Achieving national scale targets for carbon sequestration through afforestation: Geospatial assessment of feasibility and policy implications

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Abstract

To explore the feasibility of meeting recently proposed large-scale tree planting targets, a UK wide assessment of land available for afforestation was carried out, considering a range of physical, environmental and policy constraints in three hypothetical planting scenarios. Results show there is sufficient space to meet these targets in all three scenarios, even if planting is prevented on good to moderate quality agricultural land and within protected areas. However, this would require planting on a large proportion of unconstrained land, especially for the more ambitious targets, which is unevenly distributed across the UK. This would limit opportunities for spatially targeting woodland creation, which may restrict the provision of additional ecosystem services such as air pollution control and recreation, and induce widespread negative impacts on landscapes and communities. In order to overcome these limitations, relaxing constraints, such as permitting afforestation of higher quality agricultural land, will need to be considered. Meeting many of the proposed afforestation targets would result in a transformational change in British land cover, which could replace or significantly impact the business models of tens of thousands of farms, and see the replacement of hundreds of thousands to millions of hectares of grassland, arable and horticultural land and other land covers. This would require rates of planting that far exceed those seen historically. Policies and mechanisms that could be used to encourage this planting, both by the state and private sectors, are discussed.

KEYWORDS: Afforestation; ecosystem services; suitability mapping; constraints; site selection; woodland; natural capital; policy development

1. Introduction

Greenhouse gas emissions from human activity are giving rise to what is now being described as a ‘climate emergency’ (Ripple et al., 2020). These emissions are estimated to have caused warming of approximately 1° C above pre-industrial levels, and this is likely to reach 1.5° C, described as ‘dangerous climate change’ (Lewis, 2016), between 2030 and 2052 if they continue at the current rate (IPCC, 2018). Climate-related risks to health, livelihoods, food security, water supply, human security and economic growth are projected to increase with global warming of 1.5° C, and increase further with warming of 2° C (IPCC, 2018). It has been suggested that Earth is approaching thresholds that if crossed could cause continued warming and a ‘Hothouse Earth’ scenario, with consequences for ecosystems, economies and society (Steffen et al., 2018).

Stabilization of the Earth system to avoid risks related to global climate change will require rapid decarbonisation through both cuts to greenhouse gas emissions, and the protection and enhancement of biosphere carbon sinks (Rockström et al., 2017). At a global scale, afforestation and reforestation has the potential to be our single largest natural climate solution (Griscom et al., 2017; Bastin et al., 2019), and recent years have seen numerous international policies and agreements with the aim of protecting and extending the world's forests. Article 5 of the Paris Agreement encourages parties to conserve and enhance carbon sinks, including forests (United Nations, 2015), while the Bonn Challenge (bonnchallenge.org), initiated by IUCN and the Government of Germany in 2011, has gathered 62 commitments by governments and other organisations to restore over 170 million hectares of woodland by 2030 to provide carbon sequestration and other benefits. Carbon credits, introduced by the Kyoto protocol, allow for carbon sequestration to offset emission elsewhere, providing funding for the developing of forestry projects (Kula, 2010).

Within Europe, the European Union aims to cut emissions by 40% by 2030 (European Commission, 2014), including emissions and removals by the land use, land use change and forestry sector (Regulation (EU) 2018/841 of the European Parliament and of the Council (2018)), and to be climate neutral by 2050 (European Union, 2020), and has proposed that this be made law (European Commission, 2017). Although the EU does not have a common forestry policy, the EU Forest Strategy recognizes the ecosystem services provided by forests, including climate change mitigation (European Commission, 2013), and funding for forestry and afforestation is provided through the Common Agricultural Policy. Individual nations also have their own targets for afforestation with varying levels of ambition (Department of Communications Climate Action and Environment, 2019; Palaghianu, 2015; Andrasevits et al., 2005).

The UK is the first major economy to pass net zero emission laws, which require it to bring all greenhouse gas emissions to net zero by 2050 (Climate Change Act 2008 (c. 27) (as amended)), as recommended by the Committee on Climate Change, the UK's independent climate change advisory body. To achieve this, the Committee recommends planting 30,000 ha of woodland per year, along with an increase in woodland management, to increase the net forestry sink to 22 $MtCO_2e$ per year by 2050 (Committee on Climate Change, 2019). Numerous other targets for woodland creation in the UK have also been proposed in recent years by bodies including learned societies, charities and government departments. These targets, which largely aim to deliver carbon sequestration and storage to various degrees and in various timeframes, advocate for the establishment of hundreds of thousands to millions of hectares of new woodland within the next 30 to 80 years. Zero Carbon Britain for example suggests planting 3 million ha of woodland to achieve carbon neutrality by 2030 (Centre for Alternative Technology, 2013), while The Royal Society and Royal Academy of Engineering propose planting 1.2 Mha of land by 2050 (Royal Society and Royal Academy of Engineering, 2018). Despite this prevalence of targets, less has been said of where these trees could or should be planted, the mechanisms for doing so, and the potential environmental and societal impacts this transformational change in British land cover could have.

Woodland cover in the UK is low by European standards (FAO, 2015). It currently stands at 3.19 million hectares, or 13% of total land area (Forestry Commission, 2019a), up from a low of approximately 5% at the start of the 20th century (Aldhous, 1997). Inappropriate siting of forests has the potential to cause environmental and ecological damage (Warren, 2000; Stroud et al., 2015; Sloan et al., 2018). Farmers are also often reluctant to convert productive land to forestry (Lawrence and Dandy, 2014), while a shortage of agricultural land in the UK is projected by 2030 (CISL, 2014). Therefore, further expansion of woodland area is constrained by a number of policy and environmental considerations, as well as by the availability of physically suitable land for trees to grow upon.

To date there has been no UK-focused assessment of space available for tree planting. Several studies have focused on identifying land available for afforestation at a global scale. Nilsson and Schopfhauser (1995) aggregated estimates of suitable and available land for plantations in the world's regions, finding 345 Mha available for the purpose of sequestering carbon, although this did not take spatial issues into consideration. Benítez et al. (2007) used a spatial approach, assuming planting was possible on certain types of land cover (e.g. shrublands), but removing areas subject to various constraints, such as highly productive agricultural land, to identify land available for afforestation and reforestation at a spatial resolution of 0.5°. A similar process was used by Zomer et al. (2008) at a higher spatial resolution of 500 m; however, they only considered developing countries. More recently, Bastin et al. (2019) used measurements of tree cover in protected areas with machine learning algorithms to map the tree cover that could potentially exist globally with minimal human activity, accounting for climatic and environmental conditions, with a spatial resolution of 30 arc seconds.

While these studies provide dramatic examples of the potential for afforestation at global and continental scales, they are of limited value for implementing it at the national scale. This is due to the coarse resolution of the inputs and constraints considered, which do not adequately reflect those of relevance to individual countries. In Europe, some analysis has been carried out at a national and regional scale. For example, Farrelly and Gallagher (2015) found 4.65 million hectares of land in the Republic of Ireland to be potentially suitable for forestry, accounting for a range of physical and environmental constraints. Within the UK, similar assessments have been carried out for Scotland (Sing et al., 2013) and Snowdonia National Park in Wales (Gkaraveli et al., 2004); however, the lack of a detailed and comprehensive assessment of space available for afforestation means the feasibility of meeting UK wide planting targets is uncertain.

Not only does the availability of space available for these targets need to be considered, but also where planting could take place and what impacts this would have. While afforestation can bring public benefits, the level of which vary spatially (Bateman et al., 2014; Gimona and Van Der Horst, 2007; Bailey et al., 2006), inappropriate siting of woodland has the potential to negatively impact local communities and landscapes (van der Horst, 2006; Ní Dhubháin et al., 2009). Meeting these targets will also require rates of planting far beyond those that have been achieved in recent years (Forestry Commission, 2019a), and appropriate mechanisms and policies for this will need to be identified.

