as to where crops can be established

Short rotation forestry (SRF)

	Opportunities	Constraints	Mitigation measures
Political			
Economic			
Social			
Technological (including agronomic)	• SRF grown as coppice gives very rapid growth, limited period of bare ground and reduction in costs of establishing the next rotation	• Limited specialist machinery for SRF management (Unpublished Ricardo report, 2019) • Exotic species such as Eucalyptus not adapted to Scotland (Unpublished Ricardo report, 2019) • Long term investment (Unpublished Ricardo report, 2019) • Woodlands typically have limited access for large machinery (Unpublished Ricardo report, 2019) • Shortage of trained foresters (Unpublished Ricardo report, 2019) • Planting material supply is limited	• Selection of species and provenances suited to anticipated climate • Smaller scale machinery is an option • A vibrant market for any species that are specific to bioenergy crops will ensure adequate supply in <5 years

	Opportunities	Constraints	Mitigation measures
Environmental	• Improved soil stability (Land Use Consultants, 2007) • Potential to improve the soil organic carbon content (McKay, 2011) • Benefit for local water supplies due to low inputs (Land Use Consultants, 2007) • Land remediation opportunity (McKay, 2011) • Flooding alleviation due to high water use • Flood alleviation by slowing rate of flow when rivers burst their banks; flood peaks in different catchments are desynchronised so the peak downstream flood levels are reduced. • Increase in bird population and diversity if native species are introduced (Land Use Consultants, 2007)	• Landscape change with use of non-native species such as Eucalyptus (Land Use Consultants, 2007) • Ground feeding birds and other 'open land' wildlife deterred (Land Use Consultants, 2007) • Irreversible conversion of agricultural land to SRF (Unpublished Ricardo report, 2019) • Trade-off between high water demand and improved local water quality (McKay, 2011) • Negative impacts of harvest: - Soil compaction - Disturbance and erosion increasing sediment levels in water courses - Soil organic matter (SOM) loss - Reduction in soil microorganisms - Reduction in soil nutrients - Reduced water retention • SRF should not be planted on land with a high conservation value (Land Use Consultants, 2007)	• Wildlife corridors should be introduced to connect areas of SRF (Land Use Consultants, 2007) • Native species with a lighter canopy can mitigate effects on biodiversity (Land Use Consultants, 2007) • Consideration of soil type and proximity to surface water will limit impacts (Land Use Consultants, 2007)

	Opportunities	Constraints	Mitigation measures
Legal		• An Environmental Impact Assessment is required to convert agricultural land to forestry (Bates, The potential contribution of bioenergy to Scotland's energy system. Ricardo report for ClimateXChange, 2018)	

Appendix 2: Potential for sustainable expansion of perennial energy crops

Rulesets

The exclusion-based GIS approach used for the identification of suitable land for bioenergy crop growth relies on a range of freely available datasets (detailed in Table 3). For each of these datasets a series of assumptions based on the literature and expert judgement are used to determine what variables within these datasets should be used to exclude land area to ultimately derive suitable available land for bioenergy crop growth. The rulesets are presented briefly in Table 4, but the detail behind the individual rulesets is presented in full in Table 8. Following this table specific assumptions for datasets are presented along with detail on the processing of the topographic and climate datasets (these being data derived from processing of raster data rather than direct use of the other freely available vector datasets).

Table 8: Detailed dataset and rulesets table

Ruleset	**Datasets**	**Exclusion criteria**		
		Short Rotation Forestry	**Short Rotation Coppice**	**Miscanthus**
Land capability - agriculture	James Hutton Institute: Land Capability for Agriculture, 1:250,000	**N/A**	Land Capability classes removed: • 1 • 2 • 3.1 • 3.2 • 6.2 • 6.3 • 7 Additional non-agricultural land classes removed include: • 888 (Built up areas). • 999 (Inland water). • 9500 (Unencoded islands).	Land Capability classes removed: • 1 • 2 • 3.1 • 3.2 • 6.1 • 6.2 • 6.3 • 7 Additional non-agricultural land classes removed include: • 888 (Built up areas). • 999 (Inland water). • 9500 (Unencoded islands)
Land capability - forestry	James Hutton Institute: Land Capability for Forestry, 1:250,000	Land Capability classes removed: • F6 • F7 • F8 • F9	**N/A**	
Elevation	Ordnance Survey: Terrain 50 (50m cell resolution DEM).	**N/A**	Below 300m.	>55-56° latitude <100m. ≤55° latitude <300m.

Ruleset	Datasets	Exclusion criteria		
		Short Rotation Forestry	**Short Rotation Coppice**	**Miscanthus**
	Forestry Commission Ecological Site Classification	Exclude DAMS exposure >18 (exposed site).	**N/A**	**N/A**
Slope angle	Ordnance Survey: Terrain 50 (50m cell resolution DEM).	Slope >20°.	Slope >15°.	Slope >15°.
Rainfall	Centre for Ecology and Hydrology: Gridded Estimates of Areal Rainfall (GEAR) (1km cell resolution).	**N/A**	>650mm per year during April to October.	>650mm per year during April to October.
	Forestry Commission Ecological Site Classification	Exclude sites classed as Very Dry, Dry and Very Wet.	**N/A**	**N/A**
Temperature	Centre for Ecology and Hydrology: Climate Hydrology and Ecology research Support System (CHESS) (1km cell resolution).	**N/A**	<10 - >25°C	<3 - >28°C between May to September.
	Forestry Commission Ecological Site Classification	Exclude sites classed as Alpine, Sub-alpine and Warm Dry.	**N/A**	**N/A**
Soil type	James Hutton Institute: National Soils of Scotland, 1:250,000	Exclusion dataset created by selecting the following soils from the dataset (selected using *SERCDE1* attribute field and code): • Bare rock (*SERCDE1* code 99998). • Basin peat (*SERCDE1* codes 60610 and 6061092). • Blanket peat (*SERCDE1* codes 60660, 6066098, 60662, 6066292 and 6066092). • Saline alluvial soils (*SERCDE1* code 72499). • Saline gleys (*SERCDE1* code 08706 and 76906). • Scree (*SERCDE1* code 99997).		

Ruleset	Datasets	Exclusion criteria		
		Short Rotation Forestry	**Short Rotation Coppice**	**Miscanthus**
		All other categories were removed.		
Peat land	Scottish Natural Heritage: Carbon and Peatland Map 2016	Exclusion dataset created by selecting the following peat classes from the dataset (using *PRIMARY_LA* attribute field from the dataset): • Blanket bog/peat veg. • Industrial peat. • Other peat. • Wetlands. All other categories were removed.		
Forestry	Forestry Commission: National Forestry Inventory Woodland Scotland 2017 (areas of 0.5ha and greater)	Exclusion dataset created by selecting the following forestry classes from the dataset (using the IFT_IOA attribute field from the dataset): • Broadleaved. • Conifer. • Coppice. • Coppice with standards. • Mixed mainly broadleaved. • Mixed mainly conifer. • Young trees. Specific classes removed due to ambiguity or not representing suitable land include: • Non woodland. • Ground prep. • Assumed woodland. • Felled. • Cloud \ shadow. • Failed. • Uncertain. Three classes were removed to represent potential planting opportunities for SRF in the future:		

<table>
<tr><th rowspan="2">Ruleset</th><th rowspan="2">Datasets</th><th colspan="3">Exclusion criteria</th></tr>
<tr><th>Short Rotation Forestry</th><th>Short Rotation Coppice</th><th>Miscanthus</th></tr>
<tr><td></td><td></td><td colspan="3">• Low density (includes areas which could have opportunity for tree planting).
• Shrub (uncertain, but possibly may grow into trees in the future).
• Windblow (areas of trees uprooted by the wind but not removed).

