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The Carbon Sequestration Potential of the Irish Uplands

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Declaration

This declaration is to certify that the work I have submitted is my own and has not been submitted for any other degree, either at University College Cork, or elsewhere. All external references and sources have been clearly acknowledged and identified within the contents. I have read and fully understood the regulations of University College Cork concerning plagiarism.

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I would like to thank my supervisors Simon and Tim for their help and knowledge over the past year. This would not have been possible without them. I also wish to thank my relatives and friends for lending their support throughout this process.

Abstract

The Irish uplands, which cover much of the western half of the country, have long been known as a bare, treeless landscape, used for grazing livestock. They are characterised by thin, peaty unproductive soils, and tend to provide poor economic returns to those farming them. A land use shift is currently occurring across the uplands, with many farmers ceasing actively to exploit the land and leaving the industry, a process exacerbated by isolation, poor incomes, and a lack of successors willing to continue farming the family landholdings. This comes at a time when Ireland is urgently seeking novel approaches to sequester carbon from the atmosphere, and offset GHG emissions from intensive agriculture. Expanding woodland cover onto degraded agricultural land is one of several potential methods being explored worldwide to increase terrestrial carbon sequestration and storage. This study aims to determine the future carbon sequestration potential of the Irish uplands, through the potential regeneration of native woodland, in the event that their land use shifts away from livestock grazing and the associated vegetation management of burning. We chose the Iveragh peninsular, Co. Kerry, SW Ireland as our study site. This is an area of extensive upland landscape, with a long history of extensive cattle and sheep grazing on the unenclosed land, including a considerable area of upland commonage.

We used two approaches to estimate the potential carbon sequestration potential of regenerating woodland in the uplands. Firstly, we wished to determine the environmental and anthropogenic factors associated with woodland regeneration currently observed within the study site, so as to better predict the location and extent of any future woodland regrowth. This was achieved using a combination of online GIS mapping techniques, coupled with ground-truthing of the extent of tree regrowth. Secondly, we wished to establish the realistic nature of any potential future natural woodland cover, in terms of species composition, density and growth form of trees and in the soil composition underneath such woodland. We surveyed the woodland cover of a number of small, uninhabited and unexploited islands within lakes of the southwestern uplands. These islands were ascertained to have been ungrazed since at least the middle 19th century and likely for much longer, owing to their small size and inaccessibility to grazing animals. The vegetation and soil data were then used to calculate the potential carbon storage of any future woodland regeneration.

GIS analysis revealed that slope, elevation, soil type, controlled burning practises and proximity to woodland seed source all influenced the current extent of tree regeneration in the study site. Significant differences were observed between the vegetative composition of the islands and adjacent mainland sites, with dense woodland cover consisting primarily of holly, rowan and birch observed across islands. This island vegetation sequestered ten times more carbon per hectare than adjacent mainland sites, which predominantly consisted of *Molinia* grassland, with no woodland growth noted. Soils in mainland sampling areas were consistently wetter and less carbon rich than those sampled on islands.

Based on these factors, it was determined that within 40 years, 0.6% of the Irish uplands could show natural woodland regeneration, should barriers to re-growth (sheep grazing and vegetation burning) be removed. A higher percentage woodland regeneration could be achieved with additional proactive tree planting programme, which is likely necessary to establish woodland growth in areas remote from existing trees and which have been treeless for many centuries. Despite such a small, predicted increase in percentage tree cover via natural means, this still provides the potential to store over 600,000 tonnes of carbon, thus providing Ireland with valuable ways to offset carbon emissions, along with increasing biodiversity and reduce flood risk over the coming years.

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Chapter 1

1.1 Aims and Objectives

The aim of this thesis is to explore the carbon sequestration potential of the Irish uplands, should native woodland be allowed to regenerate. This has been achieved in the following ways:

- Using QGIS to predict where trees will grow based on environmental and anthropogenic factors
- Using an aerial drone to determine the accuracy of satellite and aerial maps in showing percentage tree cover
- Comparing the vegetative composition, and soils of lake islands and the adjacent mainland in County Kerry
- Determining and comparing the potential carbon sequestration per hectare for island and mainland vegetation, based on vegetative composition studies
- Determining a realistic carbon sequestration rate for an area of the uplands over a given time scale

1.2Thesis Structure

This chapter contains the outline of the thesis and lays out the structure

Chapter 2 provides a literature review of current research surrounding the study

Chapter 3 provides an outline of the material and methodology used to carry out this research

Chapter 4 gives the results and discusses their implications

Chapter 2

2. Literature Review

2.1 What are the uplands?

The Irish uplands cover approximately 10,000km^2 and are distributed throughout the west, southwest and southeast of the country (O'Keeffe & Crowley, 2019) (Figure 1).

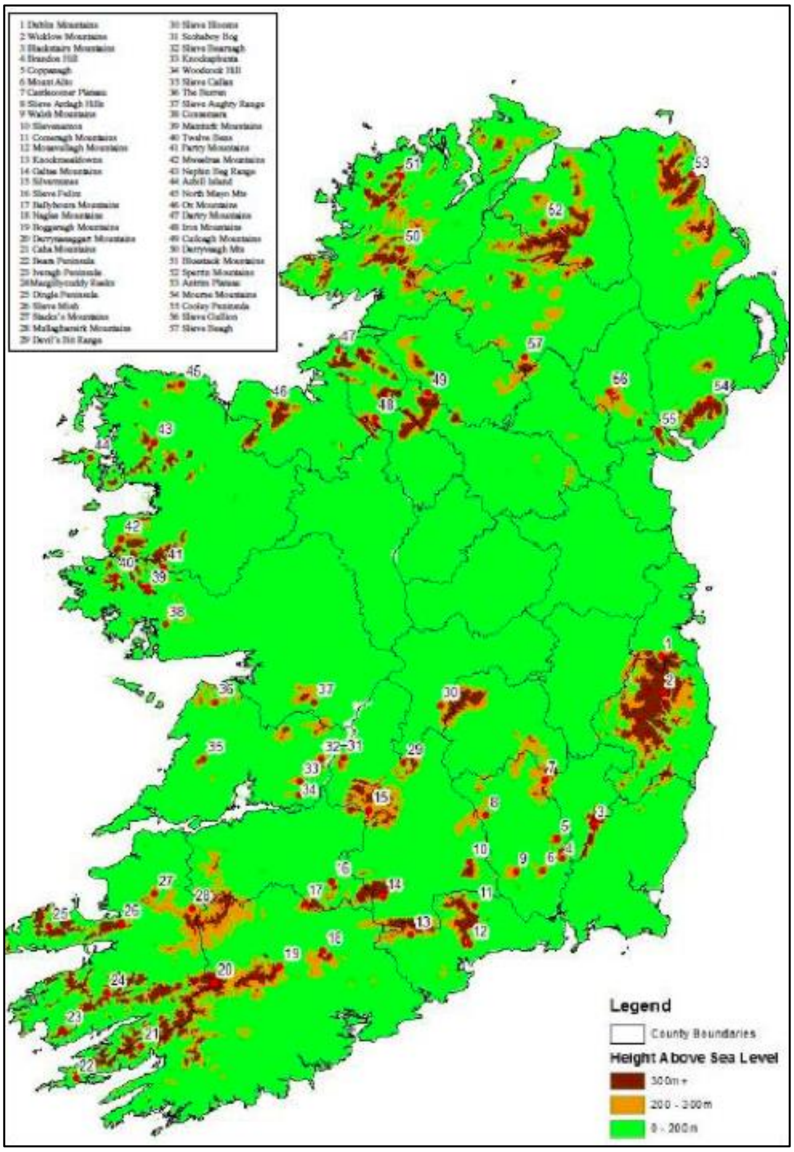

Figure 1. Distribution of the Irish uplands, shown in grey, taken from Crowley *et al.* (2019).

For the purposes of this project, upland habitats in Ireland are described based on descriptions provided by Perrin *et al.* (2009). They are defined as unenclosed areas of land over 150 m altitude, and any contiguous areas of related habitats below this altitude. The main upland habitats include blanket bog, heaths, flushes, dense bracken, habitats of exposed rock and scree, and semi-natural acidic grasslands. Several of these habitats regularly occur together as mosaics, with transitions resulting from changes in topography, edaphic conditions, drainage, management and climate. Unenclosed lands are defined as those outside man-made boundaries that are unimproved and not used for agriculture other than extensive grazing. Unimproved lands demarcated by old or defunct boundaries (e.g. some pre-famine walls) or boundary fencing are not regarded as enclosed and are thus within the remit of this project. Upland regions are characterised by low intensity sheep and cattle grazing (Kramm *et al.* 2010), which, combined with physical and climatic factors, has led to the formation of the bare landscape we generally associate with them (O'Rourke & Kramm, 2009). This bare landscape is often considered to be the natural state of the uplands; however, this is not the case, as pollen records have shown the Beara peninsula was woodland dominated from the Neolithic period, into the late bronze age (Overland & O'Connell, 2008), while the Dingle peninsula was covered with open birch and willow woodland during the early Holocene period (Dodson, 1990). On the Iveragh peninsula, not only are there historic maps from the mid 17th century depicting woodland cover across many of the slopes, but the townland names are littered with words such as *doire*, meaning 'oakwood' (Costello, 2020a) (Table 1). However, while there are many examples of woodland related townland names, this may in fact indicate rarity of woodland, making its use in town names noteworthy. Therefore, one cannot rely on town names alone to indicate the presence of widespread woodland.

Table 1. Townland names associated with woodland growth in the Irish uplands, reproduced from a table in Costello, 2020a.

Townland names
Doire na Féinne—Oakwood of the Fenian Band
Crosdoirí—Transverse oakwoods.
Doire Ard—High oakwood.
Doire Chearna—Oakwood of (Kearney?).
Doire Garbh—Rough oakwood.
Doire Leathan—Wide oakwood
Doire Liath—Grey oakwood.
Doire Loiseagán—Oakwood of (?)
Drom Darach—Oak ridge.
Drom Dúire—Ridge of black-oakwood.
An Gaorthadh—Riparian grove.
An Gaorthadh Mín—Smooth riparian grove.
Macha an Leamháin—Milking-place of the elm.
Doire na Bláiche—Oakwood of the buttermilk.

Na Doiríní—The little oakwoods
Botha Coille—Huts of the wood
Doire Lice—Oakwood of the flagstone
18. Doire Ghearráin Thuaidh—Oakwood of the gelding, North
Doire Ghearráin Theas—Oakwood of the gelding, South
An Gaorthadh Thuaidh—The riparian grove, north
An Scairtín—The thicket
Doirín Finnleithid—Little oakwood of the (white width?)
Gaorthadh Saileach—Willow riparian grove
Doire na Fuinse—Oakwood of the ash
Doirín Uí Chathail—Ó Cathail's little oakwood
Doire Coinche—Oakwood of (?)
Doire Blonaige—Oakwood of the lard
Crannach—Place of trees
Gort Doire Fhraoigh—Field of the heather oakwood
Gort Doire Chasáin—Field of the footpath oakwood
Mucros—Pig-wood
Oileán an Rois—Island of the wood
Cuileannach—Place of (Hollies?)
Gort an Doire—Field of the Oakwood
Cuileannach Uachtarach—Place of Hollies (?), Upper
Cuileannach Íochtarach—Place of Hollies (?), Lower
Ceann Cnóchoille—Headland of the hazelwood
Dúire—Black oakwood
Doirín na nÁiríoch—Little oakwood of the herders
Draighneach—Place of blackthorns

The transformation of the Irish uplands from woodland to a more open landscape arose as a result of transhumance grazing (Costello, 2020b). This practise has a long history in Ireland and involved the seasonal movement of cattle from the fertile lowland pastures onto marginal grazing on the hill (Porqueddu *et al.* 2005). This method decreased the likelihood of overgrazing and damage to the ground as the cows were moved from place to place (English Nature, 2004). Transhumance was practised in Ireland until the late nineteenth and early twentieth century (Costello, 2020b). With the introduction of hardy sheep breeds to Ireland, such as the Scottish blackface in the late 19th century (Irish Native Rare Breeds Society, 2021), the practise of transhumance was phased out, with the new sheep breeds able to graze in the uplands year-round, due to their ability to thrive on poor forage, in harsh climatic conditions (Gootwine, 2020). The introduction of the European mountain lamb and hogget ewe scheme in the 1970s, and the European ewe premium in 1980, resulted in stocking densities more than doubling on the Irish uplands (O'Rourke & Kramm, 2009), as under this agricultural policy, sheep were favoured over cattle production (Kramm *et al.* 2010). The great increase in sheep grazing on the uplands since the 1970's indicates that intensive sheep farming is neither ancient nor traditional, with cattle being the dominant grazer of the Irish uplands until this point (O'Rourke & Kramm, 2009). Hardier sheep breeds, combined with this change in agricultural policy (O'Rourke & Kramm, 2009), led to the intensification of sheep farming on the uplands, resulting in overgrazing (Di Falco & Van Rensburg, 2008). Since 2005, there has been a gradual destocking of livestock in upland areas, as a result of the introduction of the single farm payment, meaning supports and subsidies are no longer linked to production (Irish Times, 2004).

Uplands are multifunctional landscapes, providing people with livelihoods and resources, along with delivering essential ecosystem services such as flood alleviation, carbon sequestration, biodiversity, and cultural and aesthetic services (Glass *et al.* 2013). However, degradation due to grazing and burning practises, trampling by livestock and deforestation have caused upland regions to provide ecosystem disservices such as soil erosion, decreased water storage potential, and carbon loss (Bonn *et al.* 2008).

2.2 The economics of sheep, cattle, agriculture and forestry in the uplands

The uplands are an economically marginal landscape, generally consisting of thin, nutrient-poor, acidic soils, and high rainfall, which limit the production that is attainable in comparison to lowland regions (Crowley *et al.* 2019). As a result, the only forms of agriculture that are feasible within these areas are extensive, low-density grazing of sheep and beef cattle, with crop production being of little importance in upland regions (Bonn *et al.* 2008). Sheep farming is characterised by mountainous areas, with over a quarter of Irish sheep farms located in the west of Ireland, on marginal uplands (O'Brien, 2019).

As of 2020, there were 14,322 sheep farms in Ireland, with an average annual income of €17,913 per farm (Dillon *et al.* 2021). There are currently 4.02 million sheep in the country, across 36,163 registered holdings, representing an increase of 3.6% on the December 2020 sheep population figure of 3.88 million (Department of Agriculture, Food & the Marine, 2021a). While the sheep output price has increased steadily in the last twenty years, the real sheep price index has shown no increase since 1990, due to increases in the price of sheep inputs (Keady & Hanrahan, 2015). Without direct payments, sheep farming in the uplands would no longer be viable, with these supports contributing to over 50% of gross output (Renwick, 2013). The rising costs of fuel, feed and fertilisers due to increased inflation mean farmers will rely increasingly on financial supports to make ends meet (Murphy, 2022). Teagasc predicts lower margins for sheep farmers in 2022 as a result of these rising costs, with a family farm income of just €17,700 expected (Buckley *et al.* 2021). Traditionally, Ireland's main market for light hill lamb has been Mediterranean countries such as Portugal and Spain. However, in recent years, there has been a decrease in the number of exports to these countries (Cummins, 2018). Low margins, coupled with decreasing supports, has seen the upland sheep farming sector become significantly less profitable over the last twenty years (Teagasc, 2016). Table 2 shows the general trends in Irish sheep farming from 2015 to 2020. 2020 was a more profitable year for sheep farmers, with a higher percentage of farms considered viable. However, an aging farming population saw the average age of an Irish sheep farmer reach 60 years old for the first time. The number of sheep farms remained stable from 2018 to 2020, although the average size of farms has shown a gradual reduction since 2015. The number of sheep across the island has shown a steady increase since 2011, with numbers rising above four million in 2021 (Figure 2). There has been a long-term (historical) trend for an increase in the number of sheep in the western uplands of Kerry and Donegal since the early 1900s (Figure 3), showing that the current extensive sheep grazing in these regions is a relatively new phenomenon. The expansion of sheep in the 1800s followed the introduction of the Scottish Blackface breed, with a second increase in sheep numbers in the late 20th century as a result of a shift towards extensive sheep and away from small cattle farms. Irish sheep farming is now entering a phase of uncertainty, with an aging farming population, and many leaving the industry, meaning there is unclear future for the uplands.

Table 2. The annual state of sheep farming in Ireland, based on data reproduced from Teagasc National farm surveys 2015-2020, and National sheep and goat census 2021

Year	**Average age of hill sheep farmers**	**Average annual income**	**Number of sheep farms in Ireland**	**Average size of sheep farms (hectares)**	**% of farms considered viable**
2020	60	€17,913	14,322	44	27
2019	59.8	€14,780	14,322	47	24
2018	59.5	€13,297	14,322	48	20
2017	57.5	€16,856	12,758	51	28
2016	58	€15,708	12,758	51	23
2015	55.5	€14,500	12,723	50	26

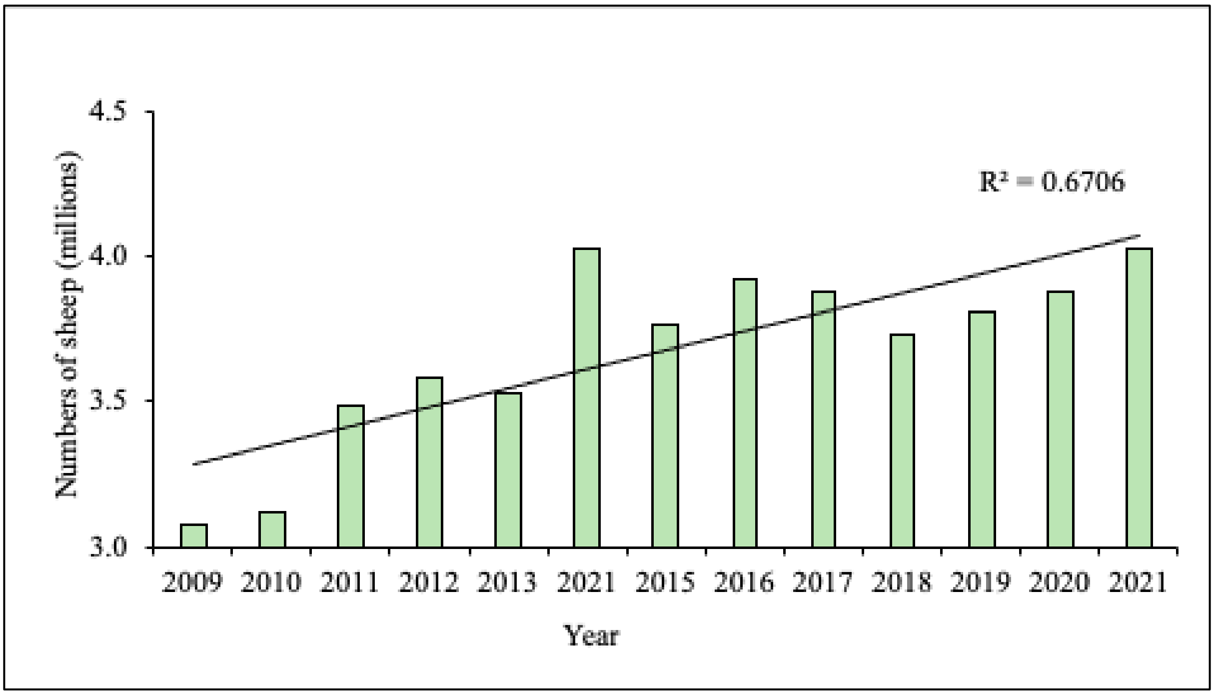

Figure 2. Total number of sheep in the Republic of Ireland between 2009 and 2021, based on data collected by the DAFM

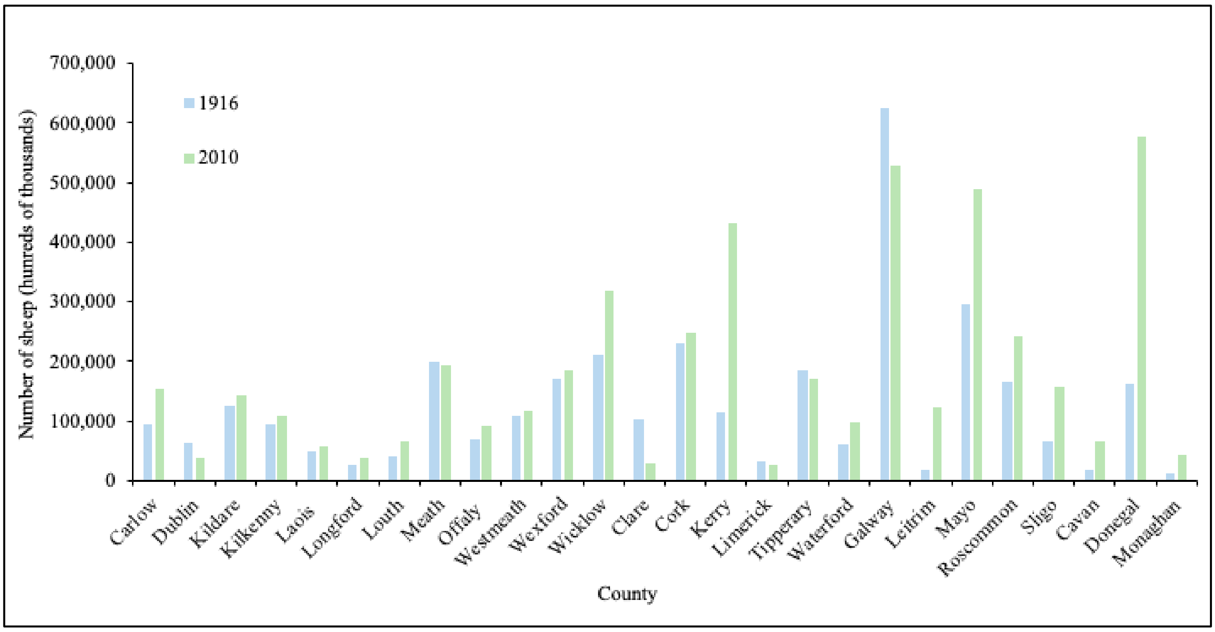

Figure 3. Number of sheep per county in Ireland in 1916 and 2020, from data collected by the CSO

Changes in agricultural subsidies have resulted in significant impacts in how upland farms are managed, with policies such as the rural environmental protection scheme (REPS) bringing an end to traditional cattle grazing on the hill (Kramm *et al.* 2010). The phasing out of production based payments has also contributed to a reduction in the number of upland farmers who keep cattle (Acs *et al.* 2010). Stocking densities measured by the central statistics office between 1970 and 2000 found a continual, gradual decline in cattle numbers in the Iveragh uplands, with much of the region containing less than 0.1 cattle livestock units per hectare by 2000 (Kramm *et al.* 2008). When milk quotas were abolished, many Irish beef farmers switched to dairy, as it is a more profitable sector. However, those living in upland areas of poor land quality have not had this option, and suckler beef is their only choice (Irish Farmers Association, 2020). In 2018, just 11% of beef farms were classified as viable (Dillon *et al.* 2019), and with a 9.8% decrease in the retail price for beef between 2015 and 2019 (Irish Farmers Association, 2020), the opportunity for farmers to make a viable income from beef is declining.