The aim of this paper is to assess the feasibility of achieving large-scale afforestation targets in the UK. To do this we address the following objectives:

- Provide the first comprehensive collation of targets for woodland creation in UK.
- Present the first high resolution UK-wide assessment of space available for woodland creation, accounting for a variety of physical, environmental and policy constraints in three hypothetical planting scenarios.
- Using these scenarios, explore spatial patterns of afforestation that could occur under different land use policies, and the potential environmental and societal impacts this could have.
- With reference to current and historic rates of planting, explore mechanisms that could be used to enable large scale afforestation, and the challenges associated with this.

2. Materials and methods

2.1. Identifying afforestation targets

Recent targets for woodland creation in the UK were identified from the literature. Where the target was given as an area, the annual rate of planting required to achieve this was calculated from the given start date and end date. If no start date was given, this was assumed to be the year the target was published. Where this target was given relative to the current woodland area, such as a doubling of this, it is assumed the current area of woodland in the UK is 13% (3.19 million hectares) (Forestry Commission, 2019a) unless given otherwise. Conversely, where the target was given as an annual rate of planting, the area of woodland this would result in was calculated from the given start date and end date.

2.2. Identifying constraints on woodland creation

To identify locations where woodland planting would be possible, a number of constraints were considered (Table 1). These constraints were assigned to three broad categories. The first category (‘physical constraints’) includes land already covered in woodland and land where physical factors would make large-scale woodland planting impossible or prohibitively difficult, such as water bodies. Here we define the natural treeline as 600 m, its approximate location in England (Backshall, 2001), although the exact elevation will depend on local variations in temperature, shelter and humidity (Ratcliffe and Thompson, 1988; Pearsall, 1989).

Table 1: Constraints and data sources used.

Constraint	Devolved Administration	Source	Product
Base			
Land area	England, Scotland, Wales	Ordnance Survey (OS)	Boundary-Line
	Northern Ireland	Ordnance Survey of Northern Ireland (OSNI)	Open Data Largescale Boundaries – NI Outline
Physical constraints			
Existing woodland	England, Scotland, Wales	Forest Research	National Forest Inventory (NFI)
	Northern Ireland	UK Centre for Ecology & Hydrology (UKCEH)	Land Cover Map 2015 (LCM2015)
Water, rock and coastal sediment	England, Scotland, Wales, Northern Ireland	UK Centre for Ecology & Hydrology	Land Cover Map 2015
Climatic treeline (600 m)	England, Scotland, Wales	Ordnance Survey	OS Terrain 50
	Northern Ireland	Ordnance Survey of Northern Ireland	Open Data 50m Digital Terrain Model
Urban and suburban areas	England, Scotland, Wales, Northern Ireland	UK Centre for Ecology & Hydrology	Land Cover Map 2015
Environmental Constraints			
Peat	England, Scotland, Wales, Northern Ireland	British Geological Survey (BGS)	Geology 625k
Bog	England, Scotland, Wales, Northern Ireland	UK Centre for Ecology and Hydrology	Land Cover Map 2015
Policy constraints			
Protected areas	England	Natural England, Historic England	Site boundaries. See **Table S2**.
	Scotland	Scottish Government, Scottish Natural Heritage, Historic Environment Scotland	
	Wales	Natural Resources Wales, Cadw	
	Northern Ireland	Department of Agriculture, Environment and Rural Affairs (Daera), Department for Communities	
Agricultural land	England	Natural England	Provisional Agricultural Land Classification (ALC)
	Scotland	Hutton Institute	Land Capability for Agriculture Scotland
	Wales	Welsh Government	Predictive Agricultural Land Classification
	Northern Ireland	UK Centre for Ecology & Hydrology	Land Cover Map 2015

The second category ('environmental constraints') includes areas where planting is possible, but where doing so would cause environmental harm. This category includes both peat and bog. While some studies have shown a potential for some afforested peatland to act as a carbon sink, the dynamics of carbon sequestration from peatland afforestation are complex and hindered by a lack of data (Crane, 2020), and carbon benefits from woodland creation are generally greatest on soils with low levels of organic matter (Forestry Commission, 2017). Past planting on peatland habitats has caused significant environmental damage (Warren, 2000; Stroud et al., 2015) and the UK Forestry Standard now prohibits planting on peat exceeding 50 cm in depth, and on sites that would compromise the hydrology of bog or wetland habitats (Forestry Commission, 2017). Recent evidence suggests that rewetting and full restoration of wetlands is an effective means of generating carbon sinks (Evans et al., 2021) and, should be carried out promptly to have the most beneficial effects during predicted peak warming (Günther et al., 2020).

The third category ('policy constraints') includes areas where planting would also be possible, but may be restricted for planning or policy reasons. This category includes both protected or designated areas (Table S2) and higher quality agricultural land. Practically, planting within a protected area such as a National Park or Area of Outstanding Natural Beauty ('AONB') is difficult as it generally requires completion of an Environmental Impact Assessment (Forestry Commission, 2019b). Historically, forestry in the UK has competed with agriculture for space (Edlin, 1969). Today, farmers are often reluctant to convert productive land to forestry (Lawrence and Dandy, 2014), and a shortfall of farmland in the UK is projected by 2030 (CISL, 2014). For this reason, higher quality agricultural land is included as a constraint on woodland planting.

When collecting data to map some of the constraints, it was found that some parts of the UK were not covered by datasets that otherwise extended across the majority of the country. In these cases, alternative data sources or proxies had to be used to achieve full coverage of the constraint. Notably, there is no unified agricultural land classification for the UK. For Great Britain, agricultural land classifications for England, Scotland and Wales were harmonised (Table 2). An agricultural land classification map was not available for Northern Ireland, hence the Arable and Horticulture class from CEH LCM2015 (Centre for Ecology & Hydrology, 2017) was used instead, under the assumption that if land is currently being used for cropping rather than pasture, it is likely to be of good quality. Furthermore, the British Geological Survey Geology 625k dataset was used to identify peat, although this does not to extend to the western limit of Northern Ireland. The LCM2015 Bog class, which maps ericaceous, herbaceous and mossy swards in areas with a peat depth greater than 50 cm does, however, have national coverage and is also included in the environmental constraints. Issues surrounding data access and availability are discussed further in Section 3.4.

Table 2: Harmonisation of UK agricultural land classification maps, and their use in scenarios.