Non-woodland was identified in the dataset Category attribute field. All others were identified in the IFT_IOA attribute field.</td></tr>
<tr><td>Other land cover</td><td>European Space Agency: CORINE 2018 (100m cell resolution).</td><td colspan="3">Exclusion dataset created by selecting the following land cover classes from the dataset (CORINE land cover description and CORINE ID (in brackets) noted):

• Continuous_urban_fabric (111).
• Discontinuous_urban_fabric (112).
• Industrial_or_commercial_units (121).
• Road_and_rail_networks_and_associated_land (122).
• Port_areas (123).
• Airports (124).
• Mineral_extraction_sites (131).
• Dump_sites (132).
• Construction_sites (133).
• Green_urban_areas (141).
• Sport_and_leisure_facilities (142).
• Pastures (231).
• Natural_grasslands (321).
• Bare_rocks (332).
• Inland_marshes (411).
• Salt_marshes (421).
• Salines (422).
• Intertidal_flats (423).
• Water_courses (511).
• Water_bodies (512).
• Coastal_lagoons (521).
• Estuaries (522).
• Sea_and_ocean (523).
• NODATA (999).</td></tr>
</table>

Ruleset	Datasets	Exclusion criteria		
		Short Rotation Forestry	**Short Rotation Coppice**	**Miscanthus**
		All other land cover classes were removed from the dataset.		
Waterbodies	Ordnance Survey: Open Zoomstack	Features maintained in the dataset include: • Rivers • Lakes All other features were removed.		
Landscape designations	Scottish Natural Heritage: multiple datasets	Designated areas to exclude from land suitability: • Cairngorms National Park. • Loch Lomond and the Trossachs National Park. • Country Parks. • National Scenic Areas. • Council of Europe diploma sites.		
Cultural designations	Scottish Natural Heritage: multiple datasets	Designated areas to exclude from land suitability: • Battlefields. • Conservation areas. • Gardens and designated landscapes. • Historic Marine Protected Areas. • Listed buildings. • Scheduled Monuments. • World Heritage Sites.		
Scientific designations	Scottish Natural Heritage: multiple datasets	Designated areas to exclude from land suitability: • Ancient woodland. • Biogenetic Reserve. • Biosphere Reserve. • Geological Conservation Review sites • Local Nature Reserves. • National Nature Reserves. • Nature Reserves.		

Ruleset	Datasets	Exclusion criteria		
		Short Rotation Forestry	Short Rotation Coppice	Miscanthus
		• Ramsar. • SAC. • SPA. • SSSI.		

Data exclusions and assumptions

Notes on the reasons for excluding data and the assumptions applied to datasets are provided below on a per dataset basis.

Land capability – agriculture

The Land Capability for Agriculture layer forms the base layer for the land suitability assessment as it contains all land within Scotland classified for its suitability for growing agricultural crops. For the assessment the Land Capability for Agriculture dataset was considered for SRC and miscanthus only (SRF was considered within a different dataset discussed in the following section).

Summary descriptions of all Land Capability for Agriculture classes are presented in Table 9 in order to help understand the differences between each land use class. These are summary descriptions only since each of the actual descriptions are verbose and detailed. The full original descriptions can be found in Bibby et al. (1991)[9] with useful summaries and visual information presented in *Land Capability for Agriculture in Scotland*[10].

As the remit of the project is to identify opportunities for expansion in bioenergy crop production on underutilised or low grade agricultural land it was critical to exclude prime agricultural land and agriculturally unsuitable land (for SRC and miscanthus), therefore these relevant classes were removed from the dataset (highlighted in light grey in Table 9).

[9] Bibby, J.S., Douglas, H.A., Thomasson, A.J., and Robertson, J.S. (1991). Land Capability Classification for Agriculture. Macaulay Land Use Research Institute, Aberdeen. 84pp.
[10] https://www.hutton.ac.uk/sites/default/files/files/soils/lca_leaflet_hutton.pdf (accessed 28 October 2019).

Table 9: Land Capability for Agriculture class descriptions

Land Capability for Agriculture class ID	Summary class description
1	Very wide range of crops.
2	Wide range of crops.
3.1	Moderate range of crops - high yield (cereals and grass), moderate yield (potatoes, field beans, root crops).
3.2	Moderate range of crops - average production. High yields barley, oats and grass.
4.1	Narrow range of crops - suited to rotations.
4.2	Narrow range of crops - primarily grassland, limited potential other crops.
5.1	Improved grassland - grass sward.
5.2	Improved grassland - grass sward, moderate to low trafficability issues.
5.3	Improved grassland - grass sward, serious trafficability issues.
6.1	Rough grazing - high proportions of palatable herbage.
6.2	Rough grazing - moderate quality of palatable herbage.
6.3	Rough grazing - low grazing values.
7	Very limited agricultural value.

The remaining land capability classes (4.1, 4.2, 5.1, 5.2, 5.3 and 6.1) were those used in the dataset for subsequent exclusion of all other datasets listed in Table 8.

Land capability – forestry

The Land Capability for Forestry layer essentially forms the base layer for the land suitability assessment for SRF as it contains all land within Scotland classified for its suitability for growing trees.

Summary descriptions of all Land Capability for Forestry classes are presented in Table 10 in order to help understand the differences between each land use class. These are the summary descriptions which accompanying the full class descriptions. The full descriptions can be found in Bibby et al. (1988)[11] and in *The Land Capability for Forestry*[12] document.

[11] Bibby, J.S., Heslop, R.E.F. and Hartnup, R. (1988). Land Capability Classification for Forestry in Britain. Soil Survey Monograph. The Macaulay Land Use Research Institute, Aberdeen. 41pp.
[12] https://www.hutton.ac.uk/sites/default/files/files/soils/Land_Capability_for_Forestry_description.pdf (accessed 28 October 2019).

As the remit of the project is to identify opportunities for expansion in bioenergy crop production only areas of land suitable for tree growth, and hence SRF, were selected, the remaining classes were unsuitable and were removed from the dataset (highlighted in light grey in Table 10).

Table 10: Land Capability for Forestry class descriptions (for SRF only)

Land Capability for Forestry class ID	Summary class description
F1	Land with excellent flexibility for the growth and management of tree crops.
F2	Land with very good flexibility for the growth and management of tree crops.
F3	Land with good flexibility for the growth and management of tree crops.
F4	Land with moderate flexibility for the growth and management of tree crops.
F5	Land with limited flexibility for the growth and management of tree crops.
F6	Land with very limited flexibility for the growth and management of tree crops.
F7	Land unsuitable for producing tree crops.
F8	Built up area.
F9	Water.

The remaining land capability classes (F1, F2, F3, F4, F5 and F5) were those used in the dataset for subsequent exclusion of all other datasets listed in Table 8 following the methodology in Section 5.

While these categories are suitable for aims of the project and broadly identifying suitable land for SRF planting, site specific decisions on planting trees for bioenergy crop production need to be considered in significantly more detail. This is because specific tree species have varying requirements and limiting factors to their growth, for example accumulated temperature, continentality, exposure, moisture deficit, soil moisture regime and soil nutrient regime. For such decisions, the Forestry Commission Ecological Site Classification (Pyatt et. al. (2001)[13]) should be used alongside expert guidance.

Elevation

The OS Terrain 50 DEM is the most current dataset which covers the entirety of Scotland and provides a representative view of the elevation of the Scottish landscape. Critical elevation

[13] Pyatt, G., Ray, D. and Fletcher, J. (2001). An Ecological Site Classification for Forestry in Great Britain. Bulletin 124. Forestry Commission, Edinburgh. 100pp.

parameters were selected based on literature values, specifically Hastings et. al. (2009)[14] and Bullard et. al. (2004)[15], and expert judgement. The critical values depend on latitude and exposure risk from wind. The more northerly the latitude means that lower elevations are required to achieve average crop yields. The critical elevation values for miscanthus are for the *Miscanthus Giganteus* species.

The use of elevation is an approximation to the combination of a range of more complex variables such as exposure, continentality etc. which is beyond the scope of this study. However, it is taken that elevation provides a good surrogate in this regard to understand limits on crop yield and hence land suitability.

For SRF, a measure of exposure, the Detailed Aspect Method of Scoring (DAMS), within the ESC is used to constrain forestry instead of elevation. The use of the ESC tool is the method preferred by the Forestry Commission for estimating growth conditions for forestry in Great Britain.

Slope angle

This is a dataset which is derived from geoprocessing of the OS Terrain 50 DEM. Further details on the geoprocessing of the dataset is provided below. The selection of critical slope angles for the three crop types were provided from guidance by the project team. For SRC and miscanthus, land steeper than 15° slope angle should be excluded as it is not currently physically possible to plant and establish these crops on such steep land. For SRF, land steeper than 20° slope angle should be excluded, again due to cultivation of SRF not being economic with current equipment.