Alongside agriculture, commercial conifer plantation forestry is the second major (current) land use in upland regions. However, the commercial value of this enterprise can be reduced due to a range of factors common to the uplands, including poor soil quality, high wind speeds and elevation. High winds can result in windthrow or leeward swept trees, both of which decrease markedly the economic returns from a plantation (Horgan *et al.* 2003). Any areas which will not produce a timber yield class of 14 or higher, due to prevailing soil or climatic conditions, are no longer used for conifer plantations as they are seen as unprofitable (Forest Service, 2015) – although such areas have been planted in past decades. Land above 300 metres in the west of Ireland is therefore generally classified as unplantable (Horgan *et al.* 2003). Many upland areas are characterised by poor, thin soils, exacerbated by overgrazing, (Sansom, 1999) and using these areas for conifer plantations would be uneconomical. Further, many of the upland regions are remote, with poor road infrastructure and rough terrain, greatly adding to the cost of exploiting these areas for commercial forestry.

2.3 The likely future agricultural and forestry use of the uplands: what is happening now and in the future?

The current trend in Irish upland agricultural regions is towards depopulation of these areas, and increasing areas of 'agricultural' land is either being abandoned (Irish Uplands Forum, 2021) or acquired by new owners and incorporated into larger enterprises (O'Rourke, 2019). This has been observed in rural Spain, where an exodus of sheep farmers from the landscape has resulted in those farmers remaining buying up the land (Paniagua, 2013). These larger holdings are generally owned and managed by farmers who do not live on site, and thus adapt a less labour intensive form of farming (O'Rourke, 2019). In Ireland, however, despite the lack of profits upland farmers receive for their efforts, many are continuing to farm the land, and feel compelled to do so into the future (Crowley *et al.* 2019). Two-thirds of upland farms have been owned by the same family for 200 years or more (Irish Uplands Forum, 2010) indicating that there is a strong sense of duty (or social pressure) to carry on the tradition. However, with a low future market value for sheep, there is the danger of upland farming areas being abandoned entirely in the future (Pitts, 2017). The decoupling of subsidies from production has already led to greater levels of land abandonment, and this would be compounded further should subsidies for sheep farmers be removed or reduced in the future (Acs *et al.* 2010). Similar events are currently unfolding in the Scottish uplands, with Armstrong *et al.* (2014) and Ross *et al.* (2016) noting the reduction in sheep numbers since 2005 as a result of decoupling payments to farmers. In southeast Scotland, approximately 12% of upland farms have been abandoned over the last century (Parry, 1976). Along with low levels of profitability in the sheep farming sector, the average age of farmers in the west of Ireland is 59 years of age (CSO, 2020), and many are unmarried, with no successors (O'Rourke, 2019). These factors may lead to a large number of farms becoming abandoned in the next twenty years as farmers retire from active farming activity.

There has been a recent shift in some upland areas towards ‘high nature value’ (HNV) farming, as the potential for biodiversity conservation of this land use is being increasingly recognised, with the European Commission estimating that 30% of Europe may be high nature value farmland (O’Rourke & Kramm, 2012) . High nature value farming generally occurs in areas of marginal land, with low stocking densities and high levels of semi-natural vegetation (O’Rourke, 2016). Many of the upland regions in the west of Ireland have a high likelihood of being HNV farmland, with factors such hedgerow density, semi-natural habitat cover, soil diversity and stocking density used to determine this (O’Keefe & Crowley, 2019) (Figure 4). For example, a plan for restoring the uplands of the Macgillycuddy Reeks in county Kerry is currently underway, focused on farming the uplands in a more sustainable manner (EIP-Agri, 2018). This will be achieved by reducing the intensity of farming carried out, increasing the presence of semi-natural vegetation such as unimproved grasslands, and maintaining mosaics of diverse land cover types (O’Rourke & Kramm, 2012). Farmers who participate in HNV farming are eligible for payments of up to €5000 from the green low carbon agri-environment scheme (GLAS) as of 2014 (Sargent, 2021). A move towards HNV farming in the uplands, along with an increase in subsidies to reward it, may lead to a reduction in current and future land abandonment.

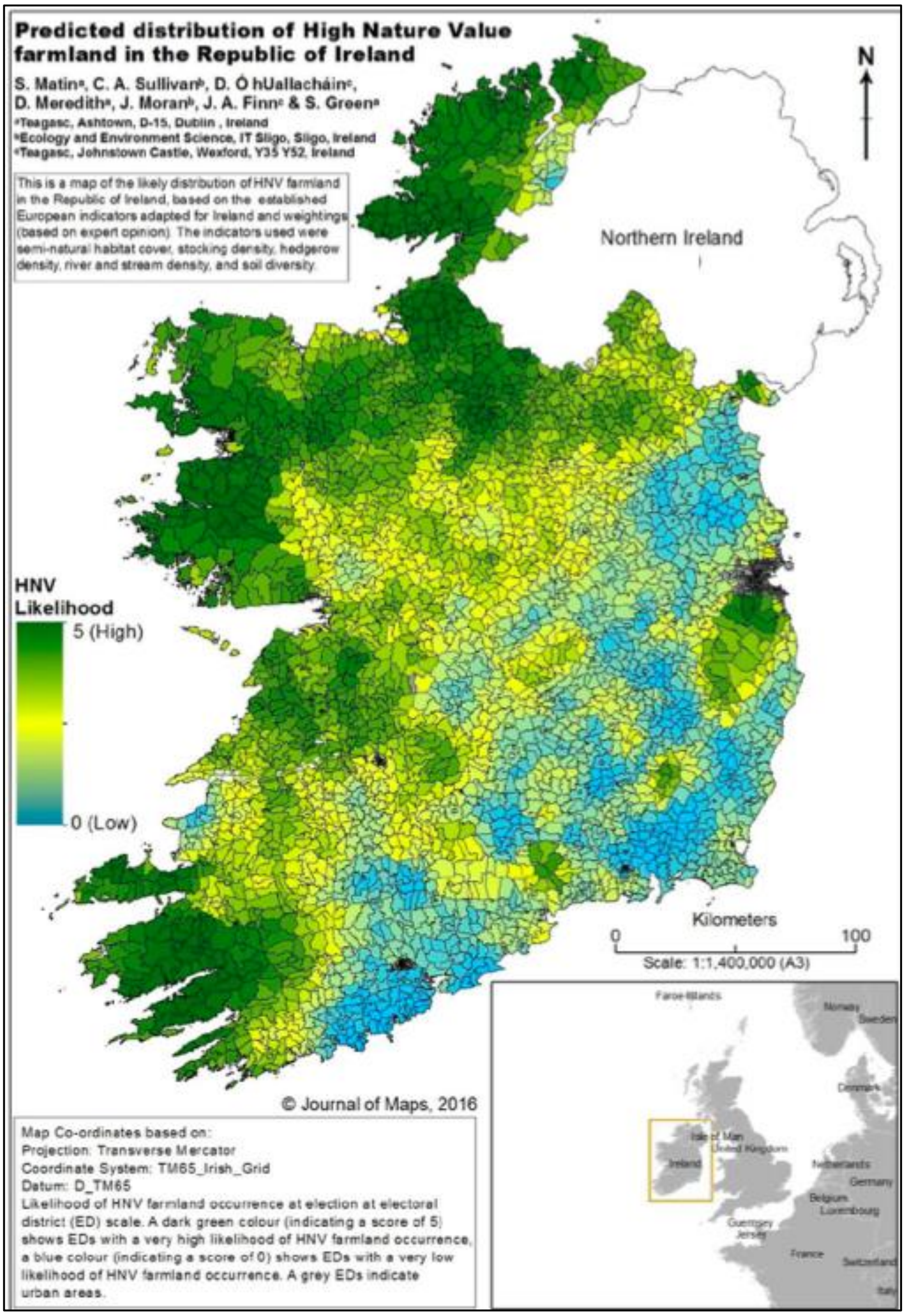

Figure 4. The predicted distribution of HNV farmland across Ireland, taken from O'Keefe & Crowley (2019)

Although there is much discussion about the need for more sustainable agriculture of the uplands in Ireland, emphasising the value of natural habitats and wildlife within the agricultural setting, there are growing pressures globally on food supplies. This may in fact shift the debate on the future of the uplands away from conservation towards animal production once more- perpetuating the pattern over the centuries of changing intensities of upland land use following changes in the demand for food both nationally and internationally. Current United Nations projections are that the global population will reach

9.7 billion people by 2050 (Roser, 2013). Food demand is expected to increase by 59-98% in the same period, as a result, leading to changes in the agricultural market (Elferink & Schierhorn, 2016). The European Unions' agricultural outlook for 2021-2031 is that world meat consumption will grow by 1.4% per year, as a result of increasing populations and higher incomes in developing countries (European Union, 2021). Demand for sheep meat in China is expected to increase, and there is growing opportunity for Irish sheep exports as the UK continues to struggle with access to the EU market (Irish Farmers Association, 2022). As of 2022, a new agreement between Ireland and the United States means that Irish sheep meat can now be exported to the US (Irish Times, 2022), and this, in combination with other global factors may lead to a rise in demand for Irish sheep meat exports, and improved prices for light hill lamb, such that upland sheep farming becomes more profitable in future. Ongoing global warming may work favourably for sheep farmers, with increased productivity of the land resulting in heavier lambs and higher stocking rates, allowing farmers to meet the demand for meat (Ross *et al.* 2016).

2.4 Biodiversity of the uplands and land use

Land use affects the biodiversity composition of the uplands greatly, with heavily grazed regions containing fewer, and different species to those present in less grazed areas, wooded areas, or conifer plantations (Bunce *et al.* 2014) The Irish uplands are included in Annex I of the European habitats directive and are considered to be of international conservation concern (Van Rensburg & Mulugeta, 2016). Damage to the uplands in the form of overgrazing may result in reduced biodiversity, productivity and usefulness of the landscape (Wick *et al.* 2016). Overgrazing arises when grazer-palatable plants are unable to persist in an area due to excessive herbivory (Wick *et al.* 2016), and it has profound effects on vegetation and animal communities (Ross *et al.* 2016), with competitive, coarse grass species such as *Molinia caerulea* and *Nardus stricta* taking over and dominating the landscape (Anderson, 2013). This leads to the conversion of dwarf shrub heath to acidic grassland habitats (Bullock *et al.* 2011), and therefore a positive feedback loop is often created in upland areas, with increased grazing resulting in the conversion of heathland to grassland, which subsequently leads to more grazing resources becoming available (Ross *et al.* 2016). In extreme cases, it leads to widespread damage to the upland environment, with bare soils becoming exposed and subsequently eroded (Kramm *et al.* 2010). Heavy livestock grazing can create a cascading effect whereby reduced heathland vegetation leads to lower levels of arthropods and reduced breeding bird territories over an extended time period (Evans *et al.* 2015). Intensive sheep grazing can also change the composition of bryophyte communities, reducing the species heterogeneity (Austrheim *et al.* 2007), and leading to an overall homogenization of the landscape (Marrs *et al.* 2020).

Low intensity grazing is seen as the best way to maintain upland biodiversity within agricultural landscapes (Toth *et al.* 2016), as it allows for high plant structural complexity to develop, with variable grazing pressure present throughout the region (Lyons *et al.* 2018). Whilst it can promote an open landscape, and plant diversification, the ability of grazing to conserve biodiversity is however largely dependent on the types of livestock present. Mixed livestock grazing tends to more successfully promote diversity than single species grazing (Van Rensburg & Mulugeta, 2016), with livestock differing in their nutritional requirements, jaw anatomy and grazing behaviours (Schmitz & Isselstein, 2020). Cattle create a more species-rich grassland environment than sheep grazing, with sheep being less selective in their grazing habits (Toth *et al.* 2016). While light, mixed grazing does not provide a win-win situation for every upland species, it can provide an ideal trade-off between 'winners' and 'losers' (Evan *et al.* 2015). In recent decades, the move away from mixed species grazing of cattle and sheep on the uplands, to a regime of only sheep - a process associated with the decline in small mixed farms in the uplands - has seen upland diversity suffer (Marrs *et al.* 2020). This has been observed in Wales, the move from mixed grazing to sheep grazing resulting in the spread of invasive *Molinia caerulea* and a reduction in heathland habitats (Fraser, 2018). Sheep graze vegetation down lower than other livestock, consuming vegetation of 3cm or more in height, while cattle prefer vegetation of 6cm or taller (Tubridy, 2013). The impacts of sheep on the biodiversity of upland species are mixed (Ross *et al.* 2016), with intensive grazing beneficial to the diversity and abundance of nesting birds in the short term (Loe *et al.* 2007), but detrimental to bird populations over longer periods (Fuller & Gough, 1999).

Controlled burning is a tool used by many upland farmers to reduce the amount of undesirable vegetation (including woody species such as gorse, as well as old, rank grasses) on grazing land (Irish uplands forum, 2015), and leads to a mosaic of grassland and heather covered areas of varying ages (Ramchunder *et al.* 2009). 'Muirburn'- a Scottish term for controlled burning of over mature 'leggy' heathlands- carried out on peatsoil heathland must be carefully timed, so that the ground is wet enough to prevent combustion of the peat (Chapman *et al.* 2017), which can cause direct loss of carbon stocks into the atmosphere

(Towers *et al.* 2016). This practice has also become increasingly controversial in recent years due to its perceived negative impact on biodiversity (Carroll *et al.* 2021). For example, increased stream acidification and subsequent reductions in freshwater invertebrate abundances and diversity have been noted after rotational burning (Ramchunder *et al.* 2009). It has also long been documented that burning can exacerbate the problem of undesirable, poor-quality vegetation (Grant *et al.* 1963), as *Molinia* is a fire tolerant species (Boyle *et al.* 2017), and shows increasing invasive spread after fires (Brys *et al.* 2005). This creates a positive feedback loop, with increasing *Molinia* leading to more burning in an attempt to control it, thus leading to reduced floral biodiversity as one species dominates.

Although overgrazing has clear negative impacts on upland ecosystems, under grazing of upland areas can also initially result in a loss in biodiversity, as vegetation communities become dominated by competitive or pioneer species, such as bracken (*Pteridium aquilinum*) and gorse (*Ulex europaeus*) (Kramm *et al*. 2008). This occurs when bracken and scrub encroachment, along with a build-up of excess dead plant material leads to a reduction in the rare biodiversity associated with the heather moorlands and blanket bogs (O'Rourke & Kramm, 2009). Bracken dominated areas are generally seen as poor for biodiversity, as it shades out other species, preventing them from establishing (Gallegos *et al.* 2015), along with being toxic to livestock and small mammals (Burge & Kirkwood, 1992). Bracken is a mid-successional species, and acts as an intermediate stage prior to the succession of woodland (Marrs *et al.* 2000).
At a recent hill sheep conference in Co. Kerry, in 2017, farmers attending all felt that reduced grazing had caused an increase in bracken coverage, and many believed the amount of grassland has decreased as a result (Boyle *et al.* 2017). After the initial dip in upland diversity due to the dominance of pioneer species (DeGabriel *et al.* 2011), reduced grazing may result in woody vegetation encroachment, and the transition from open landscape to forestry (Speed *et al.* 2010).

Native woodland occupies just 100,000 hectares of land in Ireland, and much of this is fragmented or contains a low diversity of tree species (Bullock *et al.* 2014). Although the overall benefits of reforesting for biodiversity are poorly understood, it is however generally regarded as positive for net species gain, but can result in some losses of open-ground species (Douglas *et al.* 2020), such as beetles and spiders (O'Halloran *et al.* 2011). With a decline in livestock grazing in the uplands, some areas may eventually return to native woodland and scrub, with this process previously observed in Norway (Ross *et al.* 2016; Speed *et al.* 2014). Wooded areas act as a source of food and vegetative cover for herbivorous species, resulting in higher small mammal richness, evenness and abundance than in the bare uplands (Bush *et al.* 2012). This is likely the result of increased vegetative complexity (Hamilton *et al.* 2015). These increases in biodiversity are largely associated with native woodland regrowth rather than conifer plantations, which are heavily criticized for their lack of biodiversity (Quine & Humphrey, 2009). It is thought that plantations forests provide an adequate surrogate habitat for generalist species, however the diversity of native woodland specialists is poor within them (O'Callaghan *et al.* 2017). Some researchers have found evidence for increased biodiversity in plantations (Hartley, 2002; Brockerhoff *et al.* 2008), while others suggested biodiversity suffered within afforested monocultures (Gittings *et al.* 2006; Fuller & Browne, 2003). The success of plantations in increasing biodiversity is largely dependent on previous land use; highly degraded grassland areas that are later afforested show an increase in species richness, however lightly grazed shrubland and grassland shows declines in endemic and specialist species when they are turned into plantations (Bremer & Farley, 2010). For example, bird species richness and abundance is greater in native oak and ash woodland than in mature Sitka spruce plantations (Sweeney *et al.* 2010), or unforested areas (Watts & Jump, 2022). With such small areas of native woodland across Ireland, there is a question of whether plantation forests could provide any value to native biodiversity (O'Callaghan *et al.* 2017; Quine & Humphrey, 2009).

2.5 Flood risk and woodland

Upland areas are a source of high rainfall run-off, due to both the high rainfall and steep slopes, particularly when they are under grazing pressure from livestock. Intensive land management can lead to reduced infiltration, soil compaction and removal of complex rough vegetation, resulting in increased run-off and flood risk to lowland areas (Bonn *et al.* 2008). The European floods directive (Directive 2007/60/EC) emphasises the use of natural based catchment solutions to restore hydrological systems, particularly in areas where anthropogenic impacts have resulted in increased run-off (Murphy, 2021). The planting of deciduous woodland in the uplands is thought to be a key component in the reduction of flooding by natural means, and trees can alleviate flood risk in three ways; increased water transpiration, interception of rainfall by the canopy (Dirnböck, & Grabherr, 2000), and improvement of soil structure to enhance water storage and reduce run-off (Murphy *et al.*

2020). Watts and Jump (2022) outline the importance of tree restoration in sloping areas for stabilising soils and increasing permeability, particularly in areas of degraded soils. Woodland growth can decrease the amount of run-off flow by 50% at peak times (Wheater *et al.* 2008), and in areas where trees have been planted, the ability of soil to absorb water is double that of areas with no trees present (Murphy *et al* 2020). Studies in Wales found further promising results, with a 78% reduction in soil surface run-off in wooded areas versus sheep grazed grassland, and an almost 50% reduction by simply removing livestock from an area (Ford *et al.* 2016).

Conifer plantations also reduce peak flows by 10-15%, however, only when established. The initial period of preparation prior to planting leads to a peak flow increase of up to 20%, and the time taken to reach peak flow reduces by a third (Nisbet, 2017). However, conifer plantations result in acidic run-off, which is detrimental to juvenile Atlantic salmonoid populations (Harrison, *et al.* 2014). The establishment of woodland buffer zones around upland plantations is helpful for reducing this acidity and further reducing run-off (Ryder *et al.* 2011).

Despite the ability of woodland to reduce the risk of flooding, extreme rainfall events are likely to increase in severity and frequency due to climate change (Burt & Ferranti, 2012). Woodlands have been proven to reduce run-off from routine rainfall events, however, it is unknown if they can cope with the more extreme rainfall that is likely to increase in frequency because of global warming (Bonn *et al*. 2008).

2.6 Carbon sequestration and agriculture: soils versus vegetation

Conversion of agricultural land to forestry is a valuable strategy for mitigating greenhouse gas (GHG) emissions from livestock (O'Neill *et al.* 2020), particularly in upland areas, which have a high potential for carbon storage, in terms of wooded areas, semi natural vegetation, and peatland soils (House *et al.* 2010). Abandoned agricultural land, for example, generally sees increased carbon storage due to natural vegetative regeneration (Fradette *et al.* 2021) and forestry sequesters large amounts of carbon, with forests that store 49% of Irelands vegetative carbon occupying only 5% of the total land area (Cruickshank *et al.* 2000). The natural regeneration of woodland in upland areas could greatly increase the amount of carbon sequestered, with several authors noting the significant contributions tree regrowth can have on global carbon sequestration (Brown *et al.* 1995; Cannell *et al.* 1999). For example, UK based studies have found that there are 3.9 million hectares across the Scottish uplands with potential for natural regeneration of deciduous woodland vegetation. This would represent up to 45% of the carbon removal target for UK woodlands (Fletcher *et al.* 2021). Similar approaches across the Irish uplands would result in huge increases in the amount of carbon sequestered above ground. There are highly variable results within studies examining soil organic carbon after afforestation, with previous land use and the types of forestry established having the greatest impacts on soil carbon content (Paul *et al.* 2002). A study by Post and Kwon (2000) established that wooded areas, showed lower potential for soil organic carbon than grassland areas, with trees possibly being less effective than grasses at storing soil organic carbon. However, they noted that there is considerably more aboveground vegetative carbon stored in woody plants than in grassland areas, thus indicating that woodland is still the best way to store terrestrial carbon. Restoring natural forestry is far superior to the use of commercial trees to sequester carbon, as although plantation forests will initially act as a carbon store, this is however released back into the atmosphere every 30-50 years during harvesting of trees (Lewis *et al.* 2019). In the UK, Sitka spruce (*Piceea sitichensis*) plantations contain only 8.2% of the total forest carbon, despite covering 21.4% of total forest area (Cannell & Milne, 1995), highlighting the reduced carbon storage potential of this type of forestry. Mini rotations of ten years have been found not to achieve a high carbon storage, while in the long term, over the course of 100 years, broadleaf plantations of oak and beech trees act as excellent carbon sinks (Dewer & Cannell, 1992).

Peatlands are a valuable source of carbon storage, however across the uplands and much of Ireland, they are heavily degraded, as a result of agricultural reclamation and extraction of peat for fuel (Bullock *et al.* 2012). Degraded peatlands act as a source of carbon, rather than a sink, with 1.25Mt carbon emitted from Irish peatlands annually (Malone & O'Connell, 2009). Heavy grazing and excessive burning can lead to exposed peaty soils, which are at risk of carbon loss due to erosion (Baggaley *et al.* 2021).

Grasslands occupy between 20% and 40% of the earths land surface (FAO, 2000) and are estimated to sequester between 12% (Conant *et al.* 2001) and 30% of global soil organic carbon (Scurlock & Hall, 1998). Overgrazed areas sequester significantly lower amounts of soil organic carbon than in areas of reduced grazing intensity (Conant & Paustian, 2002). While overgrazed grassland may be a poor carbon sink, areas which have experienced agricultural abandonment and subsequent growth of rank grassland can show greater sequestration potential (Ghosh & Mahanta, 2014). There is some evidence from Scotland that *Molinia* grassland contain large carbon stocks, (Baggaley *et al.* 2021), and when sheep are removed from upland areas, an increase in *Molinia* tussocks leads to greater carbon stocks. The shoot bases of *Molinia* sequester the greatest amount of carbon and are also the most sensitive to grazing pressure from sheep (Smith *et al.* 2014). There is, however, an increased fire risk associated with a build-up on *Molinia* (Brys *et al.* 2005), such that periodic fires of old dry grass in spring can lead to large amounts of carbon being released into the atmosphere, wiping out any carbon sequestration gains over preceding years. Carbon stored in upland Irish deciduous forests is very unlikely to be released by fires, as the humid ground conditions under the tree canopy and sparser ground vegetation would discourage fire from spreading.