<table>
<tr><th rowspan="3">Scenario status</th><th colspan="4">Nation and data source</th></tr>
<tr><th>England</th><th>Scotland</th><th>Wales</th><th>Northern Ireland</th></tr>
<tr><td>Provisional Agricultural Land Classification (MAFF, 1988)</td><td>Land Capability for Agriculture, Scotland (The James Hutton Institute, 1981)</td><td>Predictive Agricultural Land Classification (Welsh Government, 2017)</td><td>CEH Land Cover Map 2015 (Centre for Ecology & Hydrology, 2017)</td></tr>
<tr><td rowspan="2">Planting not permitted</td><td>Grade 1
‘Excellent quality’</td><td>Class 1
‘Land capable of producing a very wide range of crops’</td><td>Grade 1
‘Excellent quality’</td><td rowspan="2">Existing arable and horticultural land</td></tr>
<tr><td>Grade 2
‘Very good quality’</td><td>Class 2
‘Land capable of producing a wide range of crops’</td><td>Grade 2
‘Very good quality’</td></tr>
<tr><td rowspan="2">Planting permitted in Agricultural Sacrifice Scenario, but not Restrictive or Protected Areas Sacrifice Scenarios</td><td rowspan="2">Grade 3
‘Good to moderate quality’</td><td>Class 3.1
‘Land capable of producing a moderate range of crops’</td><td>Grade 3a
‘Good quality’</td><td rowspan="2"></td></tr>
<tr><td>Class 3.2
‘Land capable of producing a moderate range of crops’</td><td>Grade 3b
‘Moderate quality’</td></tr>
<tr><td>Planting permitted</td><td>Grade 4 and below</td><td>Class 4.1 and below</td><td>Grade 4 and below</td><td>Non arable and horticultural land</td></tr>
</table>

2.3. Construction of scenarios

The physical, environmental and policy constraints were used in combination to form three hypothetical planting scenarios (Table 3). In the first, referred to as the *Restrictive Scenario*, all constraints are used, and planting is not permitted on ALC grade 3 (‘good to moderate quality’) or above (England and Wales), Land Capability for Agriculture (LCA) class 3.2 or above (Scotland), or existing Arable and Horticultural land identified by the CEH Land Cover Map (Northern Ireland). The second scenario, referred to as the *Agricultural Sacrifice Scenario,* takes a more permissive approach to planting on agricultural land, using the same constraints as the Restrictive Scenario but also allowing for planting on ALC grade 3 (England and Wales) or LCA class 3.1 and 3.2 (Scotland) land that is not ruled out by other constraints. The final scenario, referred to as the *Protected Areas Sacrifice Scenario*, uses the same constraints as the Restrictive Scenario, but also allows planting in any protected or designated areas that are not ruled out by the other constraints. Note: in all scenarios, planting is not permitted on current arable and horticultural land within Northern Ireland. The three scenarios were used to represent contrasting and diverse land use strategies spanning a range of possible approaches and demonstrating their implications, as a basis for informing future policy development which may favour one of these scenarios or a mixture of approaches.

Table 3: Differences in constraints used in the three scenarios. Note that all other constraints not included in the table were applied in all scenarios.

	Restrictive Scenario	Agricultural Sacrifice Scenario	Protected Areas Sacrifice Scenario
Protected areas	Planting **not** permitted	Planting **not** permitted	Planting permitted
Agricultural land	Planting **not** permitted on:	Planting **not** permitted on:	Planting **not** permitted on:
England	ALC grade 3 or above	ALC grade 2 or above	ALC grade 3 or above
Scotland	LCA class 3.2 or above	LCA class 2 or above	LCA class 3.2 or above
Wales	ALC grade 3b or above	ALC grade 2 or above	ALC grade 3b or above
Northern Ireland	Existing arable and horticultural land	Existing arable and horticultural land	Existing arable and horticultural land

2.4. Analysis

All data input layers were converted to a 10 m resolution raster grid for use in the analysis. These layers primarily defined constraints, where planting is either possible, or permitted under a scenario, or not. The approach used was a subtractive, binary overlay methodology. The UK land area was used as the initial base layer, defining the spatial extent over which planting may potentially occur. Constraints, which define areas where planting cannot or should not take place, were then overlaid on the base layer, with unavailable land removed accordingly. The result is a map identifying land covered by one or more category of constraint described in Section 2.2 and therefore unavailable for planting, and remaining land, which is not covered by a constraint, and therefore available for afforestation. The CEH LCM2015 25 metre resolution raster product was used to identify current land cover in the UK that could be lost if afforested.

3. Results and discussion

3.1. Targets for woodland creation in the UK

Twelve targets for woodland creation were identified from six groups and organisations (Table 4). These range from 265,000 ha by 2050 (Committee on Climate Change Low Ambition), to 4,000,000 ha by 2100 (Committee on Climate Change High Ambition). The planting rates required to achieve these targets range from 9,200 ha/yr until 2050 (Committee on Climate Change Low Ambition), to 176,000 ha/yr until 2030 (Zero Carbon Britain: Rethinking the Future).

Table 4: Selected UK wide woodland planting targets. The lowest and highest targets are highlighted.

Scheme / Report	Target (ha)	Average annual planting rate (ha/yr)	Start	End	Source
Zero Carbon Britain: Rethinking the Future	3,000,000	176,000[1]	2013[2]	2030	Centre for Alternative Technology (2013)
More Trees Please	3,190,000[3]	123,000[1]	2019[2]	2045	Friends of the Earth (2019)
Greenhouse Gas Removal. Report by the UK Royal Society and Royal Academy of Engineering	1,200,000	37,500[1]	2018[2]	2050	Royal Society and Royal Academy of Engineering (2018)
Committee on Climate Change (Low Ambition)	**265,000**[4]	9,200	2016	2050	Committee on Climate Change (2018) and Thomson et al. (2018)
	724,000[4]	9,200	2016	2100	
Committee on Climate Change (Medium Ambition)	898,000[4]	31,000	2016	2050	Committee on Climate Change (2018) and Thomson et al. (2018)
	2,448,000[4]	31,000	2016	2100	
Committee on Climate Change (High Ambition)	1,477,000[4]	50,000	2016	2050	Committee on Climate Change (2018) and Thomson et al. (2018)
	3,977,000[4]	50,000	2016	2100	
Committee on Climate Change (Net Zero)	970,000[3]	30,000	2019[2]	2050	Committee on Climate Change (2019)
Committee on Climate Change (Net Zero Speculative)	1,455,000[3]	50,000	2019[2]	2050	Committee on Climate Change (2019)
Keeping it cool: How the UK can end its contribution to climate change	1,200,000[5]	40,000	2020	2050	Vivid Economics and WWF (2018)

[1] Planting rate calculated from published target area, and start and end year.
[2] No start date given, date of publication used.
[3] Assumes current UK woodland area of 13%.

[4] Assumes current UK woodland area of 15%.
[5] Target area calculated from published planting rate, and start and end year.

3.2. Constraints on woodland creation in the UK

The areas covered by each of the eight constraints on woodland planting were calculated (Table 5, Figure 1). Across the whole of the UK, policy constraints cover the greatest area, with nearly 16 million ha covered by one or more policy constraint if planting is prevented on ALC grade 3 and LCA grade 3.1 and 3.2 land (Restrictive Scenario), and over 9 million if it is permitted (Agricultural Sacrifice Scenario). There is significant variability between nations. In England, the most extensive constraint is agricultural land, with ALC grades 1 to 3 covering 8.5 million hectares, 65% of its total land area. In Scotland, the extent of good quality agricultural land is far lower, with just 2% of its land having an LCA class of 2 or above, and 17% class 3.2 above. Here protected areas form the single largest constraint, with nearly a third of the country having a protected designation of some form. The majority of environmental constraints (peat and bog) also lie within Scotland, with 1.2 million hectares of these covering 15% of the country. Northern Ireland has a similarly high proportion of land covered by environmental constraints, at 14%.

Table 5: Area covered by each physical, policy and environment constraint. The sum of the areas of each individual constraint will exceed the area of each country, due to overlapping of constraints. The subtotal for each category records the area covered by one or more constraint, accounting for overlapping.