Rainfall and temperature

Rainfall and temperature thresholds are used to exclude land based on climatic factors. These are generated from 1km resolution datasets of rainfall and air temperature. The data is taken as an average air temperature and average rainfall between 2005 to 2015. This data covers the last ten years (only temperature (CEH CHESS) extends to 2015, although rainfall extends to 2017 (CEH GEAR)) and is the most current data available. This range also covers the temporal range of most of the spatial datasets used in the exclusion methodology. The use of a 2005-2015 average provides a smoothed value over the last ten years against which to exclude land use against climate.

Climate values have been derived based on expert judgement and values identified by internal research at Uniper (Croxton and Carver, 2004 and Croxton, 2014). For SRC there are no significant temperature restraints. For miscanthus the critical temperature range is for air temperature. It should be noted that miscanthus have minimum soil temperature tolerances of -5 to -7°C as rhizomes in contact with soil at these temperatures for more than seven consecutive days will increase rhizome death. However, there is no available data with which to model soil temperature and therefore air temperature alone is used. The air temperature values for miscanthus are based on *Miscanthus Giganteus* and it is noted that other clones such as Illinois would be more resilient to extreme cold temperatures.

With respect to SRF, the ESC[16] layers provided by the Forestry Commission are used to identify sites which are suitable based on overall climatic conditions (including accumulated air temperature) and soil moisture deficit (which is more important for forestry than rainfall). The

[14] Hastings, A., Clifton-Brown, J., Wattenbach, M., Mitchell, C.P. and Smith, P. (2009). The development of MISCANFOR, a new *Miscanthus* crop growth model: towards more robust yield predictions under different climatic and soil conditions. Global Change Biology Bioenergy, Vol. 1, Issue 2, p154-170.
[15] Bullard, M.J., Lyons, H. and Nixon, P.M.I. (2004). Identifying the yield potential of *Miscanthus x giganteus*: an assessment of the spatial and temporal variability of *M. x giganteus* biomass productivity across England and Wales. Biomass and Bioenergy, Vol. 26, p3-13.
[16] Pyatt, G., Ray, D. and Fletcher, J. (2001). An Ecological Site Classification for Forestry in Great Britain. Bulletin 124. Forestry Commission, Edinburgh. 100pp.

ESC dataset has been taken to cover forestry in general, rather than specific tree species. Specific species of tree will have different tolerances to climate and as such any site specific planting needs to be considered against the species and its ESC requirements.

It should be noted that the CEH-CHESS dataset does not cover Shetland (although the CEH-GEAR dataset does). Analysis of the 2005-2015 dataset indicates that the temperature range does not exceed the critical range for either SRC or miscanthus (Table 8) outside of the highest elevation areas of the Scottish Highlands or the islands (including Orkney). Therefore non-coverage of Shetland by the temperature dataset can be concluded to not be an issue for the analysis.

Soil type

The soil type data was selected as it provided a complete coverage over the entirely of Scotland. Although a higher resolution and more up to data product available (25,000 scale soil type dataset available from the James Hutton Institute) this only offered partial coverage of the country, covering productive agriculture areas of the country only. Also, it was not possible to simply merge the 250,000 scale dataset with the 25,000 scale dataset as they were digitised differently. Additionally, the 250,000 scale dataset accorded with the scale of the Land Capability for Agriculture and Land Capability for Forestry datasets. Therefore the choice to use the 250,000 scale soil layer in this project was taken.

It was agreed to exclude soil types which had high organic matter contents (peat), soils which were excessively shallow or stony and those which had a marine or estuarine influence (saline) as these were deemed unsuitable for agricultural purposes. These exclusions applied to all three crop types considered.

Peat land

Although peat land soils were excluded from the soils layer it was concluded that a specific peat land layer should be used to exclude those areas which had been mapped as peat bogs in order to protect this extremely important land and habitat. As such the dataset selected was deemed to afford the best spatial coverage of peat land throughout Scotland and therefore would remove nearly all peat land from the land suitability estimates. However, not all datasets are accurate and obviously at the time of implementation of energy crop production specific steps should be made at a site level to prevent planting and destruction of peat land areas.

Forestry

Land currently used for forestry (regardless of the type of species planted) was excluded from the dataset to prevent these from being included as suitable land for bioenergy crop planting. The National Forestry Inventory Woodland was selected as the most current dataset (2017) which accurately represents woodland in Scotland (and the Great Britain) over 0.5 hectares in size and is updated on a five year period[17].

While SRC and miscanthus cannot be planted in these areas, there may be opportunities within existing forestry to establish SRF. It is difficult to accurately represent this within a simple approach such as the one adopted here, however the forestry dataset was prepared in such a manner as to maximise the availability of such opportunities. As noted in Table 8 a certain number of forestry type categories within the dataset were excluded (namely *low density*, *shrub* and *windblow*). Although the National Forestry Inventory metadata indicated these areas of land could possibly be covered in trees they are also areas which have opportunity for tree planting (*low density*), are uncertain if trees are present (*shrub*) and areas of trees which have been uprooted but not removed (*windblow*). These categories were taken to represent most opportunities for additional planting of SRF within existing forest areas.

[17] https://www.forestresearch.gov.uk/tools-and-resources/national-forest-inventory/about-the-nfi/ (accessed 28 October 2019).

Other land cover

The CORINE 2018 is a 100m resolution dataset representing the most current land cover dataset covering the UK (and Europe) with a thematic accuracy (i.e. how well land cover types are accurately represented from satellite derived multispectral imagery) of >85%[18]. As the name suggests it represents land cover information acquired in 2018. This dataset was important in the exclusion of the key land cover types identified in Table 8. Although the CORINE 2018 land cover dataset includes land cover such as forestry and peat bogs these were removed from the exclusion dataset as other datasets (specifically the Carbon and Peatland Map 2016 and the National Forestry Inventory Woodland Scotland 2017) were considered more appropriate and with better resolution (greater than the 100m of the CORINE 2018 dataset), to be used to exclude these important land cover types.

It should be noted that narrow linear features such as roads and railways were not included in the exclusion for land cover. The CORINE 2018 data does contain such features as they are classified within the urban classifications. However, higher resolution datasets containing road and railway information (for example the OS Open Zoomstack) only consider these features as lines with no defined width (as would be the case for these features in real life) and it is difficult to parameterise their widths without introducing errors into the dataset, and hence subsequent analyses. Roads and railways are below the general resolution of the datasets and therefore these land cover features have not been included.

Waterbodies

Waterbodies were excluded using the OS Open Zoomstack water layer. As the Open Zoomstack dataset is designed to have different visibility of features at different topographic scales only those rivers and lakes categorised as "*local*", i.e. the highest resolution data visible at the largest scales, were used. The "*regional*" and "*national*" features (essentially lower resolution version of the more detailed "*local*" features) were excluded. The *local* feature waterbodies include lakes down to around 40m^2 in area and rivers around 6m in width. Other much smaller lakes and rivers, such as tributaries and drains, were not excluded as these were deemed to be below the overall spatial resolution of the datasets used.

Landscape designations, cultural designations and scientific designations

It is key that any future bioenergy crops are not grown on currently protected areas, where these are landscape, cultural or scientific designations, in order to maintain the integrity of these sites and to protect biodiversity (where necessary). For this reason the boundaries of a range of currently established designations (Table 8) were used to exclude these areas from being considered in the available suitable land.

Any purely marine designation boundaries were excluded. However, there are some designations which are marine but have boundaries which extend on the land surface (for example some Ramsar, SAC, SSSI and Historic Marine Areas).

For World Heritage Sites generally a specific site boundary existed. However, for three sites, the Antonine Wall, Heart of Neolithic Orkney and New Lanark, these had additional boundaries which extended beyond the World Heritage Site site boundary. For these three sites the more extensive buffer zone was chosen for the exclusion boundary.

It should be noted that these are for current designations and consideration should be given to any new designations which may occur in the future during any site specific planting schemes.