2.7 Woodland growth in the uplands: soils, grazing and seed source constraints

Understanding the potential of different areas to support trees is crucial for planning the expansion of native woodland. Factors such as proximity to seed source, soil type, and the presence of herbivores influence whether trees can grow, and how quickly woodland can regenerate. Natural recolonisation is preferable to planting seedlings or saplings, as it is thought to lead to a more heterogenous woodland, along with maintaining local tree genotypes (Fuentes-Montemayor *et al.* 2022). Some human intervention may still be required within natural regeneration systems, including removal of invasive or non-native species, or minimising grazing from stray livestock (Carver, 2019).

Soil type and tree growth are closely related, with each having a mutual influence on the other (Ryan 1960). For example, birch trees, *Betula,* have strong positive effects on soil nutrients, the intensity of biological turnover and soil microorganisms (Jonczak *et al.* 2020), which in turn allows for improved tree growth, thus creating a positive feedback mechanism. Irelands mountainous regions are characterised by peaty podzolic soils which are prone to waterlogging (O' Rourke & Kramm, 2009) and centuries of overgrazing, burning, and high rain fall have resulted in soil erosion (Viney, 2018). Hillsides stripped of vegetation and soils are becoming increasingly prevalent (Sansom, 1999), and provide little potential for woodland regeneration. These podzolic soils generally do not support a high number of species in comparison to other soil types, however they are often associated with oak woodland and acidophilous species (Little *et al.* 1990). However, years of increased seed production, known as mast years, are found to decrease in frequency with increased elevation and proximity to the Atlantic seaboard (Kelly, 2002), which may impede oak woodland regeneration, particularly in more westerly upland areas.

A lack of seed source is a major limiting factor to the growth of trees in upland areas, and the bare landscape means there is likely to be a lack of trees nearby to facilitate woodland

regeneration. Grazer abandoned areas in close proximity to nearby native woodland may however show rapid regeneration, with full woodland cover possible within fifty years on lowland sites (Broughton *et al.* 2021). Oak saplings generally develop within 20 metres of adult congenerics, and at 75 metres or more, there has been no recorded establishment (Murphy *et al.* 2022).
Birch trees are a pioneer species in many upland sites, due to their large seed crop, the ability of the seeds to travel long distances by wind, and the fast growth rate of the young trees (Liu & Evans, 2021). They are also a wind pollinated species (Whitehead, 1983). Birch trees regenerate most rapidly in disturbed areas, with practises such as routine burning encouraging the seeds to germinate as this exposes mineral soil (Willoughby *et al.* 2019). There is interannual variability in birch seed production, like that of oak trees, and seeds tend to disperse within 40-50 metres of the seed tree, with dispersal being strongly influenced by slope (Tiebel *et al.* 2020). Willow seeds are dispersed by wind, and the distance they can travel is largely dependent on seed mass and the height of seed release (Gage & Cooper, 2005).

Grazing pressure is an extremely important driver of woodland dynamics during the early growth stages, when saplings have yet to reach a height great enough to avoid herbivory damage (Fuentes-Montemayor *et al.* 2022). For example, oak saplings, once established, are vulnerable to grazing from herbivores for up to a decade (Murphy *et al.* 2022). Their success is largely dependent on the exclusion of large herbivores, with species such as the Sika deer favouring oak seedlings (Kelly, 2002). Deer can have devastating impacts on woodland regeneration through grazing and browsing, causing a loss in biodiversity across many trophic levels, as habitat quality is reduced for many woodland species, leading to local extinctions (Fuller & Gill, 2001). Sheep, unlike deer, tend to avoid grazing on woody vegetation, and instead prefer graminoids and herbs. However, the encroachment of trees into upland areas remains hindered by winter sheep grazing, as the dormant vegetation is unable to recover easily when grazed (Ross *et al.* 2016). Sheep may also cause trampling and compaction, and during particularly harsh winter months, may strip trees of bark (Aylward *et al.* 2012). By excluding sheep and deer from an area for several years, there is the possibility that natural recolonisation of native woodland can occur, although the speed at which this will happen is dependent on the proximity of a seed source, slope, and the quality of the soil within the area (Evans *et al.* 2006)

2.8 The current study

This paper aims to determine the potential for colonisation of the uplands by native woodland trees and the subsequent impacts on carbon storage, should sheep and livestock grazing be reduced or ceased in these regions. Predicting how quickly upland areas will return to native woodland once grazing herbivores are removed is necessary to determine when maximum carbon sequestration potential will be reached. Many heavily degraded areas may not return to woodland vegetation for many years, due to factors such as lack of seed source, poor soil quality (Fenton, 2008), and the presence of controlled burning practises. Current burning guidelines in Ireland dictate that burning cannot be carried out near a public road, nor should it cause damage to neighbouring properties (Department of Agriculture, Food, and the Marine, 2021b). Thus, one can infer those upland areas near neighbouring land or public roads would not be subject to controlled burning, and hence may be more likely to see a return to woodland than those that are routinely burned.

The aims of this paper are to;

1. Use QGIS software, coupled with drone surveys to ground-truth GIS-derived data, to examine an area of land in county Kerry and determine the relationship, if any, between current tree growth and a suite of anthropogenic and natural environmental factors. Based on any significant factors affecting tree growth in this analysis, predictive mapping of the uplands was then performed to determine the locations in which tree growth would be likely to occur.
2. Compare the natural vegetation and soil properties of ungrazed, naturally wooded islands within larger lakes, and adjacent mainland habitats in terms of species composition, and carbon sequestration potential.
3. Determine how much carbon can be sequestered in upland landscapes, should these be recolonised by native woodland, using the information from the above studies.
4. Explore the potential for native woodland regrowth to be more socially useful than continued sheep grazing in the uplands, based on current trends in profitability of sheep farming, and projected realistic carbon sequestration potential of upland areas.

Chapter 3

3. Materials and methods

3.1 Verification of online tree presence using drone photographic surveys

Ground-truthing surveys were carried out by aerial drone, and cross referenced with GIS data across the same study area, to determine the accuracy of GIS maps in determining tree cover. The site selected for drone surveying was Girley Bog, in county Meath. The area was chosen due to the combination of forest and low woody vegetation present within the bogland habitat, giving the opportunity to determine if woody scrub is differentiated from tree cover in aerial maps and drone photographs. The bog is approximately 100 hectares in size (IPCC, 2016), and five 100x100 metre areas were picked throughout the area, based on accessibility and the presence of tree cover. The Bing Aerial layer within QGIS was chosen for assessing tree cover from aerial photographs. The clarity of images in Bing is higher compared to other sources such as Google Maps. Polygons were drawn and overlayed on all visible tree growth within each 10,000 m^2 areas, and the percentage of each area covered by polygons was calculated.

The five sites within the bog were visited over the course of three days in June 2022, to take photographs using a drone. The sites were visited during good weather periods, with the sun directly overhead to reduce the chance of strong shadows appearing within the images, and thus disrupting the ability to accurately determine tree cover. The drone used to take each of the photographs was the ‘Mini SE’, manufactured by DJI. This is a lightweight, iPhone-operated drone, capable of taking high resolution images at a maximum height of 120 metres. Each area was marked out using stakes at the four corners of the square. Standing outside of the area, so as not to appear within the images, the drone was flown to its maximum altitude of 120 metres, and photographs were taken of the marked-out areas. Visual comparisons were made between the footage taken with the drone, and those images present in Bing Aerial. Using QGIS, polygons were drawn around visible tree cover within each drone photograph, and the percentage cover of the polygons was calculated. The percentage cover was then compared between aerial photographs and drone photographs for each of the five sites.

3.2 Surveying of factors associated with tree growth

The factors associated with the current natural tree cover in the Kerry uplands were explored using QGIS mapping software. The survey area used was 49km long and 25km wide, stretching from Kenmare, south to Glengarriff woods and east to Bandon (Figure 5, Figure 6). A grid of 1km x 1km squares was created overlaying this area. 1225 squares were present within this grid, and a random number generator was used to pick one hundred of these for further analysis. Grid squares were excluded from further analysis if they contained large bodies of water, infrastructure, conifer plantations or greater than 50% cover of improved farmland.

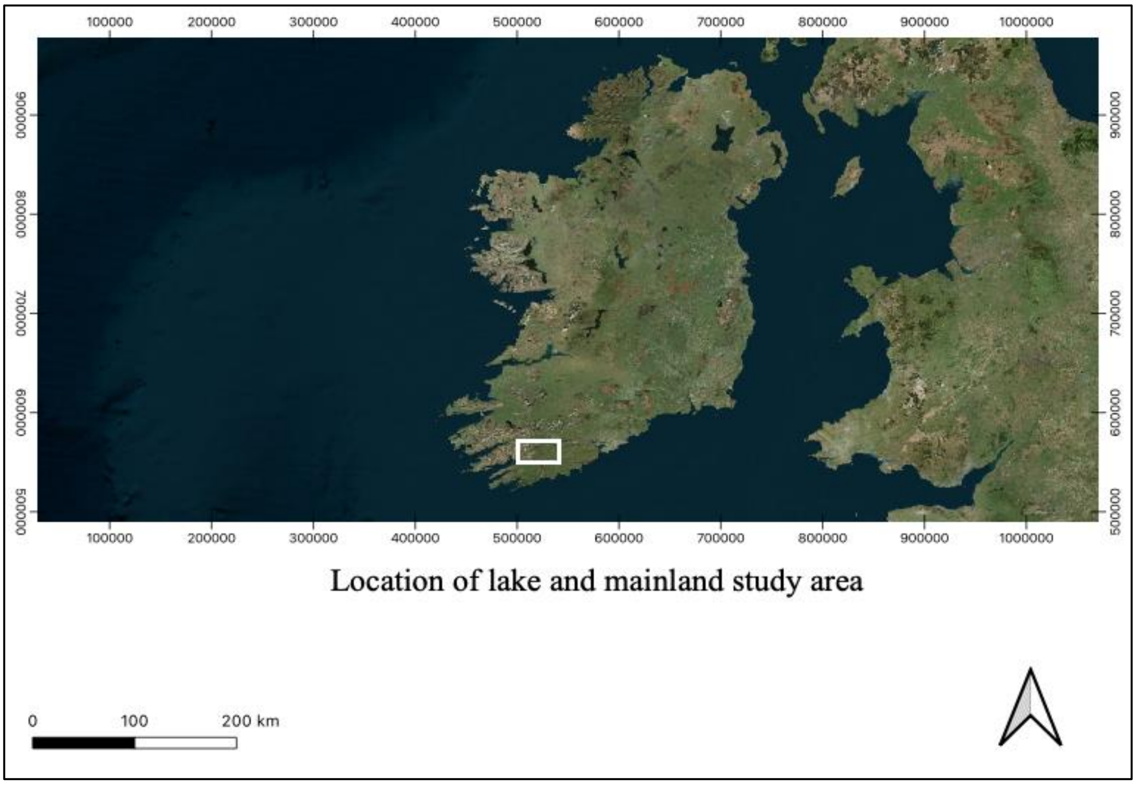

Figure 5. Location of lake and mainland study areas in Ireland

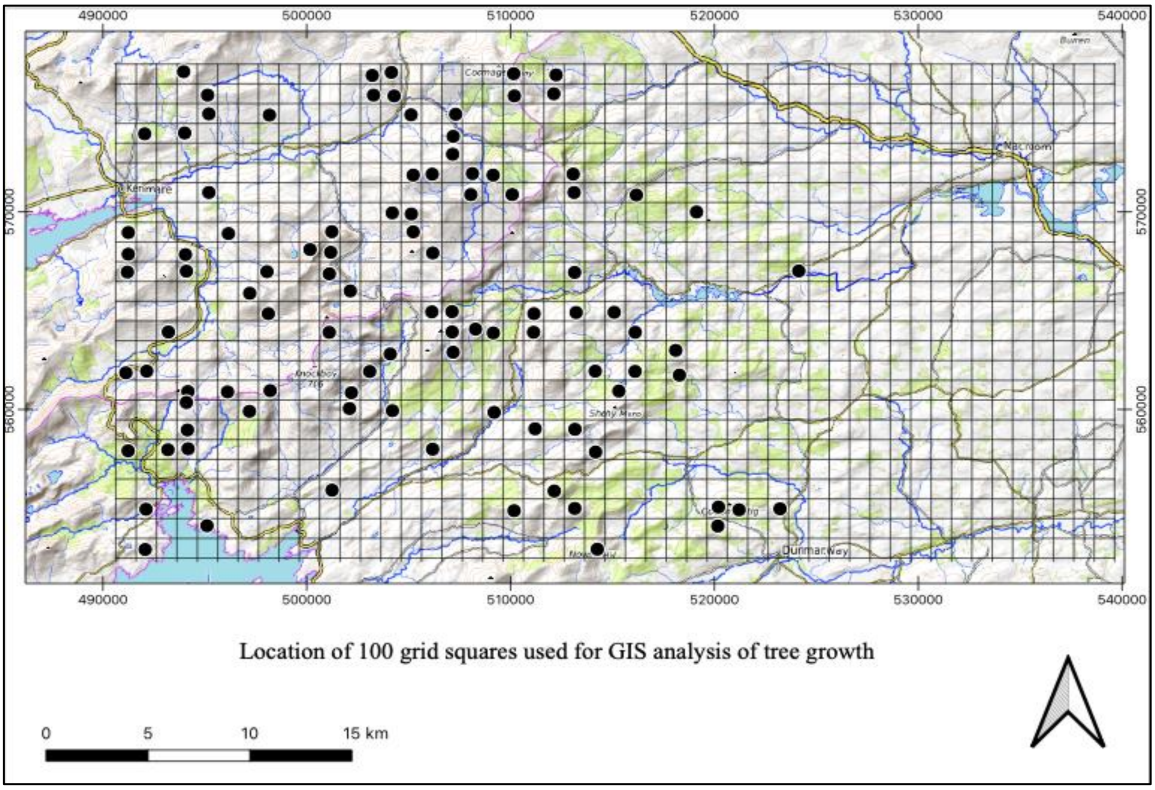

Figure 6. Location of the 100 randomly selected grid squares used for predicting the factors that in influence tree growth

3.3 Analysis of data in GIS

The selected grid squares were firstly examined visually, using the Bing Aerial map. Variables were chosen based on factors from published literature that are recognised as influencing tree growth in the uplands. Data was then gathered from visual inspection of the landscape and vegetation within the grid squares and neighbouring land and from other online mapping resources, including land use (CORINE land use) and geomorphological maps (Table 3) (Figure 8).

(1) The extent of tree cover within each of the one hundred grid squares was quantified. Both singular trees and tree clumps are visible within the Bing Aerial photographs. Tree cover was recorded as follows: 0- No trees were present, 1- A singular tree within the area, 2 -Scattered tree cover and 3 -Full cover within the grid square.

(2) Soil type was determined based on the EPA map of Irish Soil Information Systems (2014) (Figure 7) and (3) slope was calculated using rise/run methodology from SRTM elevation maps (2021). As a lack of tree regeneration can often be attributed to the (4) presence of controlled burning practises in an area, factors associated with this were explored. For example, the presence of housing or improved agricultural land on the hill above a grid

squared area would indicate burning was unlikely to have occurred there, due to the tendency of fires to spread upwards in sloping regions. The collected data was analysed using IBM SPSS statistics software, with a multivariate general linear model (GLM) used to determine the relationship between the presence or absence of tree growth, the amount of tree growth present, and variables of soil type, slope, controlled burning and (5) elevation.

Table 3. Summary of data collected for analysis of factors determining tree growth

Data type	**Source**	**Type of data**
Tree presence/absence	Bing aerial map, Corine land cover map (2018)	Categorical
Soil type	EPA soil information systems (2014)	Categorical
Slope	SRTM elevation map (2021)	Continuous
Housing/improved agricultural land presence/absence	Bing aerial map	Categorical
Elevation	SRTM elevation map (2021)	Continuous

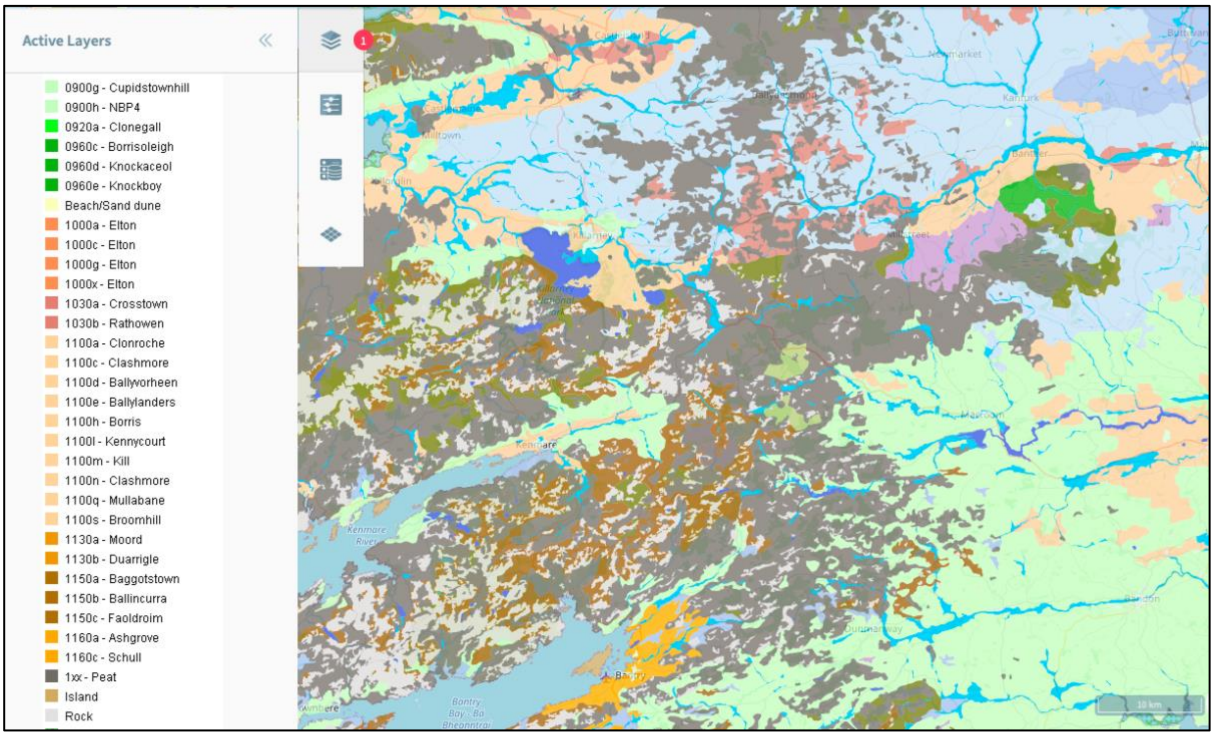

Figure 7. Soil map of Ireland (EPA SIS National Soils, 2014).

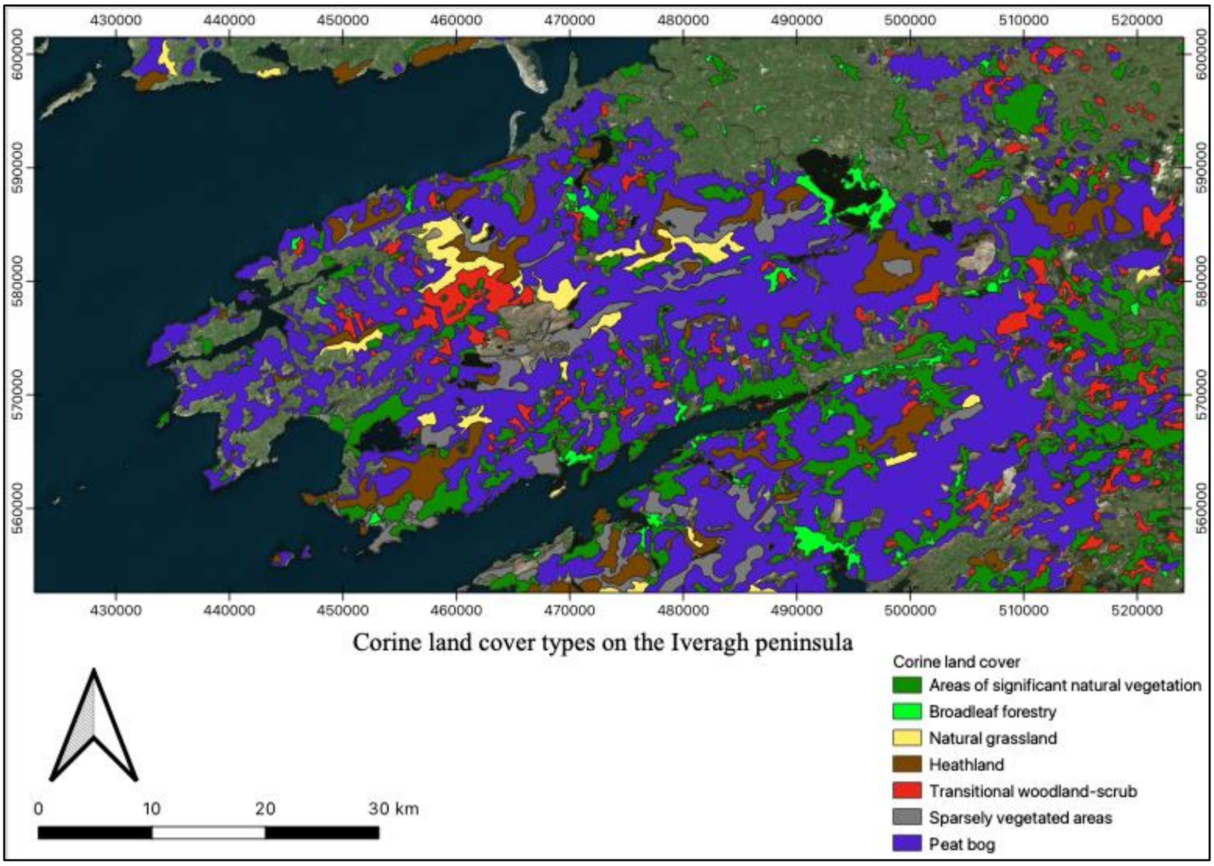

Figure 8. Corine land cover types on the Iveragh peninsula (Corine, 2018).