	Area (ha)					
	Inset (Figure 1)	**UK**	**England**	**Scotland**	**Wales**	**Northern Ireland**
UK land area	-	24,366,167	13,046,152	7,881,022	2,078,202	1,360,791
Physical constraints						
Existing woodland	a	3,135,900	1,294,952	1,416,162	305,140	119,646
Water, rock, coastal sediment	b	548,052	170,544	335,180	31,866	10,462
Climatic treeline	c	547,613	41,325	483,533	22,027	728
Urban and suburban	d	1,765,110	1,422,121	179,913	105,609	57,467
Total		5,817,400	2,882,553	2,287,712	458,834	188,301
Policy constraints						
Protected areas	e	7,132,201	3,678,497	2,458,181	622,052	373,471
Agricultural land (Restrictive Scenario and Protected Areas Sacrifice Scenario)	f	10,714,376	8,486,840	1,324,618	807,199	95,719
Agricultural land (Agricultural Sacrifice Scenario)	f	2,599,117	2,202,271	178,635	122,492	95,719
Total (Restrictive Scenario and Protected Areas Sacrifice Scenario)		15,991,647	10,575,565	3,685,493	1,286,777	443,812
Total (Agricultural Sacrifice Scenario)		9,435,182	5,651,072	2,623,232	717,066	443,812
Environmental constraints						
Peat	g	1,565,591	429,236	970,345	24,903	141,107
Bog	h	962,970	196,325	648,589	26,156	91,900
Total		1,938,537	493,275	1,203,254	47,334	194,674

Figure 1: Spatial extent of the constraints identified. a.) Existing woodland. b.) Water, rock and coastal sediment. c.) Approximate climatic treeline (600 m). d.) Urban and suburban areas. e.) Protected and designated areas. f.) Agricultural land: ALC grade 1+2 (England and Wales), LCA grade 1+2 (Scotland) shown in black; ALC grade 3 (England and Wales), LCA class 3.1+3.2 (Scotland), existing arable land (Northern Ireland) shown in grey. g.) Peat. h.) Bog.

3.3. Land available for afforestation in the UK

Constraints on woodland planting in each of the three scenarios are shown in Figures 2, 3 and 4 using a colour blending style symbology, suited to showing the locations of and interactions between three classes of data (Huck et al., 2019). Here, each of the three categories of constraint (physical, policy and environmental) are represented by a primary colour in the subtractive colour model (cyan, magenta and yellow). Where an area is covered by two or more constraints, these colours overlap to produce a new colour (e.g. cyan and magenta produce blue).

Under the Restrictive Scenario, 4.7 million ha remains available for planting in the UK (Figure 2, Table 6). This is sufficient to meet even the most ambitious goal of 4 million ha of woodland by 2100; however, this would require planting nearly 85% of available land. Meeting the goal of 1 million hectares, one of a range of measures being targeted by the UK government to meet its pledge of carbon neutrality by 2050 (Department for Business Energy and Industrial Strategy, 2017), would require planting 21% of available land. With 2.3 million ha (29% of its land area) available, Scotland holds nearly half of the UK's available land. Conversely, just 9% of England – 1.2 million ha, was identified as being available under this scenario. Northern Ireland has by far the greatest proportion of land available, with just over half having the potential for woodland expansion. However, the lack of an agricultural land classification map, and the use of currently arable and horticultural land as a proxy, will likely have contributed to this outcome (Section 3.4).

The Agricultural Sacrifice Scenario (Figure 3, Table 6) is the least restrictive of those assessed, as it more than doubles the land available for planting to 10.4 million ha, more than twice the area required for the most ambitious woodland planting target, and ten times the goal of 1 million ha. The spatial distribution of available land also changes dramatically, with the greatest area of available land now being within England (5.5 million ha), rather than Scotland (3.2 million ha).

The Protected Areas Sacrifice Scenario (Figure 4, Table 6), results in more land being available for planting than in the Restrictive Scenario, but less than the Agricultural Sacrifice Scenario, with 7.8 million hectares identified. Within England, much of this is in the north, where 30% of land is suitable for afforestation, compared with 13% in the midlands and 16% in the south.

In all three scenarios tested there is sufficient space to meet even the highest woodland creation goals (Table 4). However, this will require the afforestation of large proportions of the land identified as being available, especially for the most ambitious targets and most restrictive scenario. This has the potential to leave little flexibility to choose where to plant, whether this is to locate new woodlands in the most suitable locations, or due to the ease or difficulty of converting land from its current use to forestry. For example, the establishment of woodlands primarily in remote upland areas, as would occur with the Restrictive Scenario, risks limiting the provision of ecosystem services such as air pollution control and recreation which vary spatially (Bateman et al., 2014; Gimona and Van Der Horst, 2007; Bailey et al., 2006), restricting the benefits other than carbon sequestration these trees could provide. Efforts to encourage farmers to afforest their land has seen little success in recent years and initiatives to promote afforestation of large proportions of their holdings will be even more problematic. Likewise, compulsory purchase of land for the establishment of state woodland is likely to prove highly controversial (discussed further in Section 3.6).

These findings highlight the considerations, and likely compromises, that will need to be made when planning for large scale afforestation at a national scale. While in the Restrictive Scenario more than 80% of the UK is covered by one or more constraints, much of this is purely in the form of policy constraints – protected areas and agricultural land. Therefore, it may be preferable to allow for some planting to be undertaken in these areas, which, as the Agricultural Sacrifice and Protected Areas Sacrifice Scenarios illustrate, opens substantially more space for afforestation, potentially allowing for this planting to be better targeted spatially. These decisions will need to be considered at the full range of spatial and policy levels. Nationally, as all three scenarios show, space available for afforestation is not evenly distributed throughout the UK, and this distribution is different in each scenario. It may, for example, be considered necessary to allow for planting on agricultural land in the south of England, or protected areas in the north-west, to ensure populations in these areas have access to the benefits woodland can provide. Within the UK, nations may identify different priorities for land use. Scotland, for example, may place a higher value on protecting its comparatively low proportion of high-quality agricultural land. Finally, at a local scale afforestation can have a large impact on communities and landscapes which will need to be considered (discussed further in Section 3.5).