Processing topographic and climatic datasets

All datasets, except for the OS Terrain 50, CORINE 2018, rainfall and temperature datasets, were vector polygon datasets, i.e. shapes defined by specific vertices defined by a cartesian coordinate system which were joined between the two closest vertices by lines called

[18] https://land.copernicus.eu/pan-european/corine-land-cover (28 October 2019).

segments. Vector data were the most appropriate way to perform the geoprocessing methodology presented in Section 5.

The OS Terrain 50 and CORINE 2018 datasets were raster data, i.e. graphical data where each cell is defined as a pixel of specific size, for example 50m or 100m as for the OS Terrain 50 or CORINE 2018 datasets respectively. These datasets were processed slightly differently than the vector datasets. A brief outline of the processing steps used each of these datasets is presented below.

- **OS Terrain 50 –** In its unprocessed state, this dataset is representative of surface elevation (in metres above ordnance datum (mAOD)) and this required no processing. The slope angle dataset was derived directly from this elevation by geoprocessing using the *Slope* algorithm within QGIS. For the resulting per crop type elevation and slope angle datasets these were merged into a single raster to create a Boolean exclusion raster (e.g. 0 representing areas not to be excluded and 1 representing areas which were to be excluded). The Boolean exclusion raster was converted to a vector using the QGIS *Polygonize* function.
- **CORINE 2018 –** The raw raster data was converted into a polygon using the QGIS *Polygonize* function. Unnecessary land covers were removed from this dataset by use of a *Select Features by Expression…* algorithm in QGIS.
- **Temperature and rainfall –** The raw raster data was provided as a series of NetCDF files. These were processed into the required ranges (as detailed in Table 8) using a Geospatial Data Abstraction Library (GDAL)[19] script. The resulting output was converted to a vector using the QGIS *Polygonize* function.

Uncertainty on areas of land suitability

High accuracy is not the aim of the current approach as broad values for guidance are required. It is acknowledged that the approach has used a certain number of datasets of differing spatial scales and collection periods. However, these data are considered to represent the best available data at the time of analysis and also the most appropriate data scales for the analysis undertaken. As with all analyses the application of an error provides some level of understanding of the uncertainty in the results and a value against which conclusions reached by, and from, the data can be placed into perspective.

The major sources of error are:

- Inaccurate representation of land cover types or features.
- Inaccurate representation of the boundary of land cover types or features.
- Spatial scales not capturing land cover types or features accurately.

Due to the rapid nature of the project it has not been possible to undertake a systematic analysis of the errors in the predicted land suitability areas. However a simple comparison of the areas of selected forestry boundaries (National Forestry Inventory 2017 dataset) and land cover type boundaries (CORINE 2018 dataset) with the same areas on extant aerial imagery has identified an average error of around 4.6%. With rounding, an error of ~5% on the final calculated land suitability areas is deemed to be realistic.

Data attributions

The data used in the analysis was downloaded from multiple sources. In order to comply with their licences, as well as to acknowledge the use of the data, attributions for each data source is provided in Table 11. In all cases these attributions are those directly required by the data licence or metadata.

[19] https://gdal.org/ (accessed 28 October 2019).

Table 11: Data attributions

Dataset name and data source	Data attribution
James Hutton Institute: Land Capability for Agriculture, 1:250,000	James Hutton Institute: Land Capability for Agriculture, 1:250,000 copyright and database right The James Hutton Institute 1980. Used with permission of The James Hutton Institute. All rights reserved. Any public sector information contained in these data is licensed under the Open Government Licence v.2.0
James Hutton Institute: Land Capability for Forestry, 1:250,000	James Hutton Institute: Land Capability for Forestry, 1:250,000 copyright and database right The James Hutton Institute 1980. Used with permission of The James Hutton Institute. All rights reserved. Any public sector information contained in these data is licensed under the Open Government Licence v.2.0
Ordnance Survey: Terrain 50 50m resolution digital elevation model	Contains OS data © Crown Copyright [and database right] (2019).
Ecological Site Classification	Forestry Commission, (2019).
Centre for Ecology and Hydrology: Gridded Estimates of Areal Rainfall (GEAR)	Tanguy, M.; Dixon, H.; Prosdocimi, I.; Morris, D.G.; Keller, V.D.J. (2019). Gridded estimates of daily and monthly areal rainfall for the United Kingdom (1890-2017) [CEH-GEAR]. NERC Environmental Information Data Centre. https://doi.org/10.5285/ee9ab43d-a4fe-4e73-afd5-cd4fc4c82556
Centre for Ecology and Hydrology: Climate Hydrology and Ecology Research Support System (CHESS)	Martinez-de la Torre, A.; Blyth, E.M.; Robinson, E.L. (2018). Water, carbon and energy fluxes simulation for Great Britain using the JULES Land Surface Model and the Climate Hydrology and Ecology research Support System meteorology dataset (1961-2015) [CHESS-land]. NERC Environmental Information Data Centre. https://doi.org/10.5285/c76096d6-45d4-4a69-a310-4c67f8dcf096
James Hutton Institute: National Soils of Scotland, 1:250,000	James Hutton Institute: National Soils of Scotland, 1:250,000 copyright and database right The James Hutton Institute 2019. Used with permission of The James Hutton Institute. All rights reserved. Any public sector information contained in these data is licensed under the Open Government Licence v.2.0
Scottish Natural Heritage: Carbon and Peatland Map 2016.	Contains public sector information licensed under the Open Government Licence v3.0.
Forestry Commission: National Forestry Inventory Woodland Scotland 2017	Contains Forestry Commission information licensed under the Open Government License v3.0.
European Space Agency: CORINE 2018	© European Union, Copernicus Land Monitoring Service 2019, European Environment Agency (EEA)
Ordnance Survey: Open Zoomstack	Contains OS data © Crown Copyright [and database right] (2019).

Dataset name and data source	Data attribution
Scottish Natural Heritage: National Parks, National Scenic Areas, Country Parks etc.	Contains public sector information licensed under the Open Government Licence v3.0.
Scottish Natural Heritage: World Heritage Sites, Battlefields, Conservation Areas etc.	Contains public sector information licensed under the Open Government Licence v3.0.
Scottish Natural Heritage: Ramsar, SAC, SPA, SSSI etc.	Contains public sector information licensed under the Open Government Licence v3.0.

Results

The resulting suitable land areas for each of SRF, SRC and miscanthus based on the application of the exclusion methodology are presented in Section 5. Maps for each of these three crop types visually displaying the spatial distribution of available suitable land over the whole of Scotland are presented for reference below (Figure 2:, Figure 3: and Figure 4:).