3.4 Current vegetative composition of the Irish uplands

Thin soils and exposed rock are commonplace in the Iveragh uplands (Figure 9) although some areas do show signs of vegetative regeneration, where increased tree cover and a greater diversity of plant species is observed (Figure 10). First edition OSI maps from the mid 19th century show areas of deciduous woodland (Figure 11), which represent either natural deciduous woodland growth (or re-growth) or deciduous woodland planted in the late 18th century or early 19th century by large estate landowners to enhance game hunting and/or as visual landscape enhancement.

Figure 9. Typical landscape in the Irish uplands

Figure 10. Tree regrowth shown in the red circle, near Kenmare Road

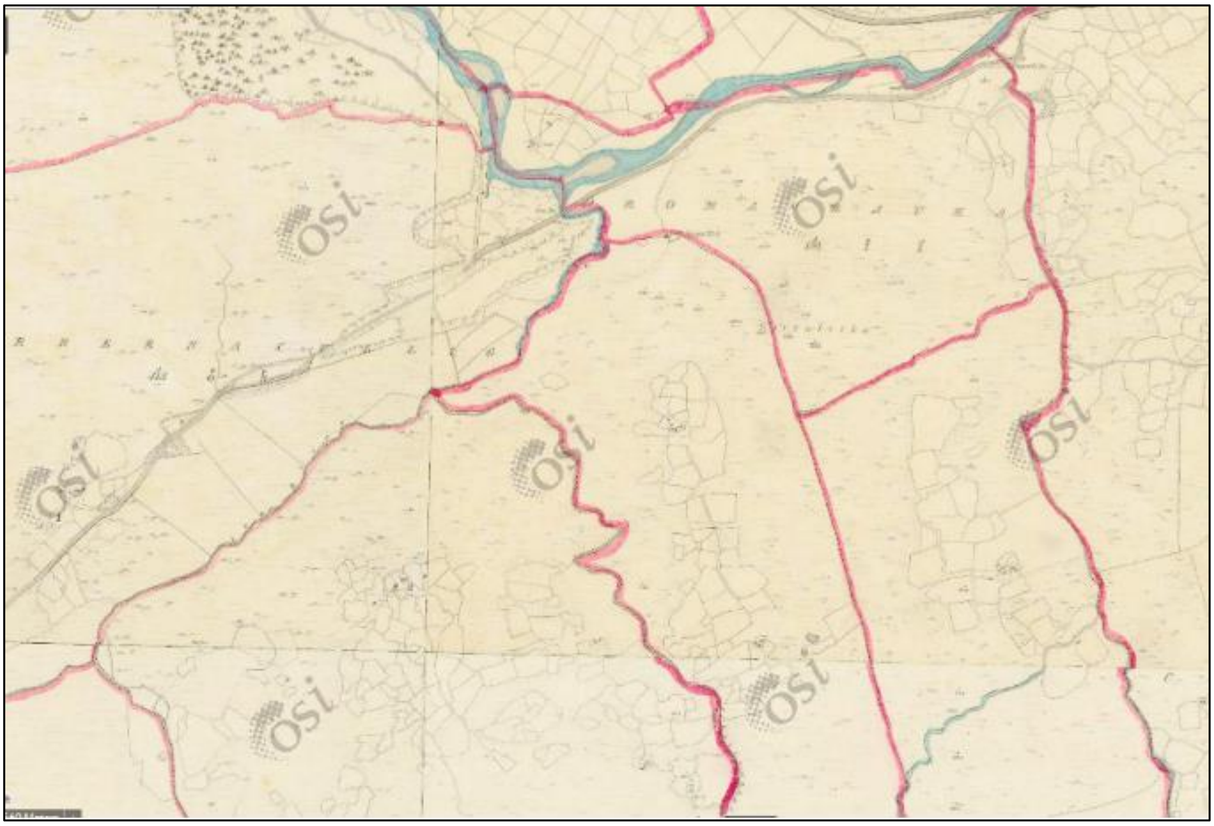

Figure 11. First edition Ordinance Survey map indicating areas of regrowth near Kenmare Road.

3.5 Lake Island sampling sites

Eight lake islands were surveyed on the Iveragh and Beara peninsulas in county Kerry (Figure 12). These islands were present across six lakes, with three islands being surveyed within Cloonee lough. Islands were chosen for this study based on the historic and current presence of deciduous woodland and ease of accessibility. Figure 13 shows the location of the islands within each of the lakes and highlights the difference in vegetation types between the mainland and islands.

The studied islands ranged in size, with the smallest at 17 metres in length (present on Barfinnihy lough), and the largest at 195 metres in length (present on Cloonee lough).

The ground level floral species of mainland areas adjacent to islands was sampled. Due to the close proximity of each island within Cloonee lake to each other and to the mainland, only one quadrat of vegetative composition was taken on the mainland adjacent.

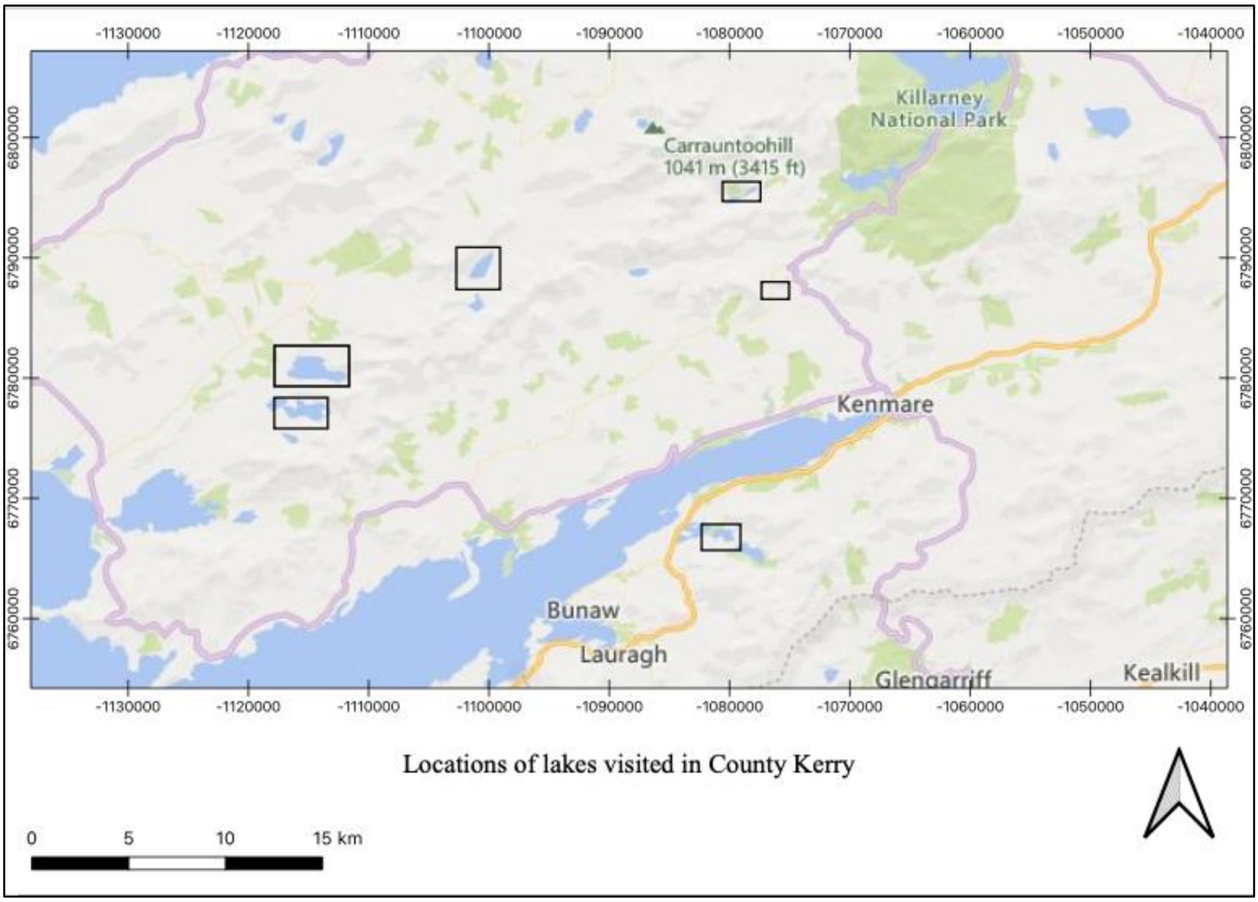

Figure 12. Map indicating the location of each of the lakes in which studied islands are present.

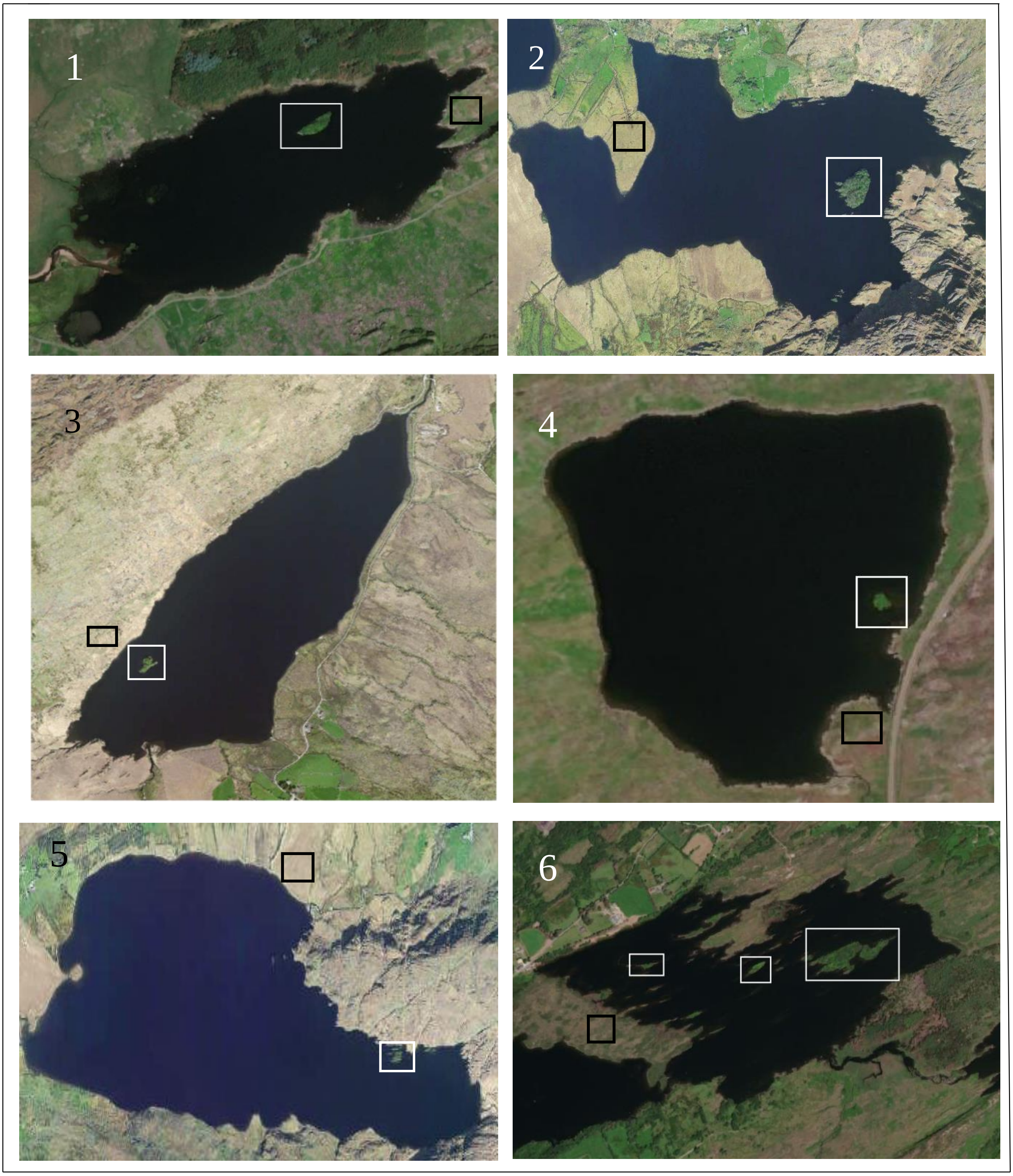

Figure 13. Aerial photographs indicating the locations of islands sampled within lakes and mainland areas sampled adjacent; 1-Cummeenduff lough, 2- Cloonaghlin lough, 3- Cloon lough, 4- Barfinnihy Lough, 5- Derriana lough, 6- Cloonee lough.

3.6 Sampling methods

Island sites were surveyed using 2x2 metre temporary quadrats, along a belt transect, using the methods outlined by Spracklen *et al.* (2013). Using a retractable tape measure, each 2x2 area was measured and subsequently marked out using white fencing stakes. In the case of the island within Cloonaghlin Lough, 4x4 metre quadrats were used as tree and vegetation cover was significantly sparser and more spread out than on previously sampled islands. Thus, larger quadrats allowed for more representative samples to be taken, as more a greater area was encapsulated within the samples.

Within each quadrat, the percentage cover of each species of ground level flora was estimated to the nearest %, and the tree species present were noted. The circumference at chest height and the overall height of each tree was recorded to the nearest metre within the quadrats. If any part of a tree's trunk was within the quadrat, all parts of the tree were counted. Any tree with two or more stems had each stem treated as a separate tree, with measurements of height and circumference at chest height taken for each stem, as per methods outlined by Zhou *et al.* 2007.

Individual 10x10 metre quadrats were taken at each mainland site, based on recommendations of minimum quadrat size for grassland vegetation sampling by Yavitt (1979). Areas were chosen based on proximity to islands, accessibility, and the presence of sufficient vegetation for sampling; areas containing large amounts of bare rock were not considered useful for further analysis, as they could not be used to provide an estimation of carbon sequestration for soils or vegetation. The different species present within each quadrat taken at mainland sites were noted, and percentage cover of each species of ground level flora was estimated.

Soil samples were taken from all islands, and adjacent mainland locations, except that within Cloon lough. Soil samples were taken using a long-bladed peat-cutting spade to cut and remove a column of soil 20cm x 15cm x 15cm. Each soil column was placed intact into a large plastic bag *in situ*. Samples were subsequently placed in cold storage (2-5 ^{o}C), within 24 hours of field sampling, until samples were analysed in the laboratory. Soil samples were visually described and photographed for comparison between mainland and island sites. In the laboratory, to analyse the carbon content of soil at different depths, samples of soil were taken at 5cm intervals down the column to a depth of 15cm, using a sharp knife to slice through the centre of the samples and separate them, as per methods outlined by Finzi *et al.*

(1998). One gram of soil from each layer was weighed out in square tin foil containers of dimensions 3.5cm(H) x10cm(W) x 12.6cm(L). All large, visible detrital and vegetative contents were removed from soil samples to prevent the introduction of inaccuracies in water content readings. One gram of soil from each layer was placed in a drying oven at 80^{o}C for 24 hours, based on recommendations by O'Kelly (2005) for accurate measurement of water content in organic soils. The temperature of 80^{o}C was chosen as oxidation and a subsequent overestimation of soil water content at temperatures greater than 85^{o}C has been noted by O'Kelly (2004). Samples were re-weighed after 23 hours in the drying oven, and again after 24 hours to determine if there was a change in mass between the two measurements. As the measurements remained the same between weighing's, it was concluded that the samples had reached equilibrium water content. After weighing, water content was expressed as a percentage of the original pre-drying weight. Dried samples were put into pre-weighed crucibles and placed in a furnace at 450^{o}C for four hours, as recommended by Cambardella *et al.* (2001), to quantify the organic matter content of soil samples. A conversion factor was applied, using the assumption that organic matter contains 58% organic carbon (Bianchi *et al.* 2008; Lunt, 1931). Using the Van Bemmelen factor, the organic matter of each soil sample was divided by 1.72.

3.7 Data analysis

The amount of carbon sequestered per tree was determined using methods outlined by the Government of Wales (2013), whereby tree circumference was converted to dry weight in kilograms, with half of the dry weight estimated to equal the amount of carbon stored. The well-documented strong positive correlation between diameter at breast height and tree height (Sumida *et al.* 2013; Dey *et al.* 2021), and subsequently the correlation between circumference and tree height, allows circumference to provide an accurate measure of biomass. Carbon storage was calculated for each tree sampled and averaged for each species on the individual islands. The number of trees sampled on each island was determined, and based on the total area sampled per island, the number of trees that would be present across one hectare was calculated. Total tree carbon for the total sample area was calculated and extrapolated to one hectare.

The carbon sequestration potential of ground level flora was also estimated, based on calculations in reviewed literature. The carbon sequestration potential of both heather, *Calluna vulgaris*, and bracken, *Pteridium aquilinum*, were determined to be two tonnes per hectare, in areas where these species were the sole vegetation type (Milne & Brown, 1997). The carbon sequestration potential of lightly sheep grazed *Molinia caerulea*, was 5.01 tonnes per hectare, in the absence of other vegetation species (Smith *et al.* 2014). Due to the lack of literature surrounding carbon sequestration potential of individual plant species, for all other ground flora species present across the islands, a carbon sequestration rate of 50% of total biomass was assumed, based on the IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (2003). Total biomass was estimated for each species present within quadrats, based on approximate height of vegetation and percentage ground cover. The biomass of a 1m x 1m area of each species was estimated, with values extrapolated from this to determine the average biomass of each species on the islands. Ground level flora which constituted an average of less than 5% cover across each island or mainland quadrat were not included in carbon sequestration analysis as their contribution was likely to be negligible.

3.8 Predicting future tree growth in the uplands

The same 49x25km area on the Iveragh peninsula in which a GIS survey was conducted, was visually examined in terms of the extent and distribution of purple moor grass and broad leaf woodland, using the CORINE land cover map. The percentage cover of woodland and *Molinia* grassland was calculated across the given area of 1225km^2. The current carbon sequestration potential for this area was based on the woodland species composition and carbon content found on the lake islands. From this calculation of carbon sequestration levels for the 49x25km area, current carbon sequestration potential was extrapolated for the whole of the Irish uplands, based on a range of hypothetical scenarios of levels of future regrowth. These hypothetical scenarios included 5%, 10%, 30% and 50% future woodland re-growth, with the area and subsequent carbon sequestration increase calculated for each scenario. This range of scenarios were used to provide a realistic indicator of how much tree growth might regenerate over time.

The same area of land was then used to predict where future tree growth might occur across the uplands, based on factors previously established to influence tree growth. The CORINE land cover map was overlaid on a Bing aerial map within QGIS, and areas shown in CORINE to contain broadleaf woodland were examined to determine if new woodland growth might radiate from them within the next 20 or 40 years. The species assumed to colonise new areas first is birch, as this is a fast growing, pioneer species (Hynynen *et al.* 2010), that colonises all soil types (Helliwell & Harrison, 1979). Soil type was not included amongst the limiting factors for tree growth, due to the ability of birch to colonise regardless of soil quality (Miles, 1981). Birch trees tend to begin flowering within their 5-10 years of life, with irregular volumes of seeds each year (Atkinson, 1992). Factors explored were the presence of houses on the hill above (indicating that controlled burning is likely absent), slope and elevation. Birch seeds tend to fall within 50 metres of a significant seed source (Atkinson, 1992); however, seedlings are observed colonising up to 250 metres from the nearest seed source. Thus, any near-future woodland regrowth is likely to occur no greater than 250 metres from the nearest appreciable clump of trees. Polygons of future regrowth were drawn to reflect this, with an extent no greater than 250 metres from the closest seed source. A time period of 20 years to reach this distance was chosen, with sufficient birch trees unlikely to reach the full distance in just 10 years.

The presence or absence of houses on the hill above grid squares is a significant factor in determining where and how many trees will grow. Inhabitants residing above these grid squares greatly increases the chance of woodland regeneration, due to the absence of controlled burning on the lower slopes. The tendency of fire to travel upwards reduces the likelihood of controlled burning occurring in areas where inhabitants are living above livestock grazing areas. Therefore, the presence of houses above grid squares is a positive influence on tree regrowth and thus is considered within this model in conjunction with other significant factors which may influence natural regeneration, such as cessation of grazing due to a removal of livestock.

Chapter 4

4. Results

4.1 Drone and aerial imagery comparison

Visual comparisons between drone photographs and Bing Aerial imagery determined that in the case of all five sites, drone footage was markedly clearer than the online source, although largely similar levels of tree cover were present in both images of the same sites (Figure 14-18). The percentage tree cover was determined for each site, from aerial imagery and subsequently from drone photographs (Figure 19). These were compared using a t-test assuming equal variances, and it was determined there was no significant difference between the tree cover present in Bing Aerial photographs, and those taken with a drone (P= 0.86) (Table 4). Therefore, aerial photographs are determined to be an accurate way of estimating tree cover.

Table 4. Summary of t-test results for tree cover in drone and aerial photographs

Degrees of freedom	P value 1 tailed	P value 2 tailed
8	0.43	0.86

Figure 14. Site A; visual comparison between photograph from Bing Aerial (left) and footage from a drone (right).

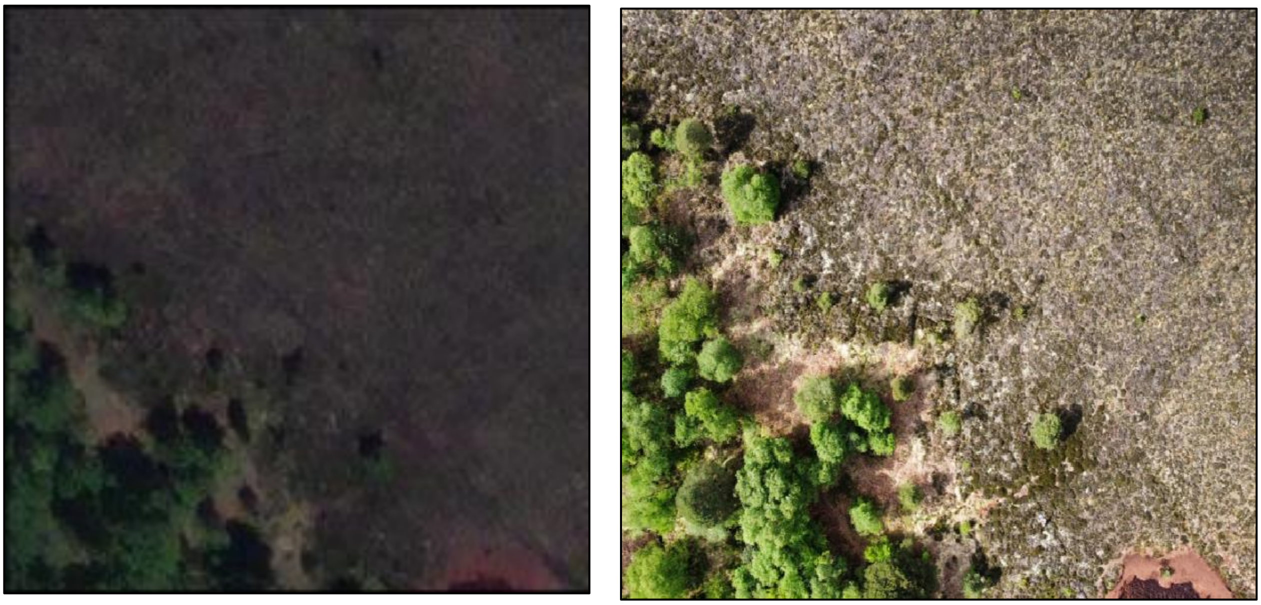

Figure 15. Site B; Bing Aerial (left) and drone footage (right).