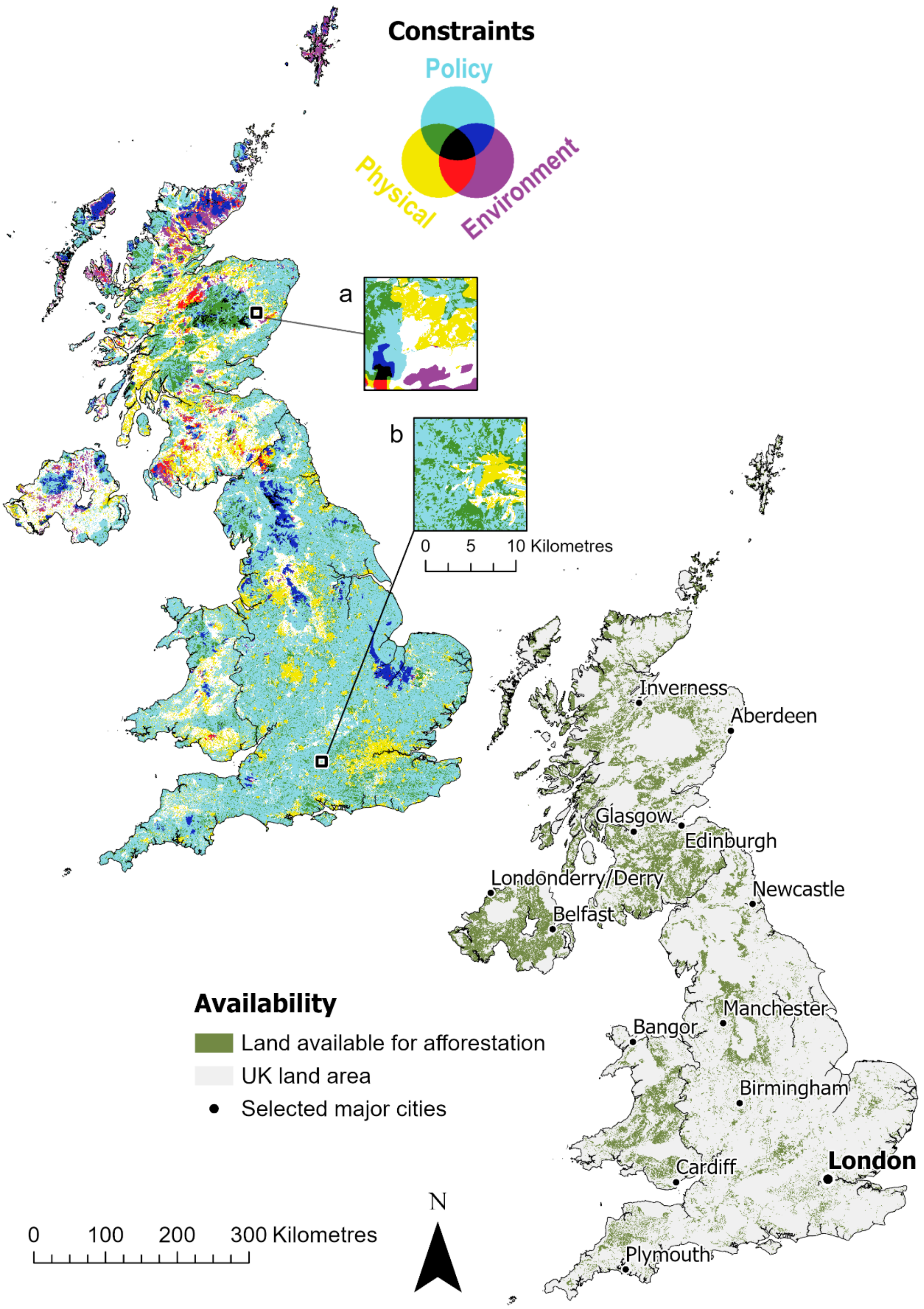

Figure 2: (Top left): Constraints on afforestation in the UK in the **Restrictive Scenario**. White indicates that there is no constraint, and that the land is therefore available for planting. This is displayed as green in (Bottom right): potential for afforestation. Selected major cities are included for context (© OpenStreetMap, openstreetmap.org/copyright).

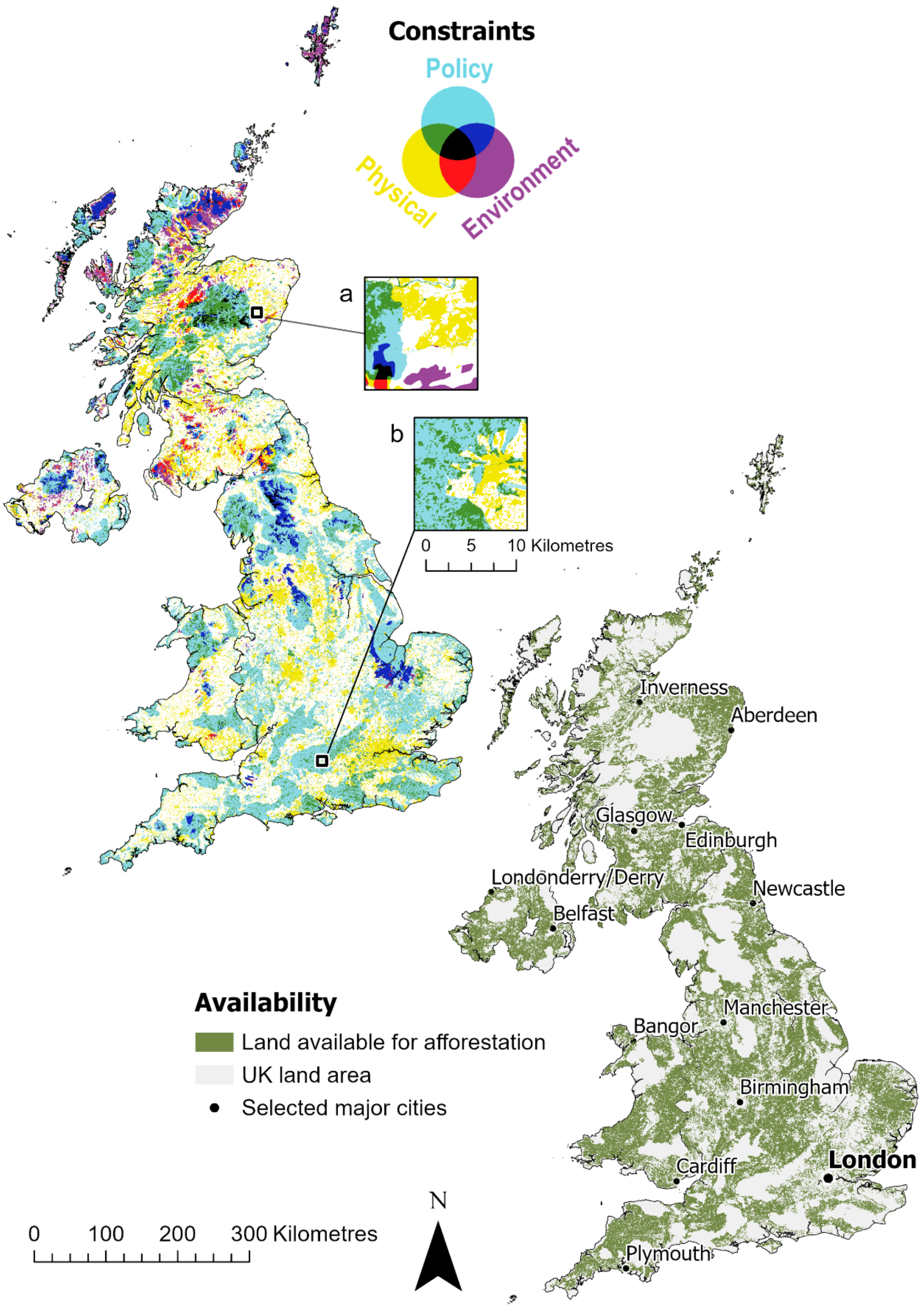

Figure 3: (Top left): Constraints on afforestation in the UK in the **Agricultural Sacrifice Scenario**. White indicates that there is no constraint, and that the land is therefore available for planting. This is displayed as green in (Bottom right): potential for afforestation. Selected major cities are included for context (© OpenStreetMap, openstreetmap.org/copyright).