Figure 2: Distribution of suitable land available for Short Rotation Forestry

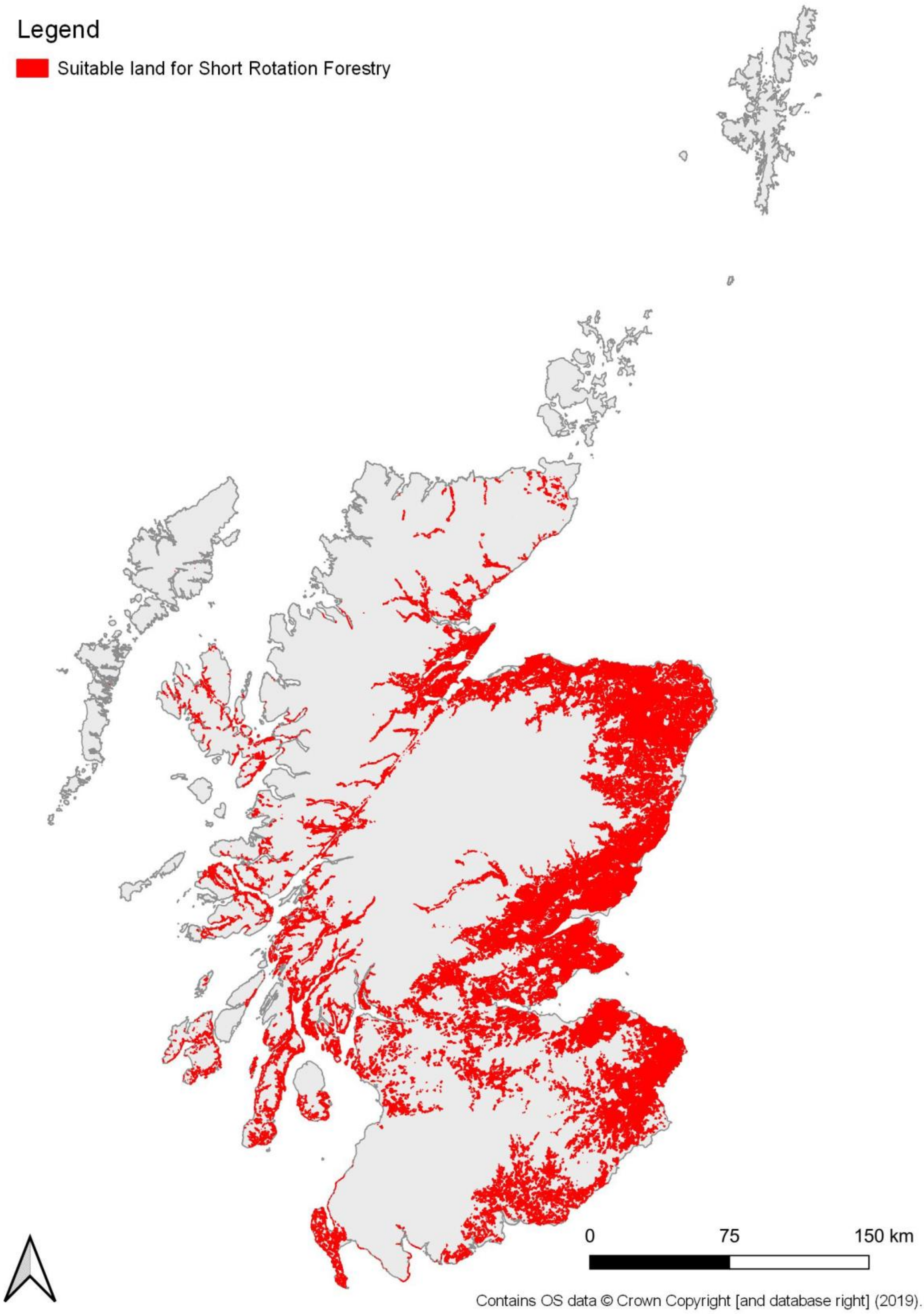


Figure 3: Distribution of suitable land available for Short Rotation Coppice

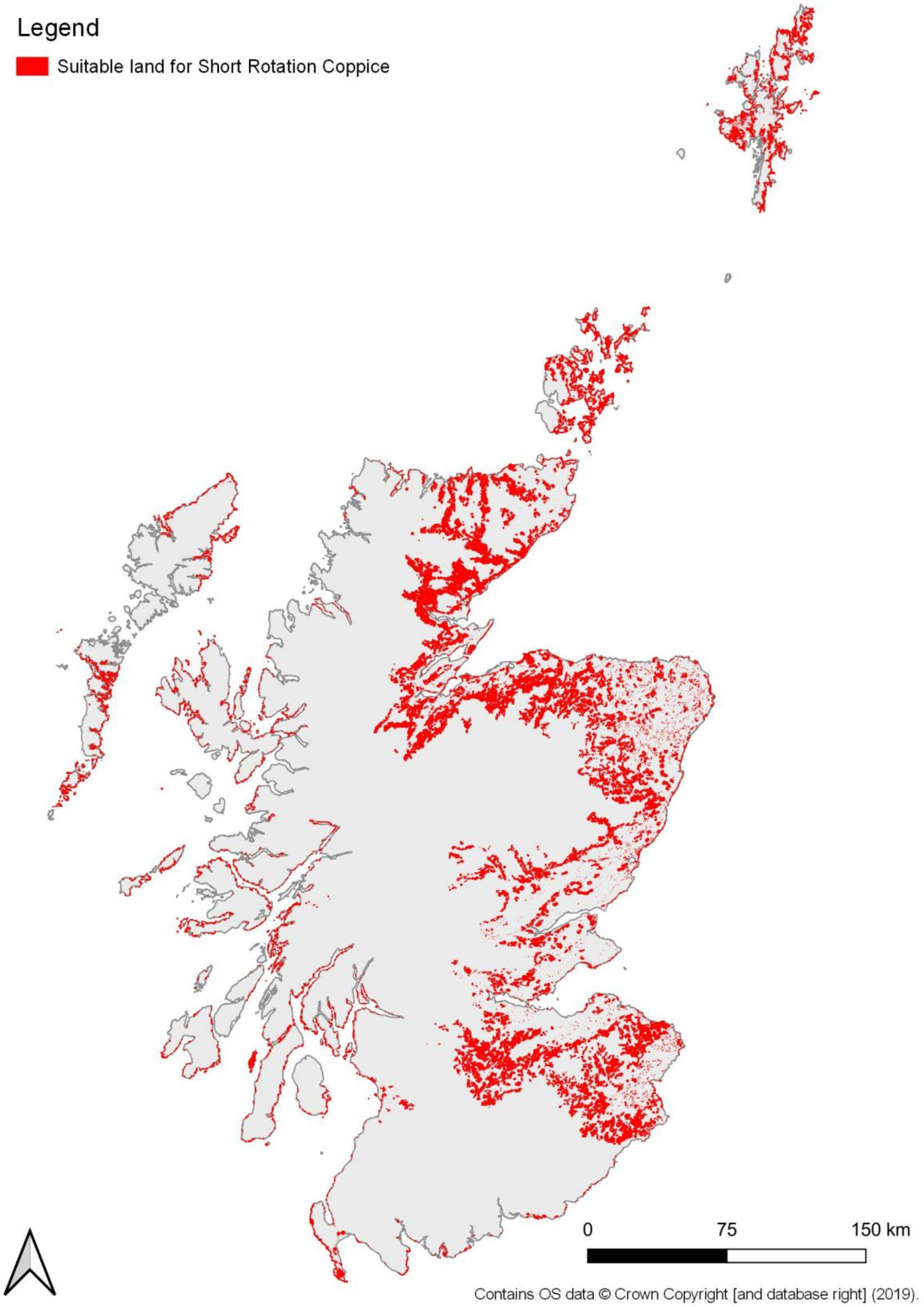
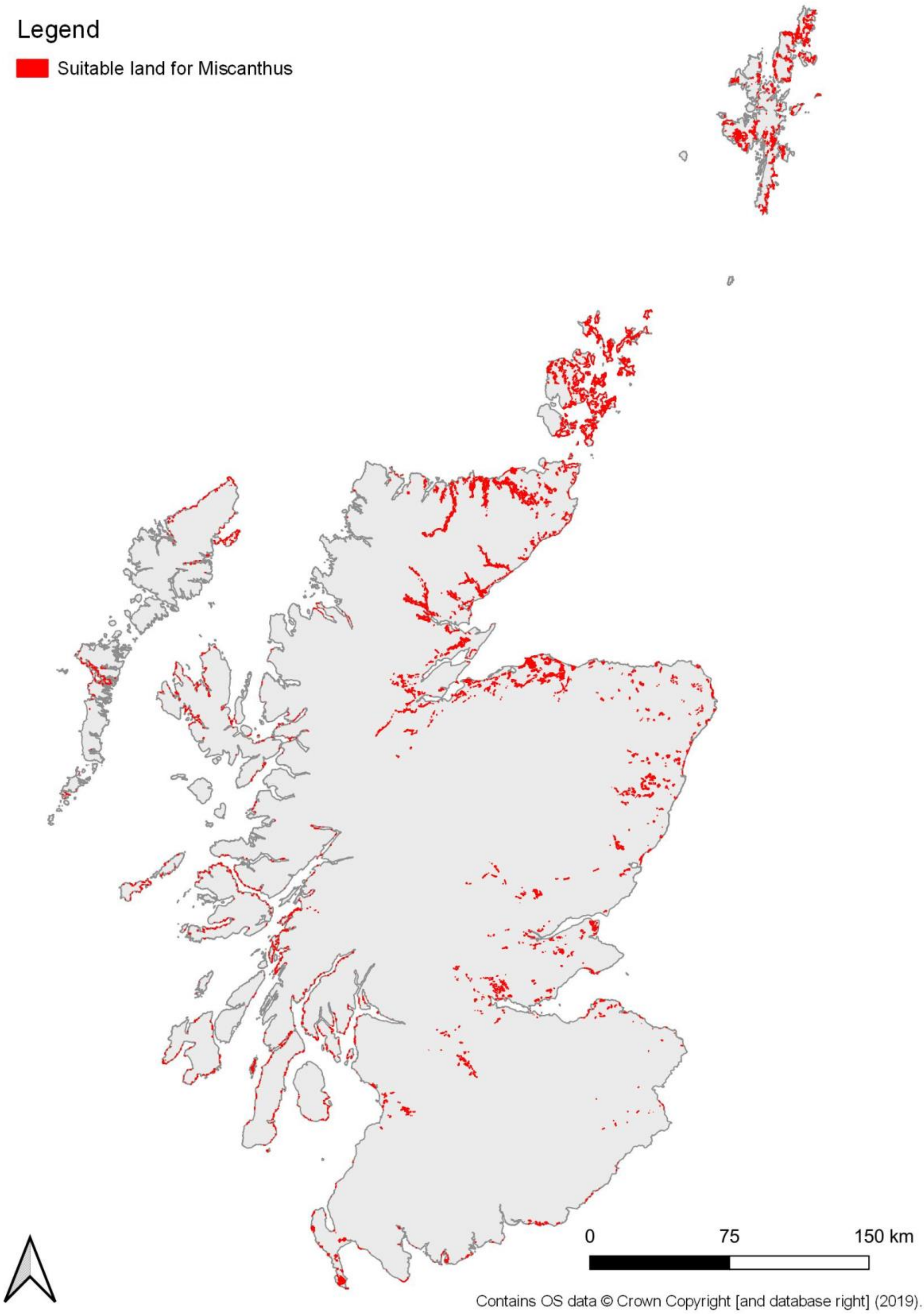