Figure 16. Site C; Bing Aerial (left) and drone footage (right).

Figure 17. Site D; Bing Aerial (left) and drone footage (right).

Figure 18. Site E; Bing Aerial (left) and drone footage (right).

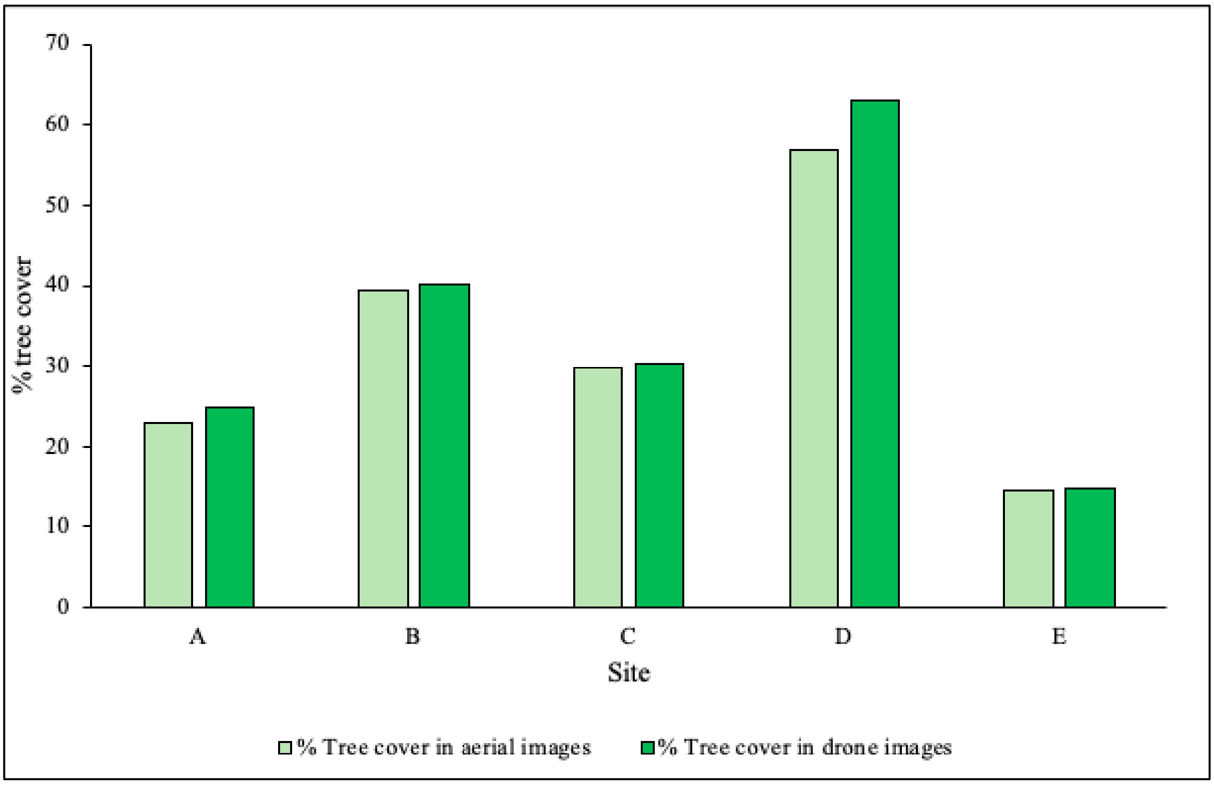

Figure 19. Comparison between the percentage tree cover present in aerial photographs and photographs taken with a drone

4.2 GIS Survey

Of the one hundred grid squares sampled, 71 contained trees, and 29 did not, with the number of grid squares containing each specified volume of trees summarised in table 5. Multivariate general linear models suggested that elevation (p<0.001), soil type (p<0.001), slope (p=0.009), the presence of houses on the hill above (p=0.024), and proximity to seed source (p<0.001) were all statistically significant factors in terms of the presence or absence of tree growth, (Table 6). A strong negative correlation (r=-0.613) was noted between the presence or absence of trees and elevation, indicating that as elevation increases, the likelihood of trees being present decreases (Table 7).

There was a weak positive correlation (r=0.242) observed between the presence or absence of trees in a grid square, and the presence or absence of houses on the hill above.

Soil type was a statistically significant factor (p=0.009) in terms of tree presence or absence. Of the 71 grid squares containing trees, 57 were on shallow reasonable drained mineral soil derived from mainly acidic parent materials, 10 were on poorly drained mineral soils with peaty topsoil derived from mainly acidic parent materials, 3 were on mountain blanket bog and 1 was on deep well-drained mineral soil, derived from mainly acidic parent materials. Of the remaining 29 grid squares that did not contain tree growth, 27 were on shallow reasonable drained mineral soil derived from mainly acidic parent materials, and 2 were on mountain blanket peat. Soil type was a statistically significant factor ($p=0.009$) in terms of tree presence or absence.

A strong negative correlation ($r= -0.721$) was observed between the presence or absence of trees and proximity to an appreciable tree clump, in this case defined as three or more trees.

Table 5. Number of grid squares within GIS sample area containing different volumes of trees

Tree amounts	**Number of grid squares**
No trees	29
One tree	13
Scattered trees	55
Full cover	3
Total	100

Table 6. Results reproduced from general linear model, with the presence/absence of trees as the dependent variable

Variable	**Degrees of freedom**	**P value**
Elevation	13	<0.001
Soil type	1	<0.001
Slope	15	0.009
Presence of houses above	1	0.024
Proximity to seed source	87	<0.001

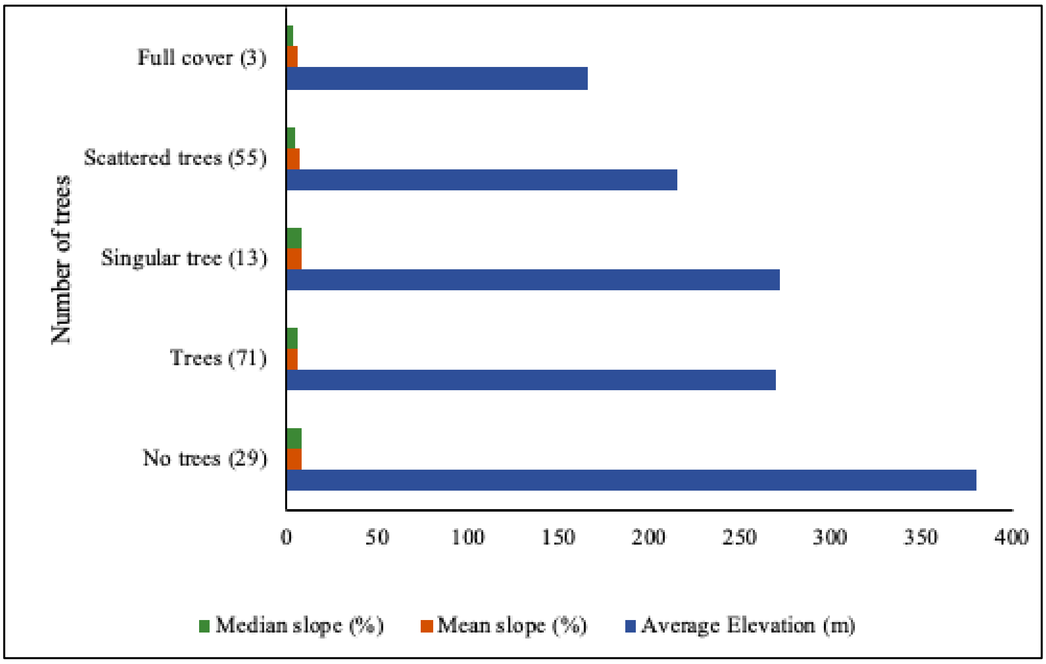

Figure 20. Relationship between number of trees, elevation, and slope

Multivariate linear models found that soil type (p=0.070), elevation (p=0.002), slope (p=0.014), the presence of houses on the hill above (p=0.040), and proximity to seed source (p<0.001) were statistically significant factors in terms of the amount of tree growth present (Table 7).

A strong negative correlation (r=0.634) was observed between the number of trees present and elevation.

There was a weak, negative correlation (r= -0.344) between the number of trees present in an area and the presence or absence of houses on the hill above.

Of the 13 grid squares containing a singular tree, 8 of these were on shallow reasonably drained mineral soil derived from mainly acidic parent materials, 1 was on mountain blanket peat and 4 were on poorly drained mineral soils with peaty topsoil derived from mainly acidic parent materials. Of the 55 grid squares containing sparse tree cover, 47 were on shallow reasonable drained mineral soil derived from mainly acidic parent materials, 1 was on deep well-drained mineral soil, derived from mainly acidic parent materials, 2 were on mountain blanket peat and 5 were on poorly drained mineral soils with peaty topsoil derived from mainly acidic parent materials. Of the three grid squares containing full tree cover, 2 were on shallow reasonable drained mineral soil derived from mainly acidic parent materials and 1 was on poorly drained mineral soils with peaty topsoil derived from mainly acidic parent materials. There is a weak positive correlation (r=0.328), between the number of trees present and soil type, however, this correlation likely stems from the dominance of shallow mineral soil across the sample area.

A strong negative correlation (r= -0.713) was noted between the number of trees present and the distance to an appreciable tree clump, with increasing numbers of trees present, as distance to a seed source decreases.

Table 8 gives an overview of factors influencing tree growth present within each grid square, and notes current presence or absence of tree cover, along with quantities of trees present in each plot, while table 9 gives a summary of these factors.

Table 7. Results reproduced from general linear model, with the quantity of trees as the dependent variable

Variable	Degrees of freedom	P value
Elevation	13	0.002
Slope	15	0.014
Soil type	1	0.070
Presence of houses above	1	0.040
Proximity to seed source	87	<0.001

Table 8. Tree occurrence and factors influencing tree growth across the one hundred randomly selected grid squares within QGIS. Tree presence/absence (1=yes, 2=no), Number of trees (0=none, 1= one tree, 2=scattered, 3=full cover), soil type (1= shallow, reasonably drained mineral soil derived from mainly acidic parent materials, 2= deep well-drained mineral soil, derived from mainly acidic parent materials, 3= mountain blanket peat, 4= Poorly drained mineral soils with peaty topsoil derived from mainly acidic parent materials).

Plot number	Trees presence/absence	Number of trees	Soil type	Elevation (M)	Proximity to tree clump (m)	Houses on hill above	Slope (%)
494	1	2	1	200	183	1	12
886	1	2	1	200	373	0	6
403	1	2	1	300	543	0	21
22	1	2	1	300	278	0	8
442	1	2	1	100	365	0	12
546	1	1	4	200	636	0	10
508	1	1	4	300	409	0	15
312	1	1	3	300	566	0	7
947	1	2	1	100	358	1	2
852	1	2	2	200	70	1	2

317	1	2	1	300	331	0	6
1132	1	2	1	20	117	1	1
268	1	2	1	450	507	0	14
320	1	2	1	300	218	0	2
457	0	0	3	500	1954	0	5
788	0	0	1	400	1001	0	9
905	1	2	1	350	811	0	12
703	0	0	1	400	638	0	7
648	0	0	3	600	1288	0	2
837	0	0	1	300	1571	0	7
845	0	0	1	300	1038	0	5
1178	1	2	1	100	30	0	6
655	1	1	1	500	937	0	8
736	1	2	3	200	510	0	7
500	0	0	1	500	1547	0	16
1101	0	0	1	400	1500	0	10
809	0	0	1	400	1232	0	11
398	1	2	1	200	94	1	5
748	1	2	1	300	443	0	15
197	1	1	1	200	676	0	4
1157	1	2	1	200	101	0	6
984	1	2	4	150	0	0	7
933	1	3	4	150	0	1	4
300	1	2	4	100	133	1	0.5
605	1	2	1	400	445	0	20
103	1	1	4	170	306	0	3
4	0	0	1	420	1783	0	4
54	0	0	1	300	2053	0	8
358	0	0	1	400	951	0	10
1040	1	2	1	100	680	0	3
1051	1	2	1	300	760	1	11
491	1	2	1	260	70	0	18

20	1	2	3	450	220	1	3
407	1	1	1	270	528	0	13
613	1	2	1	250	300	0	3
62	1	1	1	200	780	0	5
796	1	2	1	220	715	0	4
442	0	0	1	300	625	0	9
494	1	2	1	100	0	0	5
63	0	0	1	200	442	0	7
759	1	2	1	170	125	1	2
69	1	2	1	400	1138	1	3
640	1	2	1	200	0	0	6
737	1	2	1	150	0	1	3
151	1	2	4	100	260	0	2
1108	1	2	1	200	664	0	4
14	1	1	1	250	464	0	10
115	1	2	1	170	0	0	6
1111	1	2	1	150	0	0	6
847	1	2	1	100	300	1	2
763	1	2	1	250	419	1	3
263	1	2	1	250	0	0	5
932	1	3	1	100	500	0	4
662	1	2	1	130	0	0	5
792	0	0	1	470	1409	0	13
658	0	0	1	300	740	0	11
654	0	0	1	540	1330	0	6
903	1	1	1	250	970	0	5
524	1	2	1	100	175	1	0.8
261	0	0	1	420	987	0	8
164	1	2	1	250	223	0	6
501	1	1	4	350	473	0	6
264	1	2	1	300	606	0	6
106	1	2	4	150	130	0	2

840	0	0	1	300	936	0	7
260	0	0	1	400	1011	0	6
357	1	2	1	250	211	0	5
1098	1	1	1	350	694	0	9
214	1	2	1	300	630	0	4
761	0	0	1	300	786	0	7
113	1	2	1	150	521	0	4
604	0	0	1	400	807	0	9
1200	0	0	1	400	956	1	20
71	1	2	1	230	333	0	4
372	1	1	1	200	310	0	9
596	0	0	1	300	383	0	9
656	0	0	1	350	870	0	7
714	1	2	1	270	474	0	10
700	1	2	1	200	575	1	8
452	0	0	1	300	427	0	22
316	0	0	1	400	1169	0	9
513	1	2	1	200	301	0	5
13	0	0	1	350	1169	0	4
1109	1	2	1	200	251	0	9
609	1	2	4	200	299	0	5
551	1	3	1	250	137	1	9
1080	1	2	1	100	572	0	8
790	0	0	1	350	1510	0	10
611	1	2	1	250	500	0	21
955	1	2	1	200	304	0	15

Table 9. Summary table of factors influencing tree growth across the one hundred randomly selected grid squares within QGIS

Trees presence/ absence	**Number of trees**	**Soil type**	**Elevation (M)**	**Proximity to tree clump (m)**	**Slope (%)**	**Houses on hill above**
Present (1)=71	None (0) = 29	Shallow, reasonably drained mineral soil derived from mainly acidic parent materials (1) = 84	0-50= 1	0-500= 52	0-5=39	Yes (1)= 8
			51-100= 11			
	One tree (1) =13	Deep well-drained mineral soil, derived from mainly acidic parent materials (2) = 1	101-150= 7	501-1000= 31	6-10=42	
			151-200= 21			
			201-250=11			
Absent(2)=29	Scattered (2) = 55	Mountain blanket peat (3) = 5	251-300= 22	1001-1500= 11	11-15=12	No (0)= 82
			301-350= 6			
			351-400= 11			
	Full cover (3) = 3	Poorly drained mineral soils with peaty topsoil derived from mainly acidic parent materials (4) = 10	401-450= 4			
			451-500= 4	1501-2000= 5	16-20= 4	
			501-550= 1			
			551-600=1	2001-2500= 1	21-25= 3	

4.3 Comparisons between mainland and island vegetation

The landscape surrounding the lakes containing the islands investigated was largely dominated by sheep-grazed rough grassland, in turn dominated by purple moorgrass, *Molinia caerulea*. In marked contrast, the islands in the lakes were all without exception dominated by dense woodland vegetation (Figure 21). This was true even for islands separated by a few (10-100m) metres from the mainland.

Figure 21. Island in Barfinnihy Lough. Photo was taken from the shoreline, approximately 50 metres from the island. A clear contrast is evident between the high-density woody island vegetation and the low grassy mainland vegetation.

Mainland sites and islands differed greatly in vegetative composition despite their proximity (Tables 10,11). Trees were not present in any of the mainland quadrats, while ground level flora showed significant differences in species present.

Tree cover on the island at Cloon lough was dominated by holly, *Ilex aquifolium,* and large, mature downy birch trees, *Betula pubescens*. Ivy, *Hedera helix*, was recorded in 18 of the 20 plots sampled, with an average ground cover of 70%, while bramble, *Rubus fruticosus* was found in small amounts across 16 plots. Woodrush, *Luzula sylvatica*, was also dominant, with an average cover of 56%. There was no overlap between the species found on the island at Cloon lough, and species recorded on the adjacent mainland. Wetland species dominated on the mainland, with purple moor grass, *Molinia caerulea*, and sharp flower rushes, *Juncus acutiflorus*, observed in the quadrat. Small amounts of bog pimpernel, *Anagallis tenella*, were also found, along with 50% cover of moss growing under the grasses.

Tree cover at the island on Cummenduff lough was of the same composition as that found at Cloon lough, with holly once again being the dominant species. The seven birch trees observed were mature, with an average height of 9 metres. Invasive rhododendron, *Rhododendron ponticum*, was observed on both of these islands, but it was noted that regeneration was poor, with no saplings or seedlings recorded. Bracken, *Pteridium*, woodrush and *Vaccinium* sp. occupied the most ground cover at Cummeenduff, at 24.6%, 59.7% and 29.5% respectively. Honeysuckle, *Lonicera periclymenum* and ivy were present in small percentages in every plot, while bare ground was observed in two plots under rhododendron cover.

Mainland ground cover at Cummeenduff was, like Cloon, dominated by purple moor grass, with 80% cover recorded. Heather, *Calluna vulgaris* and gorse, *Ulex europaeus*, were absent from Cloon, but were present at Cummeenduff.

The island at Barfinnihy lough had just three tree species present within plots, with holly once again observed as the dominant species. Two rowans, *Sorbus* and yews, *Taxus* were observed, with both species averaging over three metres tall. Ground level flora was more diverse, with eight species recorded within the sampling plots. Of these, *Vaccinium* and woodrush were the most diverse, at an average of 62.1% and 32% ground cover respectively. Bracken was present in small percentages, and was not a dominant species on this island, in comparison to the site at Cummeenduff. Saxifrages, *Saxifraga* and wood sorrels, *Oxalis acetosella*, were not observed on previously recorded islands, but were recorded in 4 and 5 plots respectively on the island at Barfinnihy. Mainland cover at this site consisted of three species; purple moor grass, sweet vernal grass, *Anthoxanthum odoratum*, and sharp flower rushes. As with previous sites, purple moor grass was the dominant species.

Woodland cover at the first island on Cloonee lough consisted of just two species; seven strawberry trees, *Arbutus* were recorded, along with six holly trees. Ground cover consisted of five species, of which bracken and woodrush were dominant. Ivy and honeysuckle were observed in thirteen and seventeen sampling plots receptively, each averaging less than 2% ground cover.

The second island on Cloonee lough also contained just two tree species within sampling plots, with twelve holly trees and seventeen rowans recorded. Both species had an average height of less than three metres. Similar ground cover composition was observed to the first island on this lake, with woodrush, bracken and *Vaccinium* being the dominant ground level species, while honeysuckle, bramble and heather occupied 1% ground cover each.

The third island on Cloonee lough showed more diversity in woodland species. Three guelder rose, *Viburnum opulus*, a singular crab apple, *Malus* and one sycamore, *Acer pseudoplatanus*, were observed on the North side of the island. Willow trees, *Salix caprea,* were not sampled on any of the previous islands, but three were recorded on this island. Holly and rowan were recorded most frequently, and eight birch trees of an average height of 7.6 metres were observed in sampling plots. Royal fern, *Osmunda regalis* and bracken were the two most dominant ground level species. Honeysuckle was observed in much higher quantities on this island, compared to those previously sampled, with an average ground cover of 28.8% recorded. A number of species on this island were not found on any of the other sampled islands, including meadowsweet, *Filipendula ulmaria*, and marsh St. John's wort, *Hypericum virginicum*.

The mainland site adjacent to the three islands on Cloonee lough contained no overlap in species composition to any of the islands. Purple moor grass was dominant, as with all previous mainland sites. Heather, sharp flower rush and sweet vernal grass occupied 20%, 15% and 10% ground cover respectively within the sampling area. 5% cover of bog pimpernel and bog asphodel *Narthecium ossifragum*, were observed.

The island at Cloonaghlin lough had four tree species recorded within sampling plots; holly, rowan, birch and a singular beech tree, *Fagus sylvatica*. Holly was the dominant species, as observed on three of the previous islands. No bracken was observed on this island, with woodrush and ivy found to be the dominant species present, at 67.5% and 40.6% cover respectively. The mainland at Cloonaghlin lough showed an absence of purple moor grass, unlike previous plots in which it was the dominant species. Instead compact rush, *Juncus conglomeratus*, was the most frequently observed species at 60% ground cover. Yorkshire fog, *Holcus lanatus* and white clover, *Trifolium repens* were each recorded at this sampling site, with 10% cover each.

The island at Derriana lough has rowan and rhododendron as the most dominant tree species, with 33 rowan and 35 rhododendron trees recorded. One beech and one birch were recorded, along with 19 holly trees. Of all sampled islands, yew was most frequent at Derriana, with ten trees recorded. Bare ground made up an average of 80% ground cover in the plots in which it was observed, while the dominant species recorded were moss and *Vaccinium*, at 68.9% and 59.5% respectively. Bracken and woodrush were present, but not in the large amounts that had been observed on previous islands. The adjacent mainland was dominated by moss and purple moor grass cover, at 80% and 60% respectively. Bog pimpernels were present, but sparsely distributed. Perennial ryegrass, *Lolium perenn* was not observed at other mainland sites, but 15% cover of this species was observed at Derriana (Table 10).