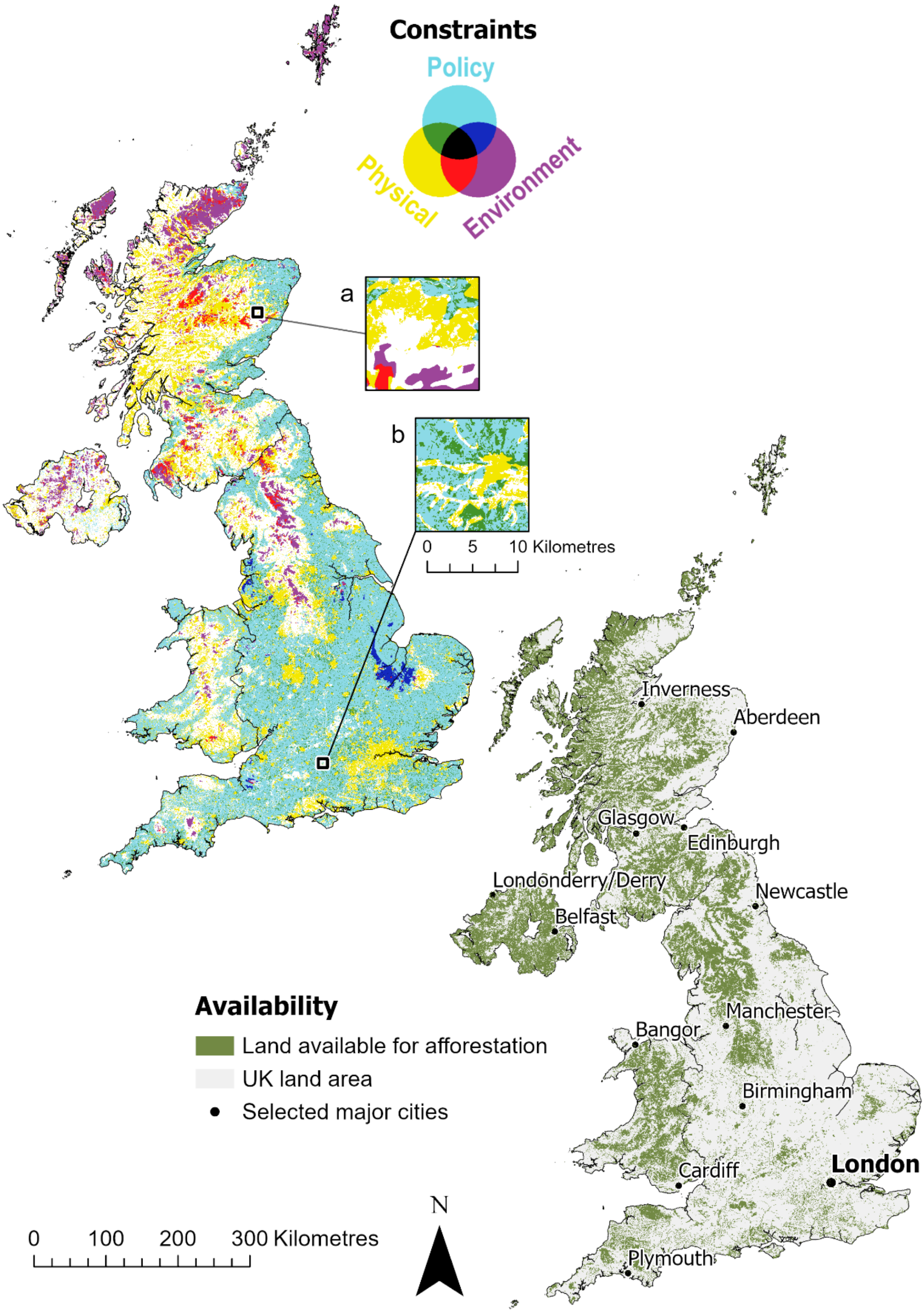

Figure 4: (Top left): Constraints on afforestation in the UK in the **Protected Areas Sacrifice Scenario**. White indicates that there is no constraint, and that the land is therefore available for planting. This is displayed as green in (Bottom right): potential for afforestation. Selected major cities are included for context (© OpenStreetMap, openstreetmap.org/copyright).

Table 6: Land available for, and constraints preventing, woodland creation in the UK under three hypothetical scenarios.

Country	Available		Physical constraint (including combined with other constraints)		Policy constraint only		Environmental constraint only		Policy & environmental constraint	
	Ha	**%**	**Ha**	**%**	**Ha**	**%**	**Ha**	**%**	**Ha**	**%**
Restrictive Scenario										
UK	4,717,880	19	5,817,400	24	12,251,353	50	694,524	3	885,014	4
England	1,230,392	9	2,882,553	22	8,504,474	65	22,776	0	405,957	3
Scotland	2,299,667	29	2,287,712	29	2,358,159	30	567,719	7	367,766	5
Wales	493,640	24	458,834	22	1,087,258	52	8,515	0	29,956	1
NI	694,181	51	188,301	14	301,462	22	95,514	7	81,335	6
Agricultural Sacrifice Scenario										
UK	10,366,648	43	5,817,400	24	6,602,581	27	724,055	3	855,481	4
England	5,445,030	42	2,882,553	22	4,289,835	33	42,822	0	385,911	3
Scotland	3,192,167	41	2,287,712	29	1,465,658	19	576,360	7	359,125	5
Wales	1,035,271	50	458,834	22	545,626	26	9,359	0	29,111	1
NI	694,180	51	188,301	14	301,462	22	95,514	7	81,334	6
Protected Areas Sacrifice Scenario										
UK	7,815,627	32	5,817,400	24	9,153,604	38	1,409,708	6	169,828	1
England	2,535,820	19	2,882,553	22	7,199,046	55	273,007	2	155,726	1
Scotland	3,558,338	45	2,287,712	29	1,099,488	14	926,346	12	9,139	0
Wales	817,966	39	458,834	22	762,931	37	37,087	2	1,383	0
NI	903,503	66	188,301	14	92,139	7	173,268	13	3,580	0

3.4. Data availability and access

This work represents a national scale, first look at space available in the UK for woodland creation. The analysis was limited to some extent by the lack of data available for certain areas. This is the case for the Agricultural Land Classification map in England. While the provisional (pre-1988) map is available nationally, this does not differentiate between grades 3a and 3b, which makes up 48% of land in England. Identifying 'best and most versatile' agricultural land (grades 1, 2 and 3a) is therefore not possible. While post-1988 mapping is available which does differentiate grades 3a and 3b, the coverage is very patchy. In other cases data exists but accessing this has not been possible. This is the case for the Agricultural Land Classification for Northern Ireland. For this analysis, current Arable and Horticultural land was used as a proxy, under the assumption that if the land is currently being farmed, it is likely to be of good quality. However, this is likely to underestimate the true area of good quality land for agriculture. For example, in England while 8.5 million ha of land are classified as ALC grade 3 or above, just 4.8 million ha are currently within the land cover class Arable and Horticulture. If judicious planning and policy development to promote large scale afforestation in the UK is to occur, these deficiencies in the existence, coverage and access to geospatial data need to be rectified.

3.5. Impacts of large-scale afforestation in the UK

All proposed woodland planting targets would see a transformational change in British land use, with large areas of land being converted to woodland, especially rough and improved grassland (Figure 5). With an average UK farm size of 81 ha (Defra et al., 2018), the establishment of 2,500,000 hectares of woodland (Committee on Climate Change medium ambition scenario, used as an example) would see the elimination of the equivalent to 31,000 farms, or 123,000 farms planting 25% of their land area, impacting the business models of these sites. Significant changes to land use policies and agricultural subsidies would need to be made to support this transition (discussed further in Section 3.6).

Studies have shown a preference for between 25% and 50% forest cover in a landscape, beyond this increases in forest cover are not appreciated by the public (van der Horst, 2006). Commercial forestry may also be viewed unfavourably by the public, especially in landscapes where it has not occurred historically (Ní Dhubháin et al., 2009). Therefore, care will need to be taken to plan planting appropriately at a local level, although the sheer scale of afforestation being proposed may make this a difficult task. More extensive, but less intensive tree planting may be one solution, for example through urban greening or silvoarable and silvopastoral agrofarming practices (Saunders et al., 2013), although the capacity for this in the UK would need to be assessed.