Figure 4: Distribution of suitable land available for miscanthus



Appendix 3: Impact of changing climate on perennial energy crops

A requirement of the study is to understand the change in available suitable land for growing SRF, SRC and miscanthus in response to climate change in 2030 and 2045. These are key dates within Scottish climate change policy for the 70% reduction in greenhouse gases by 2030 and net zero emissions by 2045.

For the purposes of this assessment it was agreed at the project inception meeting that UKCP09 predictions should be used given that UKCP18 predictions have only been released. It was concluded that the UKCP09 predictions offered a more understood and agreed dataset.

The areas of land suitability outputs from Task 3, prior to excluding the climatic threshold (rainfall, temperature and ESC) from the data, forms the basis of the calculations for predicting change in land suitability in response to climate change.

The following discusses the climate change scenarios used in the approach and outlines the methodology used to calculate the change in suitable land with climate change.

Overview of the UKCP09

As noted above the climate change predictions used in this study are taken from the UKCP09 report (Murphy et al., 2009)[20]. The UKCP09 report provides projections of changes in a range of climate variables (including rainfall and temperature) for several time periods, namely 2020s, 2050s and 2080s referenced from a baseline period of 1961-1990. The UKCP09 approach uses the results of ensemble modelling using climate models to provide probabilistic estimates of these changes for different greenhouse gas emissions scenarios, specifically low, medium and high. It is not within the scope of this work to expand on the fine details of each scenario. For a full understanding of these the reader is referred to the Intergovernmental Panel on Climate Change (2000) *Special Report on Emissions Scenarios*[21].The probabilistic values are provided as 10%, 50% and 90% predictions, for example a 10% probability is very likely to occur and a 90% probability is very unlikely to occur (Murphy et. al. (2009). Predictions are also provided for the widest range (lowest chance) and widest range (highest chance) of change. These probabilistic projections account for uncertainties from modelling natural climate processes and variability in the climate system. No model can ever be completely correct, however the results of the UKCP09 climate predictions are considered to be sufficiently accurate as to give confidence that future predictions are plausible.

The forward climate predictions are provided for a range of regions, with Scotland divided into three, Eastern Scotland, Northern Scotland and Western Scotland (c.f. Figure 4.2 in Murphy et al. (2009)). These predictions indicate that under 50% probability (i.e. most likely to happen) under a medium emissions scenario, Scotland is likely to have significantly warmer summers (3.4 – 3.9°C increase) and warmer winters (1.7 - 1.9°C increase) and wetter winters (10 – 15% increase) and drier summers (-10 to -12% decrease).

As noted above, a full appreciation of the UKCP09 approach and findings can be found in Murphy et al. (2009)[22].

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[20] Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Boorman, P.M., Booth, B.B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A., Brown, S.J., Howard, T. P., Humphrey, K. A., McCarthy, M. P., McDonald, R. E., Stephens, A., Wallace, C., Warren, R., Wilby, R., Wood, R. A. (2009), UK Climate Projections Science Report: Climate change projections. Version 3. Met Office Hadley Centre, Exeter, 193pp.
[21] Intergovernmental Panel on Climate Change. (2000). Special Report on Emissions Scenarios. Cambridge University Press. 608pp.
[22] Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Boorman, P.M., Booth, B.B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A., Brown, S.J., Howard, T. P., Humphrey, K. A., McCarthy, M. P., McDonald, R. E., Stephens, A., Wallace, C., Warren, R., Wilby, R., Wood, R. A. (2009), UK Climate

Selected climate change scenarios

Given that there are UKCP09 climate predictions for three different areas of Scotland we have chosen the Eastern Scotland region as being most representative. This is because most of the land suitable for growing bioenergy crops is located on the eastern margins of the country.

As noted above there are three climate prediction scenarios, each with their own range of probabilities. For the purposes of this project we have selected a medium emissions scenario with a 50% probability. This selection was based on the medium emissions scenario being the most likely to be realised (given current global efforts to curtail emissions) and the 50% probability being the most likely climate change outcome.

The climatic thresholds of SRC and miscanthus are defined in Table 8 (SRF is considered differently and this is explained below). The specific critical temperature and rainfall ranges vary between April to October and May to September. The UKCP09 defines the seasons as: winter (December, January and February), spring (March, April and May), summer (June, July and August) and autumn (September, October and November). The critical ranges fall between late spring and early autumn. For the purposes of this study we will therefore use the summer climate prediction scenarios, specifically as the winter scenarios do not fall within the range of the critical temperatures and rainfall.

In summary our assumptions are:

- Medium emissions scenario at 50% probability.
- Use mean summer rainfall and temperature changes.
- Climate predictions are used for Eastern Scotland.

Table 12 illustrates the raw UKCP09 forward predictions for mean summer rainfall and temperature for Eastern Scotland (Murphy et. al. (2009)).

Table 12: UKCP09 predictions for changing mean summer rainfall and mean summer temperature for Eastern Scotland for medium emissions scenario at 50% probability

	Change at each time period		
Climate variable	**2020s**	**2050s**	**2080s**
Mean summer temperature (°C)	1.4	2.3	3.5
mean summer precipitation change (%)	-6	-13	-17

The project requires forward prediction of the change in suitable land at 2030 and 2045. UKCP09 predictions are provided for 2020s, 2050s and 2080s (Table 12). There are no predictions available for interim years. In order to provide predictions for these years the temperature and rainfall change were plotted and simple regression relations were developed. The results of this approach are displayed in Table 13. These results are kept to the same number of decimal places as the UKCP09 predictions (Table 12). The values in Table 13 are those are used to forward predict changes in mean temperature and rainfall in the methodology.

Projections Science Report: Climate change projections. Version 3. Met Office Hadley Centre, Exeter, 193pp.

Table 13: UKCP09 predictions for changing mean summer rainfall and mean summer temperature for Eastern Scotland for medium emissions scenario at 50% probability scaled to 2030 and 2045

	Time period of scenario	
Climate variable	**2030**	**2045**
Mean summer temperature (°C)	1.7	2.1
Mean summer precipitation change (%)	-9	-12

For the purposes of the climate modelling approach we utilise a baseline year of 1990 (Ferreira et al. 2018)[23] from which to calculate the change in mean summer temperature and mean summer precipitation out to 2030 and 2045. As the UKCP09 predictions are based on a period at a minimum 20-30 years prior to the 2005-2015 period (used for the climatic thresholding in Task 3) there would likely be overestimations in predicted values if the UKCP09 predictions were directly applied to the 2005-2015 data (since climate change will already have affected rainfall and temperature during this period).