Table 10. Summary of average percentage cover of each understorey species present within quadrats on both island and mainland sites

Vegetation species		Cloon		Barfinnihy		Cummeenduff		Cloonaghlin		Derriana		Cloonee			
Common name	**Scientific name**	**Island**	**Main land**	**Island**	**Main land**	**Island**	**Main land**	**Island**	**Main land**	**Island**	**Main land**	**Island 1**	**Island 2**	**Island 3**	**Main land**
Woodrush	*Luzula sylvatica*	56	0	32	0	59.7	0	67.5	0	7.5	0	68.5	50.2	14	0
Bramble	*Rubus fruticosus*	4	0	0	0	0	0	1	0	0	0	0	1	0	0
Ivy	*Hedera helix*	70	0	3.9	0	10.6	0	40.6	0	3.1	0	1.6	1	0	0
Mountain wood fern	*Dryopteris campyloptera*	15	0	5	0	0	0	1.4	0	1	0	0	0	1	0
Honeysuckle	*Lonicera periclymenum*	2	0	3.2	0	3.8	0	5	0	1	0	1.9	2.8	5	0
Bracken	*Pteridium*	0	0	13.75	0	24.6	0	0	0	14.5	0	53.5	37.9	0	0
Bare ground		30	0	0	0	50	0	0	0	80	0	0	0	0	0
Vaccinium sp.	*Vaccinium*	0	0	62.1	0	29.5	0	0	0	59.5	0	14.6	71.2	0	0
Royal fern	*Osmunda regalis*	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Saxifrage	*Saxifraga*	0	0	12.75	0	0	0	0	0	0	0	0	0	0	0
Wood sorrel	*Oxalis acetosella*	0	0	18	0	0	0	1.8	0	0	0	0	0	0	0
Heather	*Calluna vulgaris*	0	0	0	0	0	20	0	0	10.5	0	0	1	0	20
Meadowsweet	*Filipendula ulmaria*	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Moss	*Bryophyta*	0	50	0	0	0	0	0	20	68.9	80	0	0	0	0
Marsh St. John's wort	*Hypericum virginicum.*	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Bog pimpernel	*Anagallis tenella*	0	5	0	0	0	0	0	0	0	1	0	0	0	0
Purple moor grass	*Molinia caerula*	0	60	0	70	0	80	0	0	0	60	0	0	0	65
Sweet vernal grass	*Anthoxanthum odoratum*	0	10	0	20	0	0	0	20	0	0	0	0	0	10
Sharp flowered rush	*Juncus acutiflorus*	0	10	0	20	0	10	0	0	0	50	0	0	0	15
Gorse	*Ulex europaeus*	0	0	0	0	0	30	0	0	0	0	0	0	0	0
Lesser spearwort	*Ranunculus flammula*	0	0	0	0	0	5	0	0	0	5	0	0	0	0
Bog myrtle	*Myrica gale*	0	0	0	0	0	0	0	0	0	0	0	0	0	5
Bog asphodel	*Narthecium ossifragum*	0	0	0	0	0	0	0	0	0	0	0	0	0	5
Compact rush	*Juncus conglomeratus*	0	0	0	0	0	0	0	60	0	0	0	0	0	0
Yorkshire fog	*Holcus lanatus*	0	0	0	0	0	0	0	10	0	0	0	0	0	0
White clover	*Trifolium repens*	0	0	0	0	0	0	0	10	0	0	0	0	0	0
Perennial rye grass	*Lolium perenn*	0	0	0	0	0	0	0	0	0	15	0	0	0	0

Table 11. Summary of average number of each tree species present within quadrats on both island and mainland sites.

Vegetation species		Cloon		Barfinnihy		Cummeenduff		Clonaghlin		Derriana		Cloonee			
Common name	**Scientific name**	**Island**	**Main land**	**Island**	**Main land**	**Island**	**Main land**	**Island**	**Main land**	**Island**	**Main land**	**Island 1**	**Island 2**	**Island 3**	**Main land**
Rowan	*Sorbus aucuparia*	2	0	2	0	7	0	2	0	33	0	0	17	14	0
Yew	*Taxus baccata*	0	0	2	0	0	0	0	0	10	0	0	0	0	0
Downy Birch	*Betula pubescens*	10	0	0	0	7	0	8	0	1	0	0	0	8	0
Willow	*Salix caprea*	0	0	0	0	0	0	0	0	0	0	0	0	3	0
Rhododendron	*Rhododendron ponticum*	2	0	0	0	10	0	0	0	35	0	0	0	0	0
Holly	*Ilex aquifolium*	21	0	20	0	29	0	19	0	19	0	6	12	12	0
Strawberry tree	*Arbutus unedo*	0	0	0	0	0	0	0	0	0	0	7	0	0	0
Guelder rose	*Viburnum opulus*	0	0	0	0	0	0	0	0	0	0	0	0	3	0
Beech	*Fagus sylvatica*	0	0	0	0	0	0	1	0	1	0	0	0	0	0
Sycamore	*Acer pseudoplatanus*	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Crab apple	*Malus*	0	0	0	0	0	0	0	0	0	0	0	0	1	0

A summary of average circumference at breast height for individual tree species on each island is presented in table 12. At Cloon, birch had the greater circumference, at 97.8cm, while juvenile rowan and rhododendron had an average of 2cm circumference. Rowan sampled at Barfinnihy were more mature than those sampled at Cloon, with a greater average cbh of 18.5cm. Holly was broadly similar in size across Cloon, Barfinnihy and Cummeenduff, ranging from 11-20cm circumference. Holly trees at Cloonaghlin were of greater average cbh, with an average of 37.3cm. Cloonaghlin had several large beech trees, with a circumference of 140cm recorded. There was little overlap between the three islands at Cloonee lake, with rowan of 8cm cbh recorded on island two and 20cm cbh on island three. Holly circumference also varied between the three sites, ranging from 16cm cbh on island two, to 31.5m cbh on island one. Seven strawberry trees of circumference 51cm were recorded on island one, but were not sampled on any other island. A singular crab apple tree was observed on island three at Cloonee, with a cbh of 50cm. Yew trees recorded at Derriana had an average cbh 10cm less than those observed at Barfinnihy, at 26cm. Beech recorded at Derriana were also significantly smaller than those observed elsewhere, at 50cm cbh.

A summary of average height for individual tree species on each island is present in table 13. The tallest observed trees on Cloon were birch, at 14 metres tall, with rhododendron reaching only 50cm on average. Holly trees average approximately 2.5 metres tall at Cloon, Barfinnihy and Cummeenduff, however, grew to almost double this at Cloonaghlin. Rowan, while only averaging one metre tall at Cloon, was recorded at over 3.5 metres tall both at Barfinnihy and Cummeenduff, and was double this at Cloonaghlin. Beech of 12 metres height were recorded at Cloonaghlin, compared to just 6 metres at Derriana. Tall birch trees were commonly observed, with 9 metres recorded at Cummeenduff, and 10 metres at Derriana. Both sycamore and crab apple were only recorded once, on the third island at Cloonee, with each tree reaching 4 metres. Holly trees generally averaged approximately 2.5 metres tall, with those at Cloonaghlin being the tallest at 4.14 metres.

Table 12. Average circumference at breast height of trees on each island

Vegetation species		**Circumference at breast height (cm)**							
Common name	**Species name**	**Cloon**	**Barfinnihy**	**Cummeenduff**	**Cloonaghlin**	**Cloonee island 1**	**Cloonee island 2**	**Cloonee island 3**	**Derriana**
Rowan	*Sorbus aucuparia*	2	18.5	23	55		8.8	20.1	11.6
Yew	*Taxus baccata*		36						26.7
Downy Birch	*Betula pubescens*	97.8		52.5	6.8			37.1	8
Willow	*Salix caprea*							51	
Rhododendron	*Rhododendron ponticum*	2		11					11.9
Holly	*Ilex aquifolium*	11.3	15.7	20.9	37.3	31.5	16	20	21.8
Strawberry tree	*Arbutus unedo*					51.1			
Guelder rose	*Viburum opulus*							5	
Beech	*Fagus sylvatica*				140				50
Sycamore	*Platanus occidentalis*							18	
Crab apple	*Malus*							50	

Table 13. Average height of trees on each island

Vegetation species		Height (cm)							
Common name	**Species name**	**Cloon**	**Barfinnihy**	**Cummeenduff**	**Cloonaghlin**	**Cloonee island 1**	**Cloonee island 2**	**Cloonee island 3**	**Derriana**
Rowan	*Sorbus aucuparia*	1	3.75	3.8	7.5		2.1	4.9	3.8
Yew	*Taxus baccata*		3.5						3
Downy Birch	*Betula pubescens*	14.2		9.1	11			7.6	10
Willow	*Salix caprea*							4.6	
Rhododendron	*Rhododendron ponticum*	0.5		1.8					3
Holly	*Ilex aquifolium*	2.5	2.45	2.6	4.14	3.75	2.5	2.75	3.4
Strawberry tree	*Arbutus unedo*					5.4			
Guelder rose	*Viburum opulus*							2	
Beech	*Fagus sylvatica*				12				6
Sycamore	*Platanus occidentalis*							4	
Crab apple	*Malus*							4	

4.5 Carbon sequestration of islands and mainland areas

The total carbon sequestration of both ground level flora and woodland tree growth is shown in table 14. No trees were present on any of the mainland sites, hence the carbon sequestration of woodland for these areas was 0kg per hectare. The island within Cloon lake showed the greater level of woodland carbon sequestration, at 419,350kg of carbon stored per hectare. The second island within Cloonee lake showed the lowest level of woodland carbon storage, at just 5387.5kg per hectare. The mean amount of carbon stored in ground level flora on islands was 2904kg per hectare, compared to 11,920.83kg per hectare in adjacent mainland areas. The dominant species sampled on mainland areas, *Molinia*, has high carbon sequestration potential even when lightly grazed by sheep, (5 tonnes of carbon per hectare). This species was not present in island quadrats and shows greater potential for carbon storage than any ground level flora sampled on islands. A t-test, assuming unequal variances, found a strongly significant difference between carbon stored in ground flora on islands and on mainland sites (P=0.012). The mean amount of total above ground carbon stored per hectare on islands was 119,094.25kg (Figure 22), while the median was 82,040.25kg. The mean amount of carbon stored per hectare on adjacent mainland sites was 11,920.83kg, while the median was 11,350kg. Woodland tree growth alone stored an average of 112,295kg per hectare.

Table 14. Carbon sequestered by ground vegetation and woodland at each mainland and island site.

Site	Habitat	Total area sampled (m^2)	Number of trees per hectare	Ground flora carbon sequestration/hectare (kg)	Woodland carbon sequestration/hectare (kg)
Derriana	Island	80	8080	2251.5	34,600
	Mainland	100	0	22,500	0
Cloonaghlin	Island	160	1875	3512.5	117,618
	Mainland	100	0	14,500	0
Cloonee	Island 1	68	1911	2013.24	118,947
	Island 2	80	3625	2462.5	5387.5
	Island 3	72	5833	3771	91,777
	Mainland	100	0	5075	0
Cummeenduff	Island	80	662.5	1907.5	66,625
	Mainland	100	0	11,200	0
Barfinnihy	Island	32	7500	5118.75	44,062.50
	Mainland	100	0	6750	0
Cloon	Island	80	4375	2200	419,350
	Mainland	100	0	11,500	0

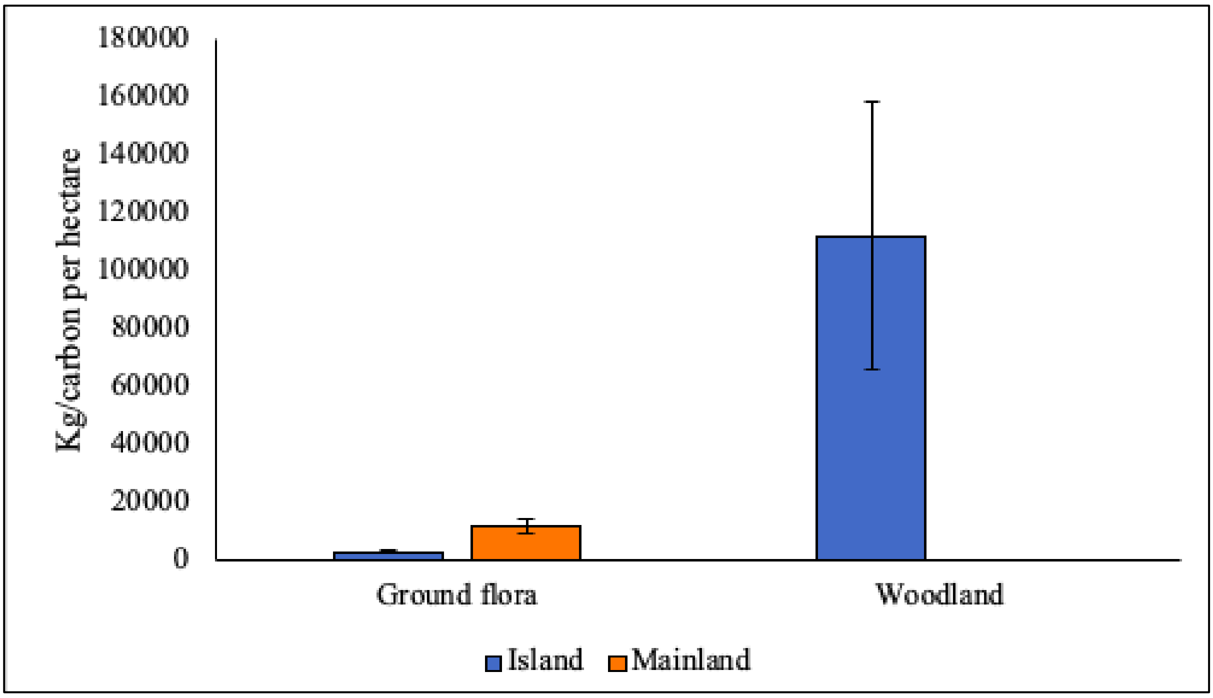

Figure 22. Average carbon storage per hectare for woodland and ground level flora at each site type, with error bars of standard deviation for each vegetation type.

4.5 Soil comparisons

Soil layers at 5cm, 10cm and 15cm within the columns were compared between mainland and island sites at each lake. At Lough Derriana, soils at 5cm were considerably more peaty and wet on the adjacent mainland (Figure 23), with the island containing less compacted soil, with more detrital material throughout the layer. This was also the case with the middle layer at 10cm (Figure 24), and the lower layer at 15cm (Figure 25), with little separation between the layers for mainland or island sites.

At Barfinnihy Lough, the island soil was considerably drier and more fibrous than that sampled at Derriana, with the soil at 5cm showing higher levels of root material than those at the same depth on the mainland. Island soil at Barfinnihy Lough was looser and drier than on the adjacent mainland, particularly in the first and second layer. Unlike the soils at Derriana Lough, there was some separation between layers, with the island soils at 15cm showing increasing levels of compaction and a less fibrous nature than the first two layers. This was also the case for the adjacent mainland site, with soil becoming increasingly dense through the layers.

At Cloonaghlin Lough, the mainland and island soils were more similar than at the previous two sites, showing a similar amount of root material in the first layer. There was little to no separation between layers, with the second and third layer showing similar water content and levels of detrital material to the layer at 5cm.

Soils on the island at Cummeenduff Lough were similar to those sampled at Barfinnihy Lough, showing the same loose texture and amount of fibrous material at 5cm deep. The mainland site showed peatier, darker soil, particularly in the first and second layer (Figure 26). However, at 15cm deep, the soils at mainland and island sites were of similar texture and water content, as the island soil had grown increasingly wet down the layers.

The first and second layers on the first island at Cloonee Lough showed little distinction between them. These were very loose soils, of low water content and high detrital content. The same three samples of mainland soils were used for comparison between islands one, two and three, due to the proximity of the islands to one another and to the mainland. Soils on the adjacent mainland contained more water and were darker in colour, however they also did not show any distinction between the first and second layer. The third layer at the first island did show a greater volume of roots than was present within the first two layers, while the third layer on the adjacent mainland showed little distinction from the previous layers.

The second island at Cloonee Lough showed very similar soils to those observed on the first island, with little distinction between layers. The soils remained very dry throughout particularly when compared to the mainland adjacent, which was compact and peaty down each layer.

The third island at Cloonee Lough had soils of similar composition to those observed on the first two islands, however, the first and second layer were slightly darker in colour and less fibrous. They showed similar amounts of root material to the soils found on the mainland but contained a lesser volume of water. The third layer, at 15cm was distinctly different from the previous two, showing a gravel-like texture and a lower volume of organic matter.

Figure 23. Comparison between soil at 5cm deep on the island within Lough Derriana (right), and the soil at 5cm deep taken from the mainland adjacent (left).

Figure 24. Comparison between soil at 10cm deep on the island within Lough Derriana (right), and the soil at 10cm deep taken from the mainland adjacent (left).

Figure 25. Comparison between soil at 15cm deep on the island within Lough Derriana (right), and the soil at 15cm deep taken from the mainland adjacent (left).

Figure 26. Comparison between soil at 10cm deep on the island at Cummeenduff Lough (right), and the soil at 10cm deep taken from the mainland adjacent (left).

4.6 Soil water content

Table 15. Average soil water content at each sampling site.

Site	Average water content (%)
Derriana island	80.3
Derriana mainland	88
Cloonaghlin island	81.3
Cloonaghlin mainland	78.3
Cloonee 1 island	66.7
Cloonee 2 island	65.3
Cloonee 3 island	63.3
Cloonee mainland	82.7
Cummeenduff island	66.3
Cummeenduff mainland	82
Barfinnihy island	75.3
Barfinnihy mainland	79

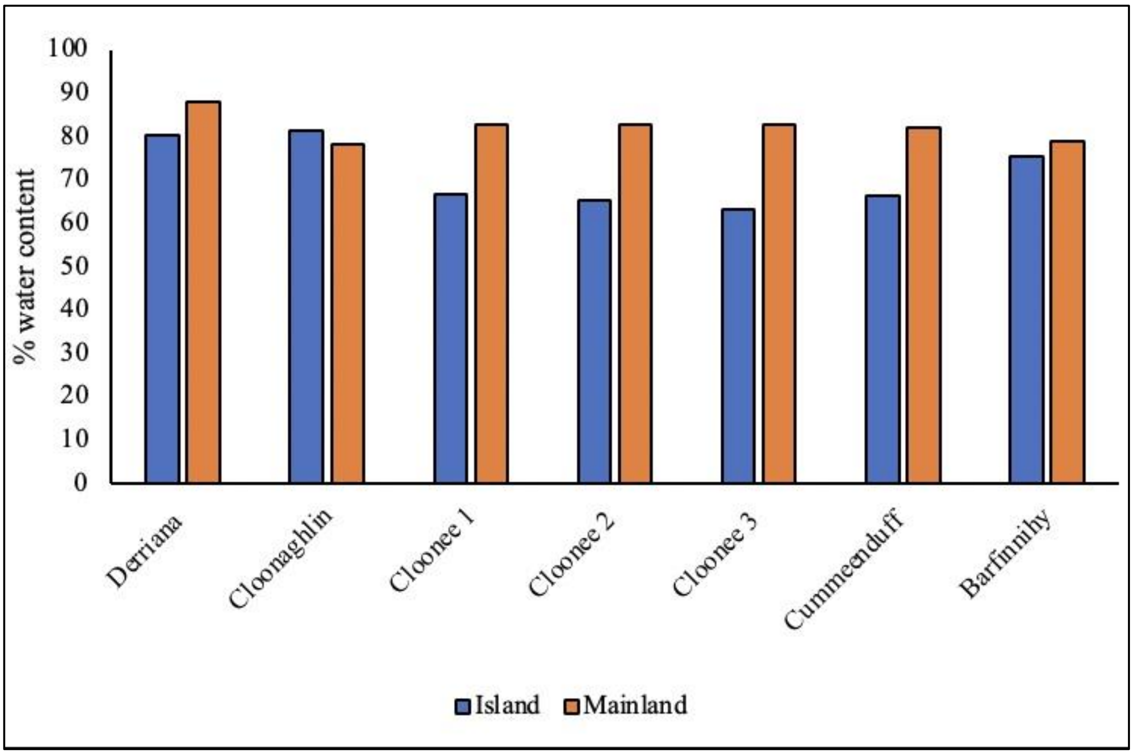

Figure 27. Comparison of percentage soil water content at each site

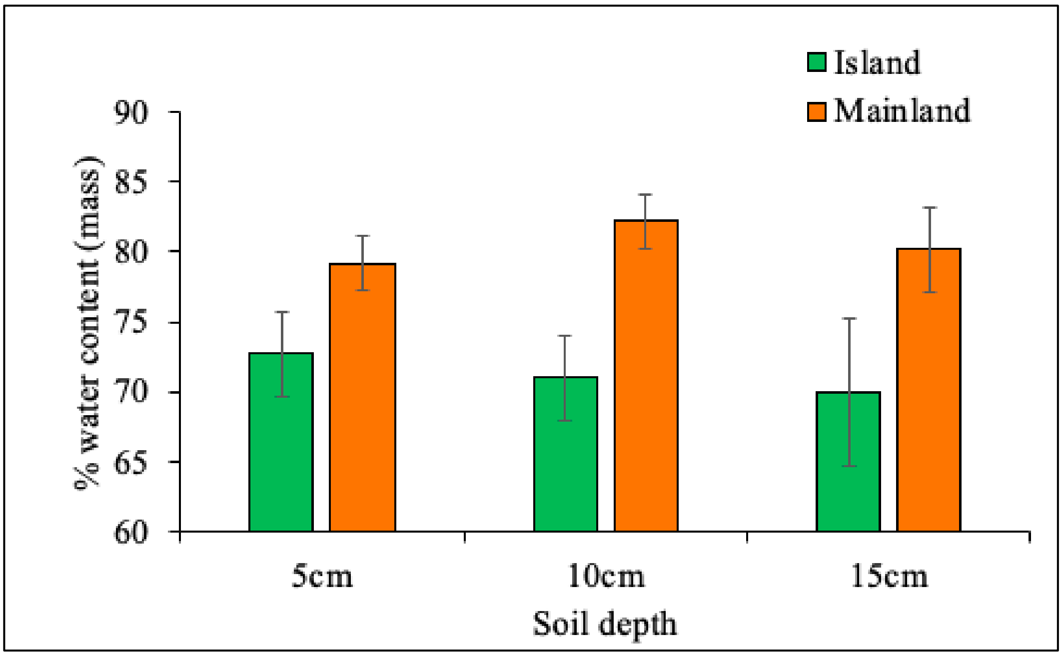

Figure 28. Comparison of average soil water content at each depth for mainland and island sites, with error bars of standard deviation for each soil depth.

The average soil water content was determined for each site (Table 15), with all islands except for the one present in Cloonaghlin Lough showing significantly lower water contents than the soils sampled on the adjacent mainland (Figure 27). The average water content across mainland sites was 82.2%, compared to an average water content of 71.2% for soil sampled on islands. Results of a t-test assuming unequal variances found there was a significant difference between the mean water content at each site (P=0.0075). Soils tended to remain consistent in water content across depths, with those on islands consistently dried than those on mainland sites, with this holding true across samples taken at 5, 10 and 15cms (Figure 28). This was also possible to determine visually, based on comparison images between the island and mainland sites, with consistently dried and looser soil observed on the islands, compared to the dark, peaty soil seen on the adjacent mainland. At Cloonaghlin Lough, soils on the island were visually similar to those on the mainland, with a similar peaty texture and water content observed during comparisons.