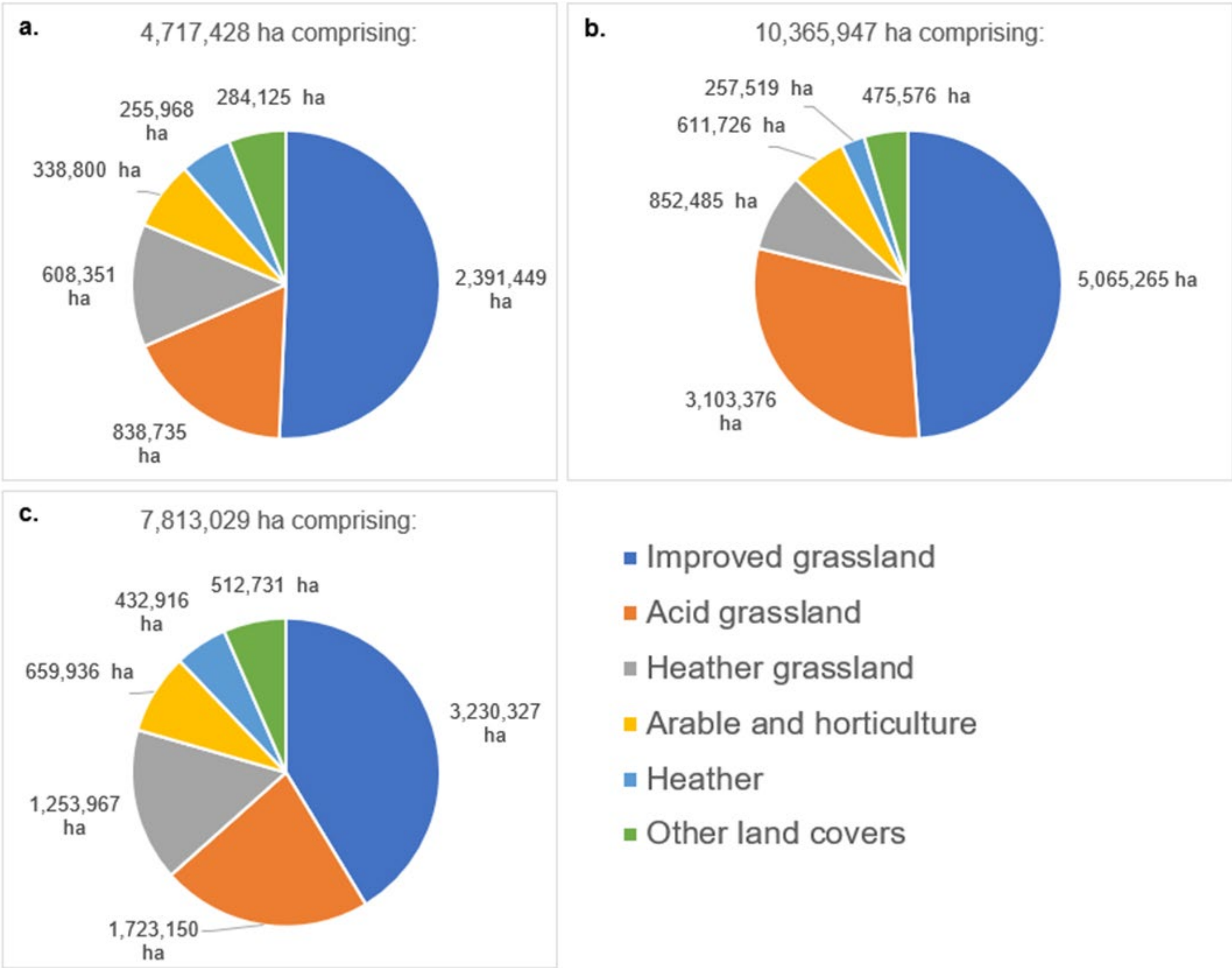

Figure 5: Approximate extent of different land cover types within areas found to be suitable for planting in the a.) Restrictive Scenario, b.) Agricultural Sacrifice Scenario and c.) Protected Areas Sacrifice Scenario.

3.6. Mechanisms for achieving proposed woodland creation goals

To meet most proposed targets, a rate of planting would be required which far exceeds that seen in recent years, or decades. Annual planting rates from the past half century range from a high of 30,270 ha in 1989, to a low of 5,440 ha in 2010 (Forestry Commission, 2019c). Therefore, it is clear that achieving a significant increase in planting, with some targets proposing up to 176,000 ha per year, will prove to be a substantial challenge (Figure 6). In order to meet this challenge, it may be prudent to learn from historical precedents. In the UK, the establishment of the Forestry Commission led to an increase in productive forest area from approximately 1.3 million ha to 2 million ha by the end of the 20th century (Aldhous, 1997). Internationally, Spain has seen 10 million hectares of woodland created since the mid-19th century (Vadell et al., 2016), while 1 million hectares were reforested in Romania in the mid-20th century (Palaghianu and Dutca, 2017). Large scale afforestation is therefore possible, and the mechanisms to achieve this are discussed further below.

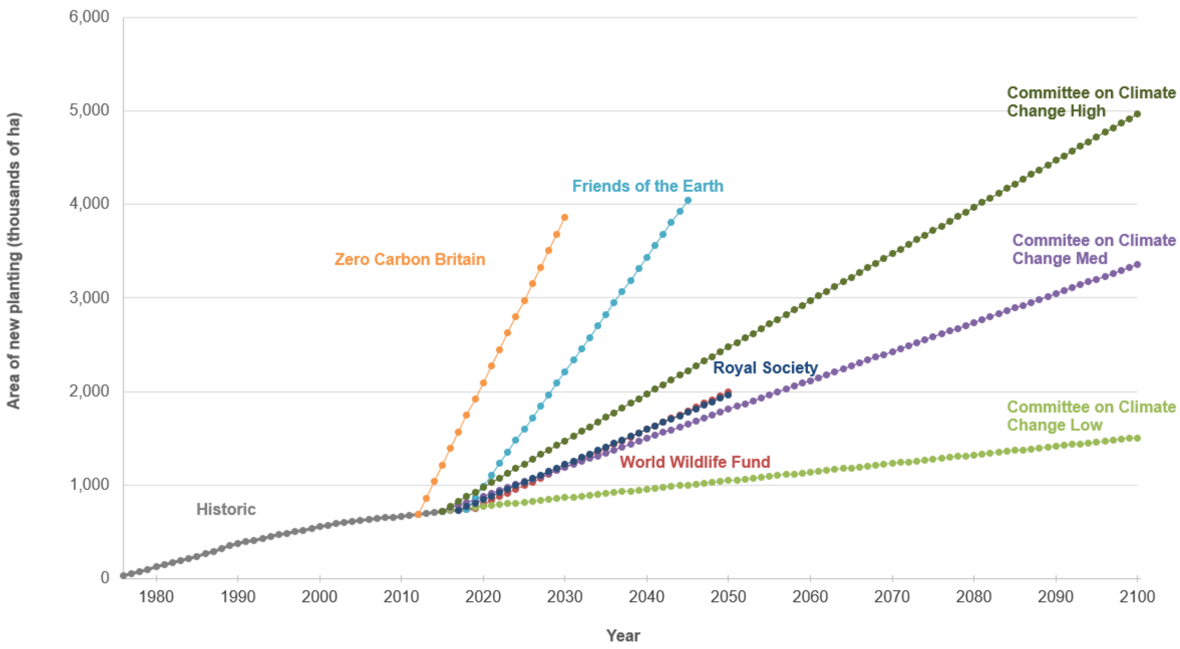

Figure 6: Cumulative area of historic and proposed new woodland planting in the UK. Historic values represent recorded areas from 1976 to present. Proposed values are calculated using average annual planting rate from the start/publication year through to the year identified for reaching the target by each scheme/report (see Table 4).

For much of its history, Britain had no formalised state forest policy, often taking a laissez faire approach to woodland management and making liberal use of cheap imports from overseas (Aldhous, 1997). As a consequence of centuries of deforestation (Smout, 2003) and little incentive for the establishment of new plantations (Aldhous, 1997), by the end of the 19th century, woodland area in Great Britain stood at around 1 million ha (Table 7), less than 5% of the total land area. This decline in wooded area accompanying a hands-off approach to woodland management and policy suggests that a proactive approach is required if afforestation is to increase substantially. This was recognised in 1919 when experiences from World War I led to the creation of the Forestry Commission in order to create a strategic timber reserve and lessen reliance on imports (Richards, 2003; Aldhous, 1997).