The methodology for applying the climate change scenario predictions to create mean summer temperature and rainfall data for 2030 and 2045 for SRC and miscanthus are presented below.

It should be noted that the CEH-CHESS dataset does not cover Shetland (although the CEH-GEAR dataset does). Analysis of the 1990, 2030 and 2045 datasets indicates that the May to September temperature range never exceeds the critical range for either SRC or miscanthus (Table 8). Therefore, non-coverage of Shetland by the temperature dataset can be concluded to not be an issue for the analysis.

The climate change data for SRF are different to those for SRC and miscanthus. As the study uses the Forestry Commission ESC data this has been previously processed for climate change predictions to 2040, 2050 and 2080. No other interim years are available and the data is not readily available for refactoring to 2030 and 2045. As such the 2040 data has been used to approximate the change in land suitability for the 2030 and 2045 range. No attempt has been made to scale the areas to these dates as there is considered to be insufficient data for SRF to accomplish this with any accuracy. However, it is likely that the 2030 land suitability areas for SRF will be slightly lower than the 2040 prediction and will be slightly higher for the 2045 predictions.

Methodology

The methodology utilised two key climatic datasets, notably the Centre for Ecology and Hydrology's (CEH) Climate, Hydrological and Ecological Research Support System (CHESS) daily temperature data for 1990 (as daily average temperature in Kelvin) and their Gridded Estimates of Areal Rainfall (GEAR) daily rainfall data for 1990 (in daily total rainfall in millimetres) (Table 8). Both were downloaded from the CEH website as NetCDF data which held daily UK temperature and data as 1km resolution gridded datasets, with each day of the dataset held as an individual daily raster array within the associated NetCDF file. Additionally, the methodology also used the Forestry Commission's ESC 2040 climate prediction datasets for SRF. These datasets were already prepared against climate change scenarios and no subsequent modification of the data (except thresholding) was required.

As the UKCP09 climate change predictions are based on seasonal changes the daily data was required to be converted to seasonal average data. As stated above this project has assumed

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[23] Ferreira, M., Martin, G.J., Smith, C. and Tarkowski, F. (2018). Environmental consequences of climate change II. Technical report for Dwr Cymru Welsh Water. 128pp.

that the climate predictions will be based around summer. Using a series of custom GDAL[24] scripts, the 1990 rainfall and temperature data were converted into seasonal averages over the required periods (April to October for rainfall for SRC and miscanthus and May to September for miscanthus). For the purposes of the assessment, temperature for SRC was taken to apply over the same date range as miscanthus. The temperature data was converted to degrees Celsius from Kelvin and the resulting temperature and rainfall outputs were clipped to Scotland. Using the resulting output datasets the predicted change in rainfall and temperature for 2030 and 2045 (Table 13) were applied to the resulting datasets using a GDAL script. This generated predicted rainfall and temperature datasets for 2030 and 2045 for SRC and miscanthus.

For the 2030 and 2045 datasets for SRC and miscanthus the appropriate rainfall and temperature threshold was used to generate a masked Boolean raster dataset which was then converted to a polygon using the QGIS *Polygonize* function. The same masking procedure was applied to the SRF ESC 2040 dataset. The resulting datasets were then excluded from the land suitability areas created in Step 6 (Section 5) in order to generate land suitability areas for SRC and miscanthus for 2030 and 2045 and areas for SRF in 2040.

Results

The resulting change in suitable land areas for each of SRF, SRC and miscanthus with climate change are presented in Section 6. Maps for each of these three crop types visually display the spatial distribution of available suitable land over the whole of Scotland for the baseline and 2040 for SRF[25] and 2030 and 2045 for SRC and miscanthus. These maps are presented for reference below (Figure 5, Figure 6 and Figure 7).

As noted above, even with the 2030 and 2045 climate change temperature increases these make no difference to the critical ranges for SRC and miscanthus as all of the changes in land suitability due to climate change are related to reductions in rainfall.

[24] GDAL – Geospatial Data Abstraction Library. *http://www.gdal.org/*.

[25] Please note, the SRF figure colour scheme differs from that used for SRC and Miscanthus (red and blue compared to purple and blue) so that the SRF baseline figure matches the colouring of the baseline figures above.

Figure 5: Distribution of suitable land available for Short Rotation Forestry with respect to climate change in 2040

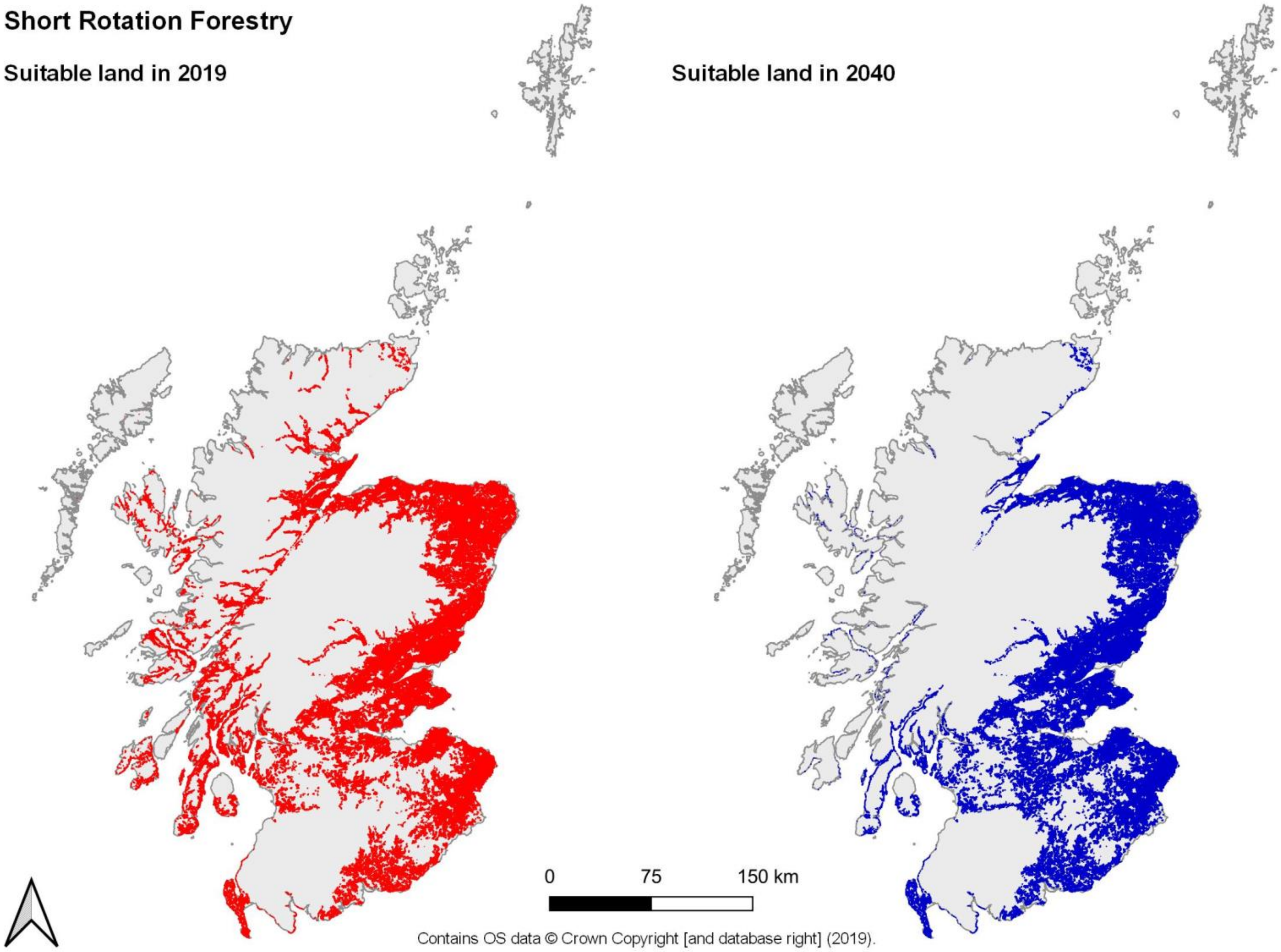


Figure 6: Distribution of suitable land available for Short Rotation Coppice with respect to climate change in 2030 and 2045