4.7 Soil Carbon content

Table 16. Average soil organic carbon content at each site.

Site	Soil Organic Carbon Content (%)
Derriana island	54.5
Derriana mainland	46.9
Cloonaghlin island	56.6
Cloonaghlin mainland	47.8
Cloonee 1 island	55.1
Cloonee 2 island	48.9
Cloonee 3 island	30.4
Cloonee mainland	52.8
Cummeenduff island	56.9
Cummeenduff mainland	49.4
Barfinnihy island	54.3
Barfinnihy mainland	50.1

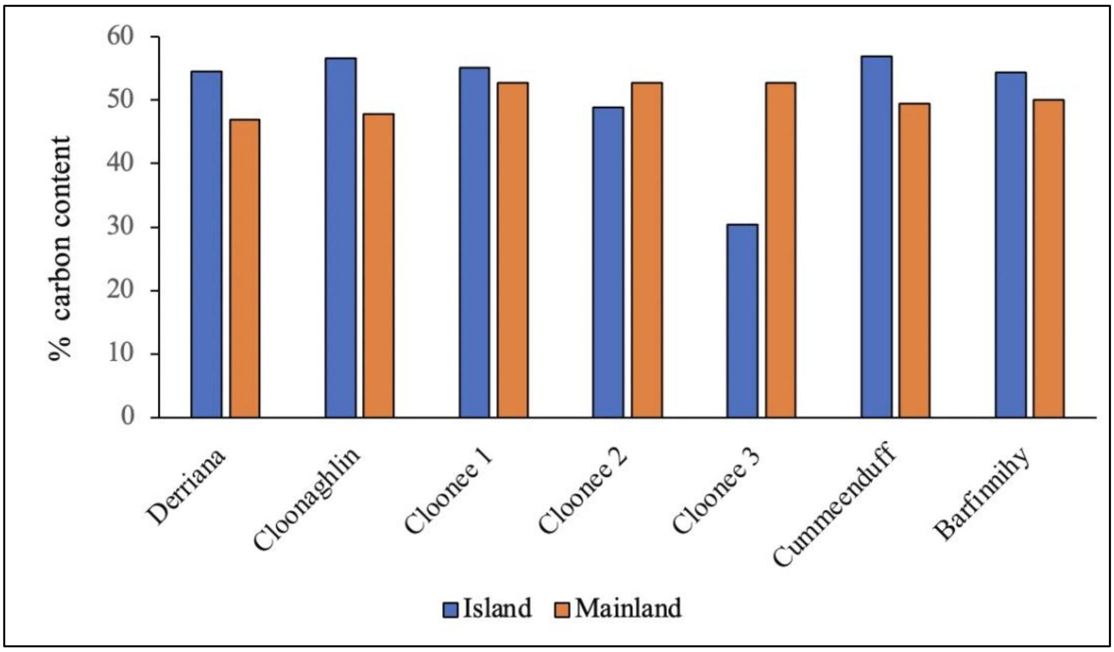

Figure 29. Comparison of percentage soil organic carbon content at each site.

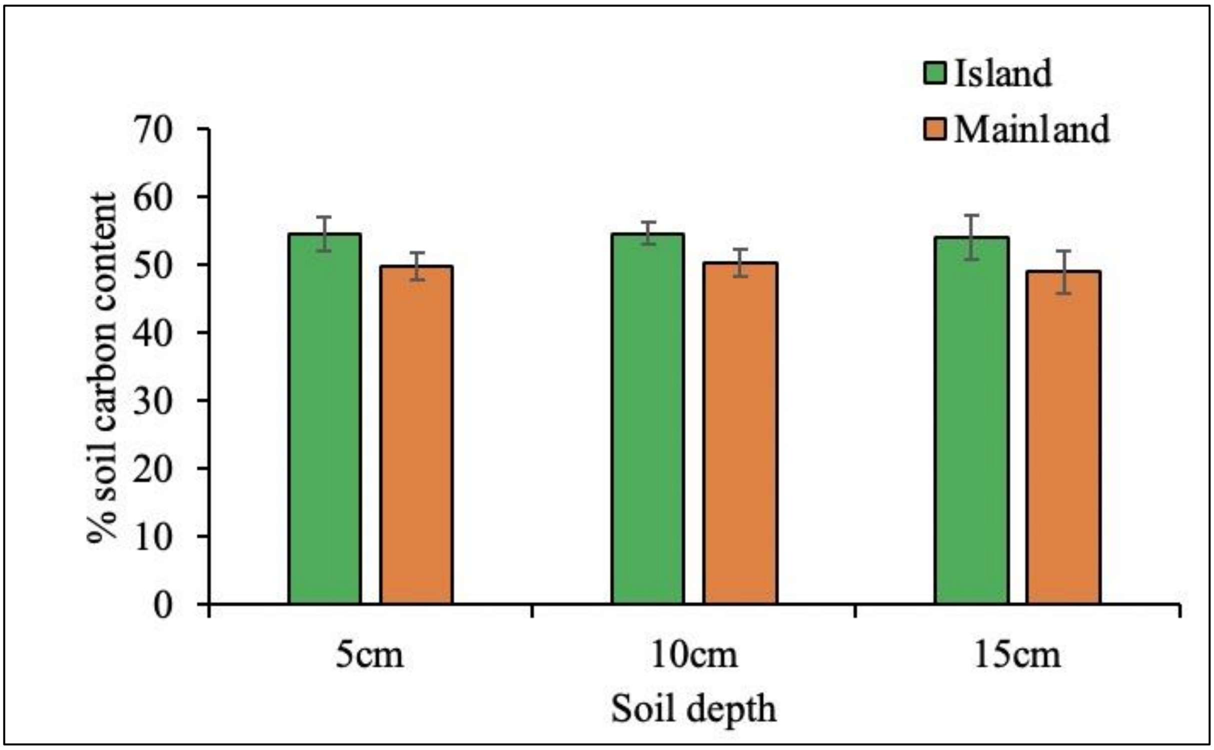

Figure 30. Comparison of average soil carbon content for mainland and island sites, with error bars of standard deviation for each soil depth.

All islands bar the second and third island sampled at Cloonee Lough showed greater levels of organic carbon than adjacent mainland sites (Table 16). The average soil organic carbon content for island soils was 50.9%, compared to the marginally lower content of 49.4% for soils sampled on the mainland. However, the outlier of 30.4% on the third island at Cloonee Lough reduces the average soil carbon content significantly for islands (Figure 29). A t-test performed to compare means found no significant difference between the two sites (P=0.87). The median value of 54.5% is a more accurate representation of soil carbon present across islands and is approximately 5% higher than the median carbon content of 49.4% on mainland sites. Similarly, to patterns in soil water content across depths, soil carbon content remained consistent throughout samples taken at 5, 10 and 15cm depth. For samples at all depths, soil organic content was greater on islands than at mainland sites (Figure 30).

4.8 Predicting carbon sequestration potential of the Irish uplands

Tree cover was determined across the Iveragh Peninsula from CORINE Land Cover maps (2018) (Figure 31), while *Molinia* and broadleaf woodland extent was determined visually from Bing aerial maps. The extent and distribution of purple moor grass and broad leaf woodland is shown in figure 32, with purple moor grass occupying a much greater extent than broadleaf woodland. Within the given area of 1225km^2, 224km^2 (22400 hectares) consisted of purple moor grass, representing 18.19% cover. 12.01km^2 (1201 hectares) was occupied by broadleaf woodland, representing 0.981% cover. These percentages can then be applied to the entire Irish uplands, to gain an estimate of approximate area currently covered by woodland and purple moor grass (Table 17).

From published literature, it was established that purple moor grass stores approximately five tonnes of carbon per hectare (Smith *et al.* 2014) and from calculations based on island vegetation, broadleaf woodland stores approximately 112 tonnes of carbon per hectare. If one assumes that woodland species composition is the same on the Iveragh peninsula as the composition found on islands, the given area can currently sequester 134,512 tonnes of carbon in native woodland cover. Purple moor grass can store an additional 112,000 tonnes of carbon across the given area, giving a total of 246,512 tonnes of carbon sequestered over an area covering 1225km^2. Despite purple moor grass occupying almost twenty times the area that broadleaf woodland covers, it sequestered 22,512 less tonnes of carbon over 1225km^2 of the Irish uplands, indicating significantly less potential for carbon storage in purple moor grass when compared to native woodland. Predictions are made for carbon sequestration rates should 5%, 10%, 30% or 50% cover of woodland regenerate within the given area of the Iveragh peninsula (Figure 33). At an increase of 50% cover, 201,768 tonnes of carbon could be sequestered in broadleaf woodland over 1801 hectares. If one assumes that the woodland cover present within this area is representative of the 10,000km^2 of the Irish uplands, we can extrapolate the potential carbon sequestration for the whole of the uplands (Table 18). If just 5% of the uplands were returned to native woodland, there would be the potential to store over 1.1 million tonnes of carbon, in the trees alone. The ground level vegetation and soil organic carbon under woodland would further increase this value.

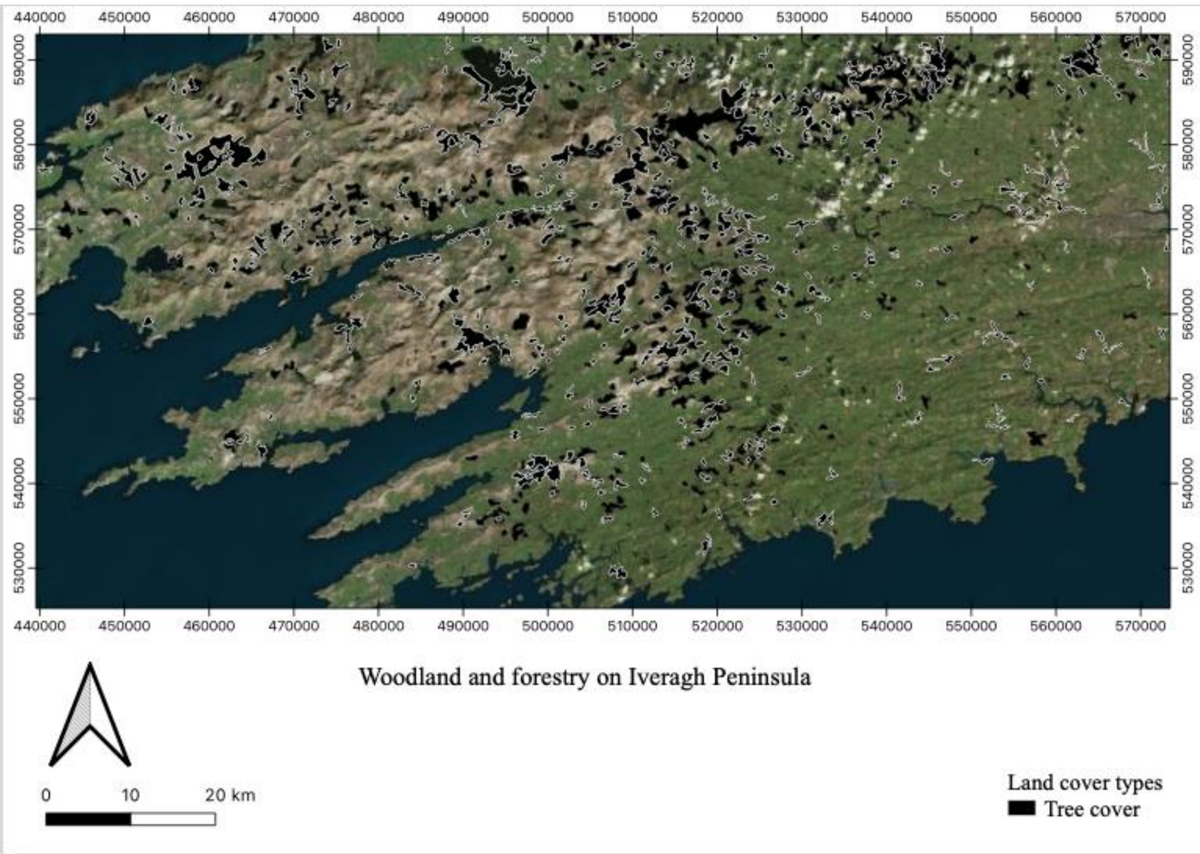

Figure 31. Tree cover across the Iveragh peninsula, based on Corine Land Cover maps (2018)

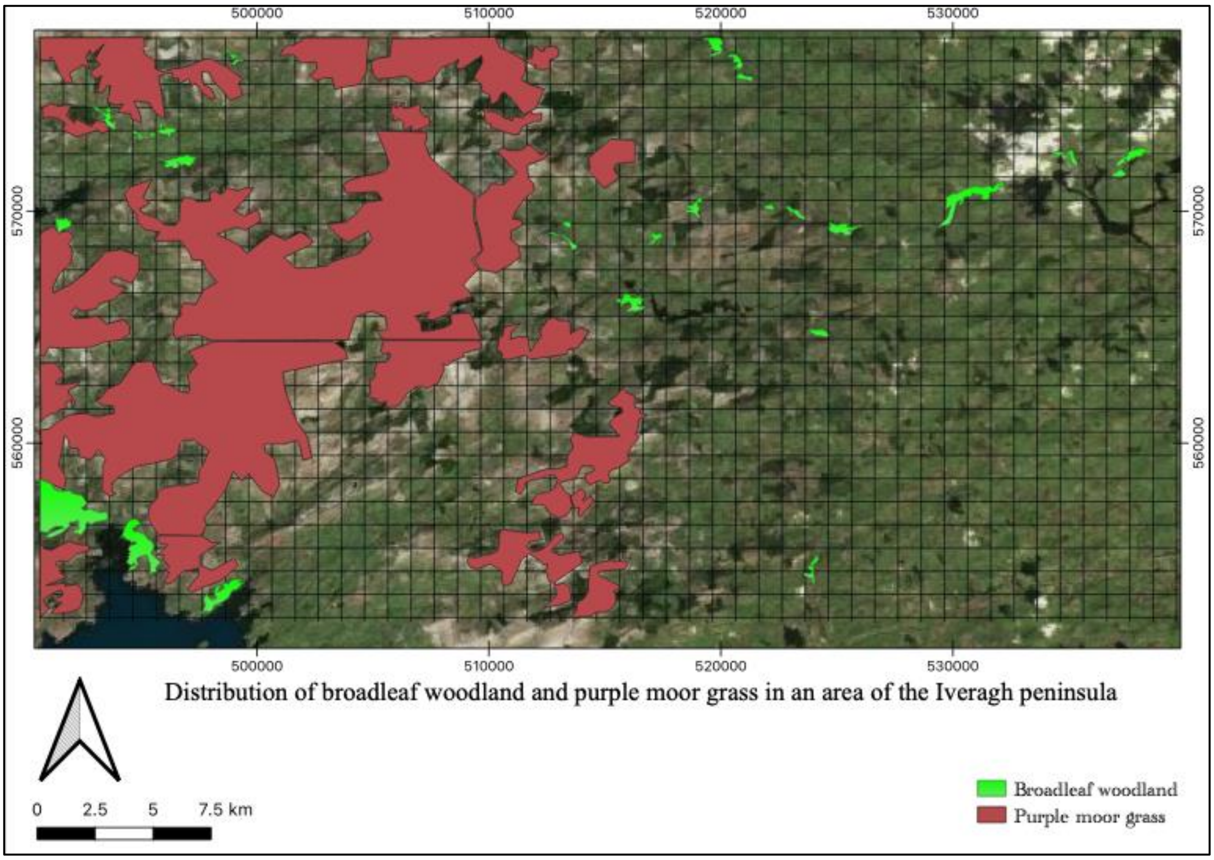

Figure 32. Distribution of broadleaf woodland and purple moor grass across a section of the Iveragh peninsula

Table 17. Current carbon sequestration potential of an area of the Iveragh peninsula

Vegetation type	Area covered within sample (hectares)	Carbon sequestration of sampling area (tonnes)
Purple moor grass	22,400	112,000
Broadleaf woodland	1201	134,512
Total	23,601	246,512

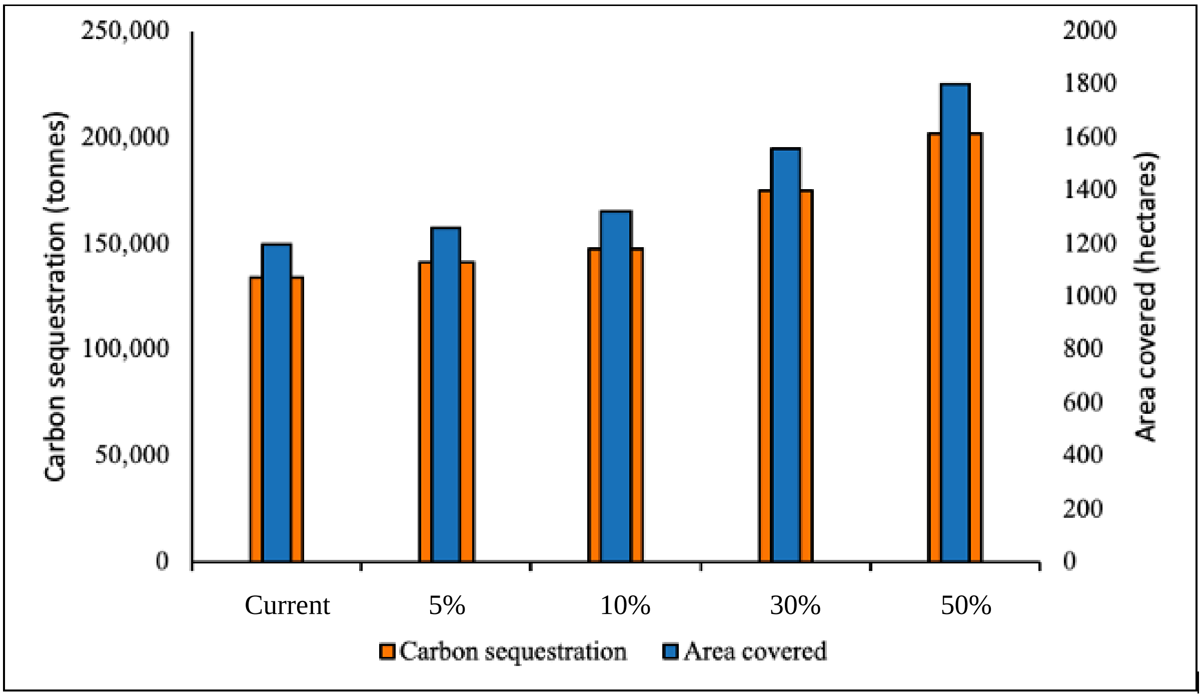

Figure 33. Carbon sequestration potential of broadleaf woodland based on current cover within a given 1225km^2 area, and sequestration rates should 5%, 10%, 30% and 50% woodland cover regenerate over time within this given area

Table 18. Carbon sequestration potential of the whole of the Irish uplands, based on scenarios of percentage regrowth of broadleaf woodland over time

	Current	5%	10%	30%	50%
Area covered (hectares)	9810	10,300.5	10,791	12,753	14,715
Carbon sequestration (tonnes)	1,098,720	1,153,656	1,208,592	1,428,336	1,648,080

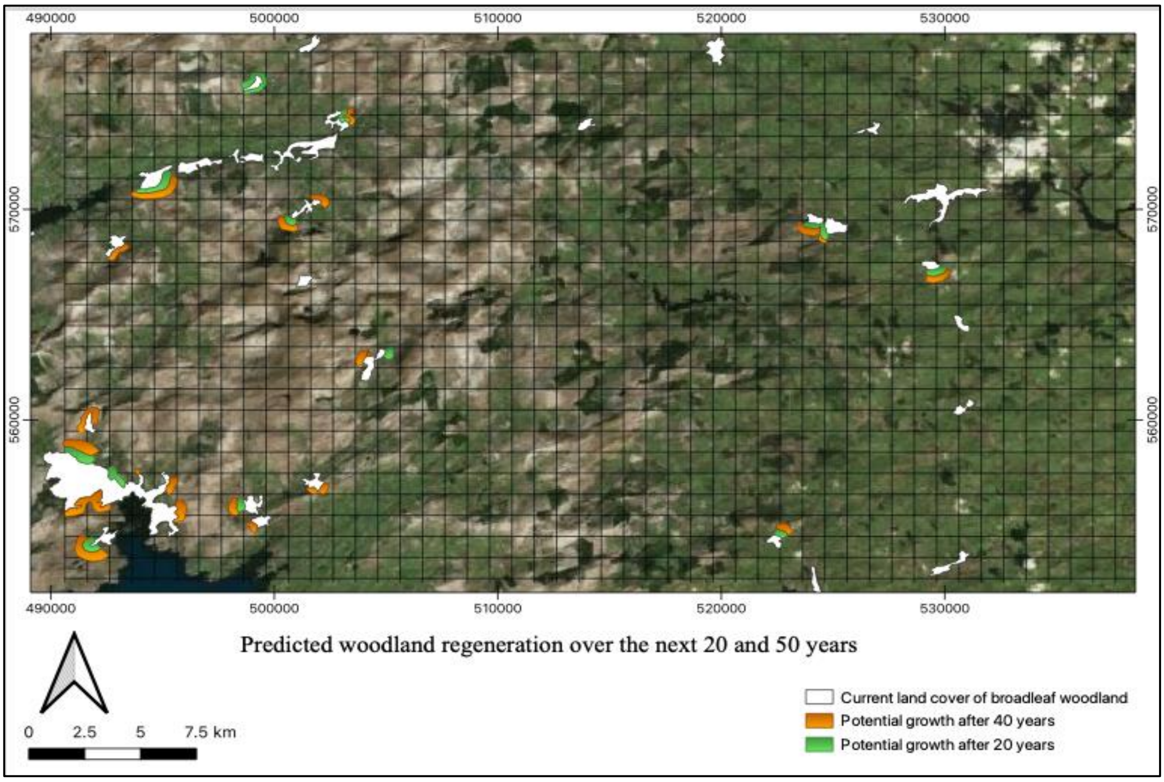

Figure 34. Map demonstrating the potential regrowth of the broadleaf woodland in a section of the Irish uplands within the next 20 years and within the next 40 years, based on the expansion of current broadleaf woodland via natural means

A predictive map of areas in which trees are likely and unlikely to regenerate over the next 20 and 40 years was produced (Figure 34), based on the results of the GIS survey of factors affecting tree growth. Soil type was not considered during this analysis, as the prevalence of shallow mineral soils on both treed and treeless areas does not indicate that soil type influences tree growth in this instance. Areas which were unlikely to have been subjected to controlled burning, due to inhabitants living on the hill above, with moderate gradient and elevation, were considered to have high potential for woodland regeneration within the next 20 years. Thus, with grazing pressure eliminated, these areas are predicted to show radiating woodland expansion a maximum of 250 metres from current trees. Subsequent regeneration from this new woodland is possible after 40 years. Some areas, with controlled burning present, and steep slopes, may take up to 40 years to show regeneration, and thus are shown on the map as such. The expansion of woodland is based on the extent of current broadleaf woodland present on the Corine land cover map.