3.6.1. State forestry

For the first 60 years, additions to the UK woodland area came primarily from an increase in the area of the state forests, rather than private plantations (Table 7). This was achieved through the purchase of large areas of land for planting, such that by 1939 the Commission had become the largest landowner in Britain (Nail, 2008). This approach of governmental land acquisition offers one possible means of meeting proposed planting targets. However, while the policy was successful when implemented in the mid-20th century, that success may not necessarily be replicated if attempted today. Early expansion of state forests in the 1920s and 30s was enabled by the availability of cheap land (Forestry Commission, n.d.); however, the price of agricultural land in England has increased substantially in real terms since 1945 (Jadevicius et al., 2018). Today, much of the remaining non-forested land tends to be higher quality agricultural land, in scenic areas or in peri-urban locations, and the purchase costs could be prohibitive. While the Commission has compulsory purchase powers, these have not been applied in practice, with land instead being purchased from willing owners (Edlin, 1969). However, this approach may not remain feasible due to the large proportion of suitable land that may need to be planted (Section 3.3), leaving little room for flexibility if used as the only mechanism to purchase land from willing owners. Attempts to use compulsory purchase in a significant way are likely to be unpopular with landowners and politically charged (NFU Scotland, 2017). In Spain, a 'consortia' approach was used during the mid-20th century where the state carried out afforestation and management of the area, but did not take control of the land, although this was typically done on publicly rather than privately owned land (Vadell et al., 2016).

3.6.2. Private forestry

Efforts to encourage private planting in the UK were initially slow to take-off, with landowners having neither the money nor interest to carry out new planting (Aldhous, 1997; Forestry Commission, n.d.). However, by the 1940s the first of a series of fiscal schemes and grants was introduced to encourage private planting (Forestry Commission, 1956).

The 1980s saw controversy with large scale private planting in The Flow Country of Scotland, driven by generous grants and a tax system that allowed for significant returns on investment, at the expense of profound environmental damage and habitat destruction (Warren, 2000; Stroud et al., 2015). This is a striking example of the dangers of poorly planned woodland policy, but, perhaps also, of the speed at which afforestation can take place given appropriately generous financial incentives. The lessons learned during this time resulted in a 'greening' of forest practice, with more vigorous assessment of grant applications and a shift to multi-purpose forestry (Warren, 2000). Today, various grant schemes are still used to encourage woodland expansion by private owners and make this financially viable (Hardaker, 2018), with the private sector being responsible for the vast majority of recent new planting in the UK (Hopkins et al., 2017).

3.6.3. Encouraging private planting

While grant payments have been instrumental in encouraging woodland expansion in the UK (Thomas et al., 2015), recent surveys have found low uptake, or planned uptake of forestry by farmers (Hopkins et al., 2017). This can be seen in the national planting rates, with an average of just 9,590 ha of new planting each year in the UK between 2010 and 2019 (Figure 6). Numerous reasons for this lack of uptake have been reported in the UK and elsewhere (Lawrence and Dandy, 2014) and include: an application process perceived as highly complex and requiring external assistance (Thomas et al., 2015); delays in receiving income (Watkins, 1996); lack of financial incentives (Duesberg et al., 2014); a loss of both productive land (Watkins, 1996; Howley et al., 2015) and ability to demonstrate farming skill (Burton, 2004); a preference for food production, land-use flexibility, and the farming lifestyle (Duesberg et al., 2014), and tradition (Duesberg et al., 2014). There are also currently few financial incentives to increase uptake of agroforestry, and indeed in Scotland agricultural subsidies may be lost depending on planting densities (Saunders et al., 2013). Barriers such as these will need to be addressed if rates of private planting are to increase to meet proposed goals.

Table 7: Woodland area in the United Kingdom. Adapted from Aldhous (1997), with the inclusion of figures from Forestry Commission (2014) and Forestry Commission (2019a).

	Effective date of survey or census									
	1895	1913	1924	1939	1947	1965	1980	1996	2014	2019
	Woodland area (thousands of ha)									
Private										
Great Britain	1076	1267	1204	1197	1205	1085	1216	1554	2268	2325
England					673	651	692	758	1087	1093
Scotland					436	351	422	669	942	988
Wales					96	83	102	127	189	192
Northern Ireland			16	16	15			19	50	51
State										
Great Britain	27	27	50	179	252	655	892	852	809	801
England						234	255	223	215	215
Scotland						304	498	508	477	469
Wales						117	139	121	117	117
Northern Ireland			2	8	9			75	62	62
Total Woodland (UK)			1272	1400	1481			2500	3139	3187

3.7. Future work and considerations

Large scale afforestation for carbon sequestration is a complex undertaking, and this work largely concerns just one aspect of this – the availability of land. While we explore the feasability of meeting proposed planting targets, we do not assess the validity of the targets themselves. In creating these, assumptions are made concerning both the level of carbon sequestration required, and the area of afforestation required to achieve this. The former will depend on factors such as future levels of emissions, and the uptake and success of other mitigation measures such as direct air carbon capture, both of which are highly uncertain (IPCC, 2018). The latter will depend on factors such as the impact of CO2 fertilization (Jiang et al., 2020), the species planted (Wang et al., 2017; Kirby and Potvin, 2007), and management regime used (Noormets et al., 2014). Therefore, while results presented here demonstrate an ability to meet proposed planting targets, whether these in turn will meet climate change mitigation targets is beyond the scope of this work.

In addition to rates of carbon sequestration, the kinds of trees, how they are grown, and where they are grown all determine the magnitude of additional ecosystem services provided by woodland, and who benefits from these (Chazdon and Brancalion, 2019). Future work will need to model the spatial variability of ecosystem service delivery from woodland to ensure maximum benefits are derived from large scale afforestation. In essence, while the present study explores where planting *could* take place in the UK, the next step will be to identify where it *should* take place and how this can be achieved.

4. Conclusion

There are a variety of proposed targets for woodland creation in the UK, ranging from hundreds of thousands to millions of hectares within the next 10 to 80 years. Numerous constraints dictate where these woodlands could not, or potentially should not, be established. Of these, those that can be described as ‘policy constraints’ – protected areas and good quality agricultural land, occupy the greatest area in the UK.

Sufficient space is available to meet the highest proposed woodland creation goals, even if planting is prevented on moderate to good quality agricultural land and within protected areas. However, this would require planting on a large proportion of available land, which is unevenly distributed across the UK. This would leave little room for flexibility to allow for woodland creation in the most optimal locations, both to optimise the provision of additional ecosystem services, such as air pollution control and recreation, and prevent negative impacts upon local communities and landscapes. This lack of flexibility could also complicate the practicalities of either acquiring land from existing owners or encouraging them to plant upon it.

While this initial analysis suggests that meeting national planting targets is possible, the scale of change being proposed and impact it could have on British landscapes is significant. Meeting many of these proposed targets would result in a transformational change in British land cover, which could result in tens of thousands of farms being converted to forestry, and the replacement of hundreds of thousands to millions of hectares of grassland, arable and horticultural land and other land covers. These more ambitious targets would also require rates of planting that far exceed those seen historically, while planting rates in recent years have been comparatively low. Expansion of British woodland in the early to mid-20th century was driven primarily by an increase in state forest area; however, the conditions that enabled this do not necessarily apply today. More recently, grant schemes have been used to encourage planting by private landowners, although participation has been low, with a variety of reasons for this being identified. These barriers will need to be addressed if targets for planting, and therefore carbon sequestration and storage, are to be met.

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