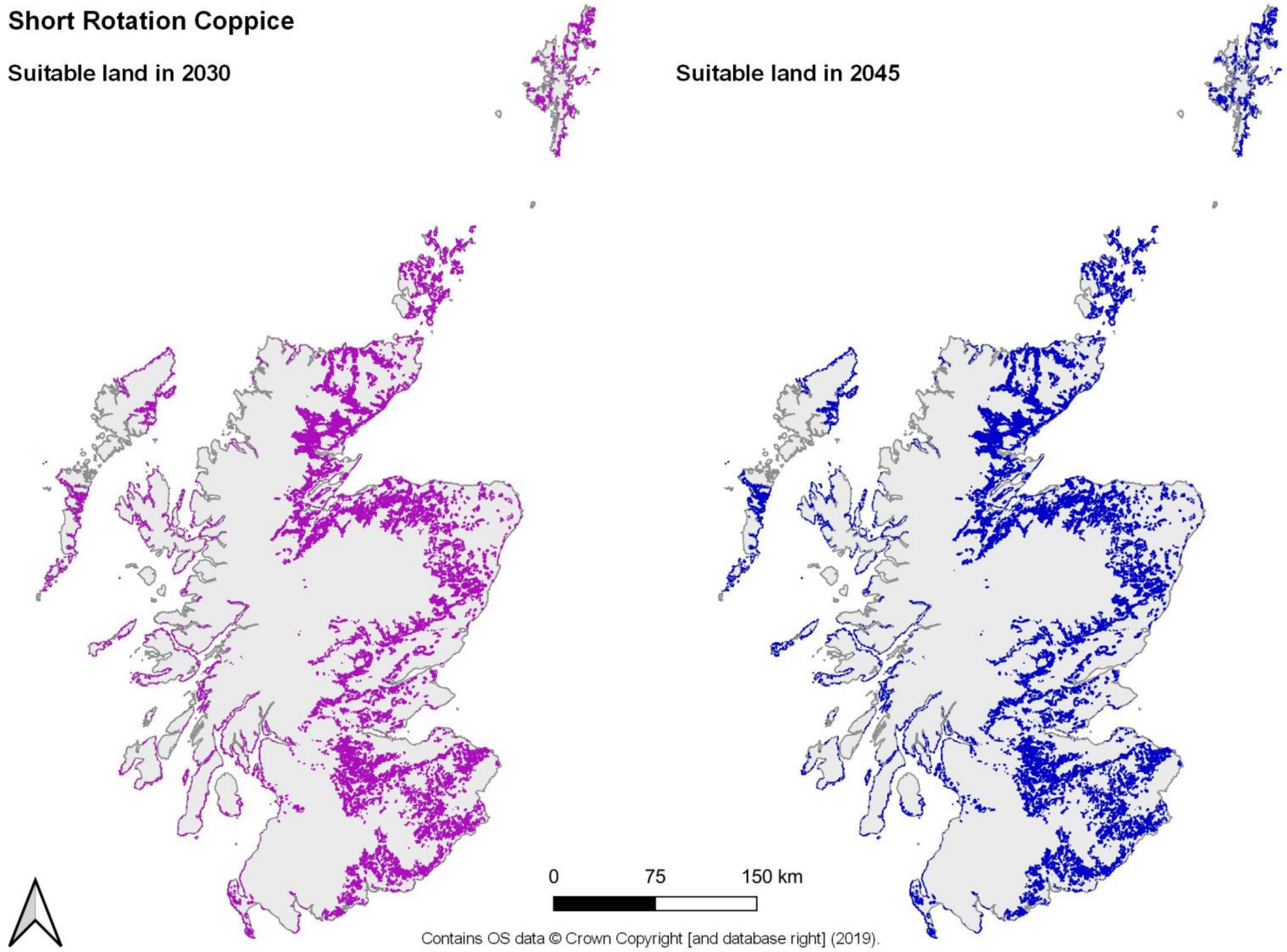
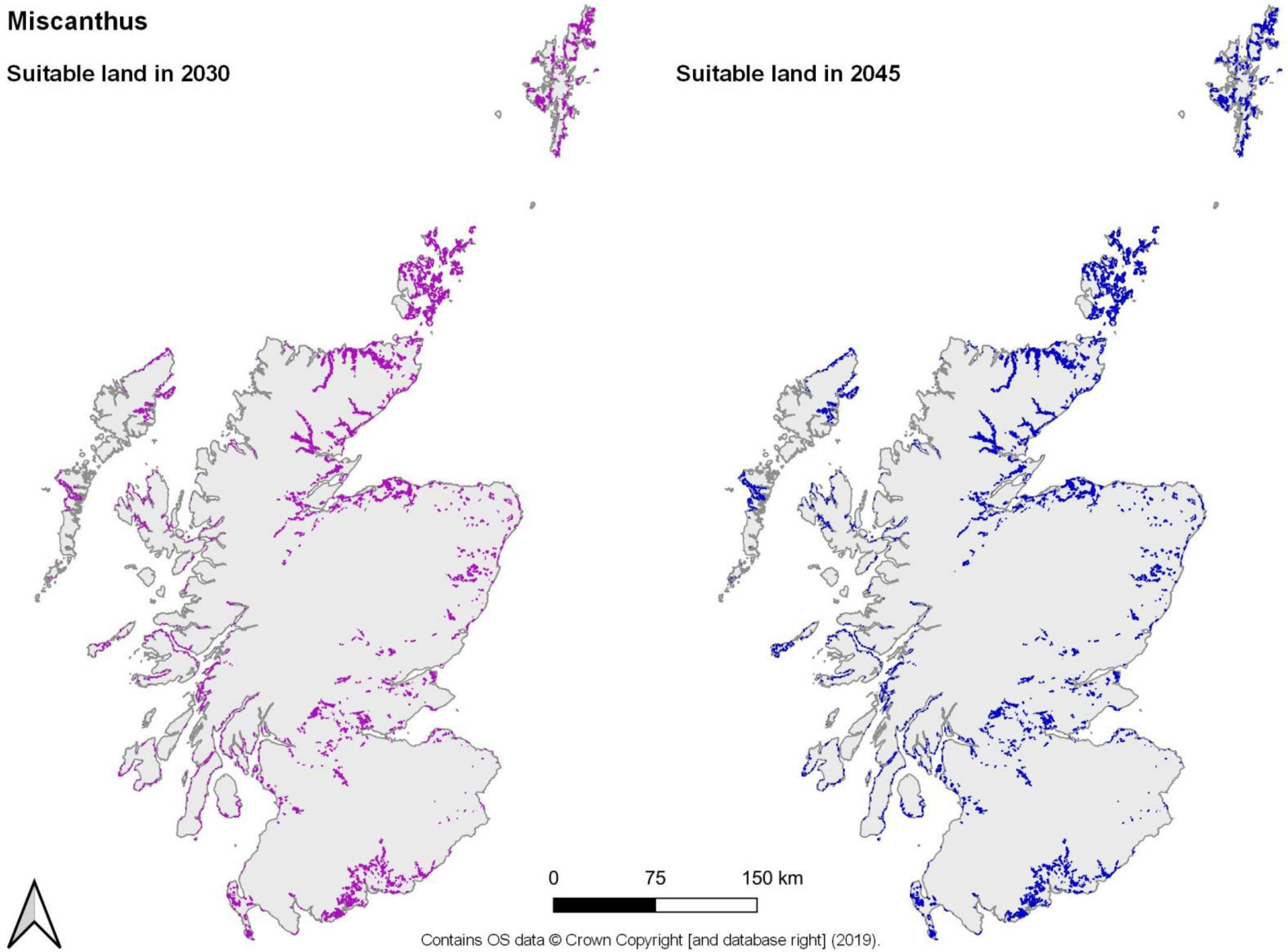


Figure 7: Distribution of suitable land available for miscanthus with respect to climate change in 2030 and 2045



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