The potential area of native woodland expansion after 20 years without grazing is approximately 373 hectares, and after 40 year is double this, at 736 hectares (Table 19). This was calculated based on the cumulative area of polygons within QGIS. With the Irish uplands covering approximately 10,000km^2, and assuming the sampling area of the Iveragh peninsula is representative of current woodland cover across the uplands, we extrapolate that within 20 years, 3049 hectares of new native woodland could regenerate naturally, and within 40 years, 6009 hectares could regenerate. This would represent 0.30% and 0.60% regrowth of native woodland across the uplands over a 20 and 40 year period respectively. Just 6000 additional hectares of woodland across the Irish uplands could sequester 371,978 tonnes of carbon in 20 years, and double that within 40 years.

Table 19. Predicted areas of new native woodland expansion over 20 and 40 years within an area of the Iveragh peninsula, and across the whole of the Irish uplands

Time period (years)	**Area within study (hectares)**	**Area across whole Irish uplands (hectares)**	**Carbon sequestered across uplands (tonnes)**
20	373.61	3049	371,978
40	736.11	6009	673,008

4.9 Discussion

Ireland's bare upland landscapes is thought largely to have originated during the Neolithic period, when deforestation (ie conversion of forest to agricultural land) of the area began (O'Connell & Molloy, 2001). In more recent centuries, extensive grazing and burning practises have further contributed to the treeless landscape (Carroll *et al.* 2021). The result of this has been thin, mineral deficient soils (Bragg & Tallis, 2001), and coarse, grazer- and fire-tolerant vegetation across the region, which has made it difficult for vegetative succession from grassland to woodland to occur (Glaves, 2015). However, there are small patches of woodland regeneration across the uplands, particularly in places inaccessible to grazers (and burning). This indicates that, despite the lack of trees across the uplands for so many years, there is still potential to return some of the area to native woodland, should grazing and burning cease. The 19th century shift to extensive sheep farming as the predominant land use in the Irish uplands has become less sustainable in recent years, with agricultural incomes in such landscapes failing to match rising incomes in other sectors of the economy (Dillon *et al.* 2017), resulting in fewer farmers willing to exploit their landholdings as in previous decades. A similar story is unfolding in the Scottish uplands with sheep farming only viable when farm labour is unpaid, and significant increases in profit would be required to allow farmers to break even (O'Neill *et al.* 2020). This raises the question of whether subsidies should continue to be provided to the sheep farming sector, with the consistent and continued lack of profitability seen across upland sheep farms. The economic importance of sheep farming has declined in recent years. For example, in the 1970's, the sector contributed 3% to Norway's GDP, with that value being only 0.5% in 2007 (Ross *et al.* 2016). The current exodus of sheep farmers from the industry in Ireland, due to lack of income, along with an aging farmer population (O'Rourke, 2019), means that now and into the future, large areas of the uplands will likely become wholly, or partly, unexploited agriculturally. This provides a valuable opportunity for a land use shift to occur, away from sheep grazing, and towards a return to native woodland, with multiple concomitant benefits. Although this may be seen, from within the farming community, as land abandonment, with associated social opprobrium for 'giving up' on the precious land long owned by families, there is now an opportunity to proactively encourage the re-growth of natural woodland within the wider population and to discuss the issue in positive terms.

While we do not know for certain what species would dominate across the upland landscape, it has been assumed that the predominant climax vegetation across Ireland's uplands would be sessile oak (*Quercus petraea*) woodland (Cross, 2006). However, the islands sampled in county Kerry were dominated by mature holly, birch, and rowan growth, with few if any oak tress encountered. The largely undisturbed and ungrazed nature of these islands suggests they are representative of the climax vegetation that would be present across the Irish uplands, should anthropogenic influence in the form of livestock grazing be removed. There was no overlap between the species found on islands and those found on the adjacent mainland, despite some islands being within 50-100 metres of mainland sites. All islands displayed mature, native woodland growth, aside from some anomalies, such as the non-native beech trees sampled at Cloonaghlin lough and lough Derriana. These two islands were also the only islands on which mature oak trees were found, and it is presumed that these were planted by the large estate owners in the early 19th century, along with the beech trees. All the observed beech trees were uniform in age and showed no signs of natural regeneration. Therefore, despite this evidence of past planting, the islands were still taken as largely natural and undisturbed, thus still providing a representation of the species composition of the adjacent mainland under natural regeneration.

The climax woodland vegetation found on islands has the potential to provide 119 tonnes of carbon per hectare, in comparison to the current mainland *Molinia*-dominated grassland vegetation, which provides only 11.9 tonnes of carbon per hectare. This suggests that native woodland and its accompanying ground level flora will provide up to ten times the carbon sequestration potential of the current sheep grazed upland landscape. This value may be even higher, as conservative values were used when estimating the biomass of each ground level floral species. Greater accuracy could be achieved through the study of biomass and carbon sequestration of individual plant species.

Comparing photographs taken from a drone to aerial photographs of the same area, found that images taken from Bing Aerial showed a smaller percentage of tree cover than that present in drone imagery, for all sites sampled. The difference in tree cover between each set of photographs was marginal, indicating that Bing Aerial photographs were taken less recently than the drone footage, and hence there has likely been an increase in tree growth in the period between when the aerial photographs were taken, and when the drone images were taken. While it isn't known when the Bing photographs were taken, it is reasonable to assume that if the two types of photographs were taken at the same time, tree cover would be approximately the same from the two methods.

Determining if aerial drone and satellite photographs accurately represent tree cover levels is important as a ground truthing exercises upon which further research can be built. These results have demonstrated that widely-available online satellite imagery, while slightly underestimating current tree cover, gives a good representation of the percentage tree cover present in an area, to within 5% of actual levels. Predictions can be made about where trees may regenerate most rapidly, based on this, by examining their presence of absence over large scales within aerial images, in conjunction with factors such as elevation, slope, and proximity to woodland seed sources. Limitations of this research include the relatively small area over which the drone footage was collected. A more comprehensive study covering a larger area of Ireland would provide greater certainty in terms of the accuracy of aerial photographs in determining tree cover.

Analysis within QGIS was undertaken, once ground truthing had established the reliability of aerial photographs in estimating percentage tree cover. Factors of elevation, slope, proximity to seed source and the presence of houses on the hill above, all had a significant effect, not only on the presence or absence of trees in an area, but also the density of trees present.

The slowing of tree growth near the treeline is a well-known phenomenon (Paulsen *et al.* 2000), with high altitudes and colder temperatures resulting in reduced growth (Irl *et al.* 2016). However, Irelands' average elevation is just 46 metres, and the highest point at Carrauntoohil is 1100 metres (topographic-map.com, 2014), meaning the likelihood of an elevation related treeline is unlikely, with global tree lines reaching up to 4000 metres or more (Irl *et al.* 2016). The lack of tree growth at higher elevations in the Irish uplands is more likely due to centuries of overgrazing (and associated burning) on the hill by sheep, with a similar phenomenon observed in Norway by Speed *et al.* (2010), in which livestock grazing limited the treeline below its potential. In Ireland, this is most likely to occur in areas known as commonage, that are held in common ownership for livestock grazing (Van Rensburg *et al.* 2009). They generally exist on the hill above improved agricultural land and are often of poor soil quality, and inaccessible to farm machinery, and thus are used solely for intensive sheep grazing (Hynes *et al.* 2007). Extensive pollen records show uplands areas on the Beara peninsula were forested in the past, with human activity resulting in the reduction of trees (Overland & O'Connell, 2008). We can therefore assume that elevation is a factor in determining tree growth, but only indirectly, due to the farming practises which occur in these locations.

Slope was also found to be an influencing factor, with areas of a lesser gradient being more likely to contain trees, and more likely to contain a higher number of trees. This factor, like elevation, may be related to the presence of livestock grazing, with the less steep, lowland areas generally less overgrazed, and thus containing higher levels of tree growth, while the steep, upland slopes used for commonage show deficiencies in tree growth, with sheep grazing generally present here year-round. These areas of lesser slope are also more likely to be near improved farmland, and thus hedgerows which provide a valuable seed source for woodland regeneration.

Proximity to appreciable clumps of three or more trees was strongly correlated with both the presence or absence of trees, and the density of trees present. Tree clumps act as a seed source and their proximity to a given site greatly determines the likelihood of successional growth occurring and influences how many trees can grow. There is likely a relationship between factors of elevation and proximity to seed source, with regions of higher elevations containing a lower seed source due to overgrazing, and thus, containing less trees. This creates a positive feedback mechanism in which lack of trees begets lack of trees, meaning that despite some upland areas showing abandonment and greatly reduced grazing, the lack of seed source at higher elevations results in the treeless landscape that remains for many years without signs of vegetative succession (Fenton, 2008).

The presence of houses on the hill above a given area is not in itself a factor affecting the growth of trees, however, it does reduce the likelihood that routine burning has occurred within the area. Due to the nature of fires spreading upwards in sloping areas, controlled burning is not carried out where there are heavily sloping areas, and neighbouring land or buildings in close proximity (Department of Agriculture, Food & the Marine, 2021b). Thus, the absence of burning practises results in a higher chance of vegetative succession occurring. In commonage areas, routine grazing and burning has been carried out for decades, to remove rank vegetation and improve the areas for livestock grazing (Carroll *et al.* 2021). The prevalence of burning not only results in the removal of dwarf shrub species such as heather (O'Rourke & Kramm, 2009), but also increases the pervasiveness of fire tolerant species such as purple moor grass (Jacquemyn *et al.* 2005), which form rank tussocks of dead vegetation, shading out tree seedlings. The layers of dead purple moor grass are routinely burnt, creating a positive feedback mechanism of increasing dominance of this species, and burning to remove it. Thus, areas above the housing line that are used for livestock grazing, are more likely to show reduced vegetative succession as a result of burning practises.

While slope was a limiting factor in tree regeneration, with seeds less likely to spread upwards, elevation was not a limiting factor in many cases, as much of the tree growth currently observed on the Corine land cover map is in lower areas below 200 metres elevation. However, the likelihood of tree growth within the next 50 to 100 years in the bare uplands at high elevation remains low, as seeds will not reach these areas for a long time unless human intervention is provided. Assuming this sample is representative of the Irish uplands as a whole, predictive mapping indicates that less than a 1% of upland regions are likely to see natural woodland regrowth within the next forty years, should livestock grazing be removed. Approximately 2% of the Irish landscape is currently wooded with native broadleaves (Coillte, 2020), which represents 140,000 hectares of land area. While an additional 6000 hectares within forty years does not represent a large increase in woodland cover, it does contribute to a significant increase in carbon storage, with the potential to store 673,008 tonnes of carbon within a very small area of land. The high levels of carbon predicted to be stored in native woodland are closely reflected in the NPWS above ground vegetation carbon storage map (Figure 35). Darker areas closely align with the presence of current woodland habitat, indicating the enormous carbon storage potential of trees.

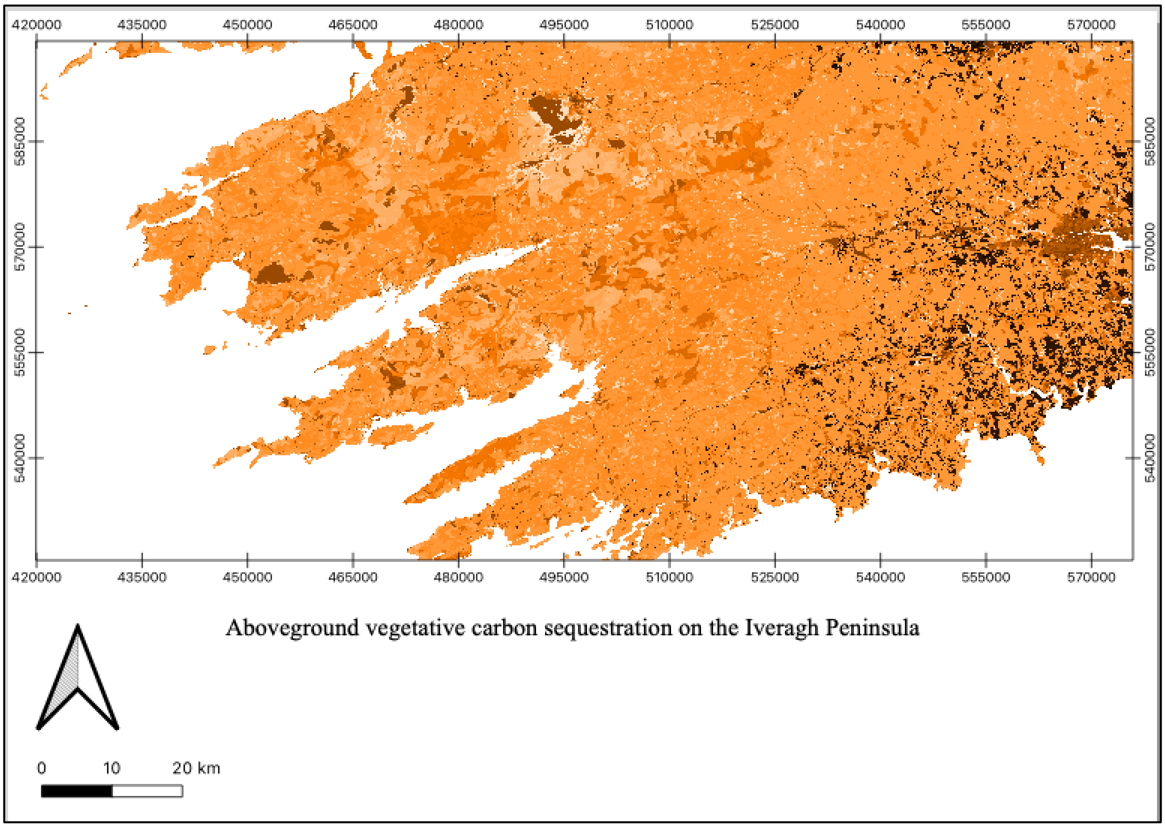

Figure 35. Aboveground vegetative carbon sequestration, with darker areas indicating high ability to store carbon (NPWS, 2017).

While a limited number of factors were explored in relation to woodland regrowth, and many more are likely to have an influence, these figures highlight the massive potential of the Irish uplands for sequestering carbon. Assuming the natural woodland that regenerates across the uplands is of the same or similar species composition to the woodland observed on islands, if only 5% woodland regeneration occurred, over 1.1 million tonnes of carbon could be sequestered, which would significantly aid Ireland in achieving its' climate targets. Other research on carbon sequestration potential often focuses on hypothetical scenarios, for example Fletcher *et al.* (2021), who calculated the carbon sequestration potential of the Scottish uplands, based on 100% tree cover. This was calculated by implementing the Native Woodland Model (NWM), to predict the potential woodland types expected under current soil and vegetation conditions. While the information provided is invaluable, this research aims to provide a realistic value for carbon sequestration over an achievable time scale.
If we can predict where native woodland is likely to grow without any human intervention, intervention planting efforts can be concentrated in other areas that are less likely to show regrowth on their own. Carrifran 'wildwood' in southern Scotland provides one of the best examples of successful intervention planting of the uplands (BordersForestTrust.org, 2021). The Scottish uplands have been subject to the same burning and grazing practises as their Irish counterparts (Adair, 2016), resulting in a greatly similar, degraded landscape.

The degraded treeless landscape is widely accepted within Ireland as the normal, if not natural, state of the uplands, with the dominant land use accepted as being one of agricultural exploitation and production. However, there are growing efforts by communities in these landscapes to 're-think' the landscape in terms of a more natural woodland-dominated vegetation community, leading to attempts to recreate 'wildwoods'. Rewilding seeks to create large scale ecosystems that can look after themselves (Walker *et al* 2018), and self-regulate (Prior& Brady, 2017). In the UK, differences in rewilding efforts have been noted between upland and lowland areas, with woodland regeneration preferred in the uplands, while lowland areas see an increase in herbivory in an effort to combat tree and scrub encroachment into areas of conservation concern (Sandom *et al.* 2019).

A Scottish example of this attempt to recreate natural woodland cover on previously grazed upland is seen in the southern Scottish borders at Carrifran. Over 640 hectares of a valley in the Moffat hills has been planted by a group of volunteers (Prior & Brady, 2017), with trees deemed native to the area, based on the British National Vegetation Classification system (Savory, 2016). The valley was purchased by the Borders Forest Trust in 2000, in order to restore it to native woodland (Savory, 2016), and since then, over half a million trees have been planted, transforming the valley from a sheep grazed landscape, into transitional, semi-mature woodland. With the ongoing land use shift in Ireland, towards abandonment of upland farms, there is the potential for a similar approach to be taken here, albeit on a smaller scale than Carrifran wildwood. The islands sampled in this study provide valuable information on the native species composition that would be present across the uplands, thus helping to determine which tree species to plant and in what proportions to plant them, should intervention planting be carried out across the region.

While expanding cover of native woodland is valuable for increasing above ground carbon sequestration, it also provides the opportunity for increased below ground carbon storage in the soil (Ostle *et al.* 2009). In this study, soil organic carbon was observed to be greater on islands than in mainland areas, indicating that degraded peaty soils store less carbon than soils under native woodland. However, consideration must be given to the possible limitations of sub-sampling at 5cm, 10cm and 15cm intervals, as this assumes the depth profile of the soils is the same across islands and mainland sampling areas. This may result in misleading water and organic carbon content calculations and should therefore be noted. Soil carbon for Ireland has been estimated by the NPWS (Figure 35), with darker areas indicating a higher potential for carbon sequestration. These darker areas correspond with the presence of peat bogs (Figure 37), indicating the high potential of peat for storage of carbon. Intact heathland and peat bog habitat may be of greater use than increased tree cover in terms of carbon storage in the soil. For example, in the UK, heathlands sequester approximately 120 Mt of carbon in the first 15cm of topsoil (Field *et al.* 2017), while peatland in Scotland, is estimated to store 4523 Mt of carbon (Payne *et al.* 2016). However, the degradation of these habitats through overgrazing leads to reductions in their ability to store carbon (Loisel & Gallego-Sala, 2022), and causes them to become a source, rather than a sink (Leifeld & Menichetti, 2018). Repairing them may be of more use for carbon storage in the soil than regeneration of woodland, with a study by Milne and Brown (1997) estimating there are far greater carbon stocks in Scottish peatlands than in Scottish forestry. Evidence is unclear as to whether the planting of trees on peatland would lead to a greater loss of carbon from the peat, than would be gained back by planting trees (Payne *et al.* 2016). Restoration of heathland often involves soil disturbance or removal, leading to the release of carbon emissions

(Matthew, 2022), with restored heathland taking many decades to reach soil carbon levels that replicate those present in intact heathland habitat (Tibbett *et al.* 2019). Similarly, re-vegetation of degraded peatlands can lead to reductions in its' carbon emissions within 2-4 years, but total regeneration may take decades (Bonn *et* al 2014). This evidence indicates, that while restoring heath and peatland habitats would be beneficial for soil carbon storage in the long term, it would take many years to achieve this. Soil carbon sequestered under woodland likely not only takes place in the top layer, but also in deeper layers, acting as a sink (Blaser *et al.* 2014), potentially indicating greater levels of below-woodland soil carbon storage potential than what has been estimated in this study. While relatively little is known about the changes in soil carbon content during woodland regeneration, it is assumed that natural regeneration is preferable as there is little disturbance of the soil, and thus less carbon is lost (Fletcher, 2021). Expanding native woodland would result in two-fold increases in carbon storage, both in the vegetation and in the soil, further strengthening the argument for tree regrowth in the Irish uplands.

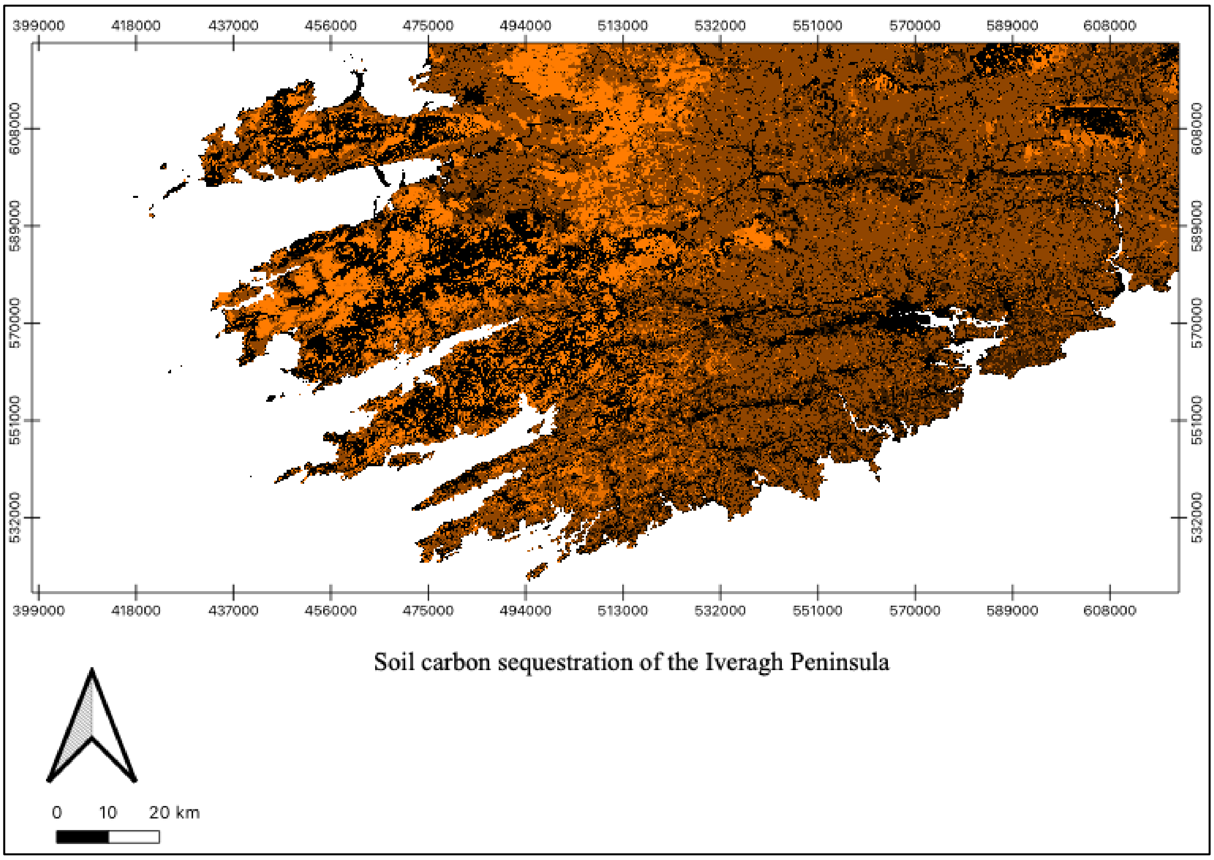

Figure 36. Soil carbon stocks in the Iveragh peninsula, with darker areas indicating higher potential for sequestration (NPWS, 2017).

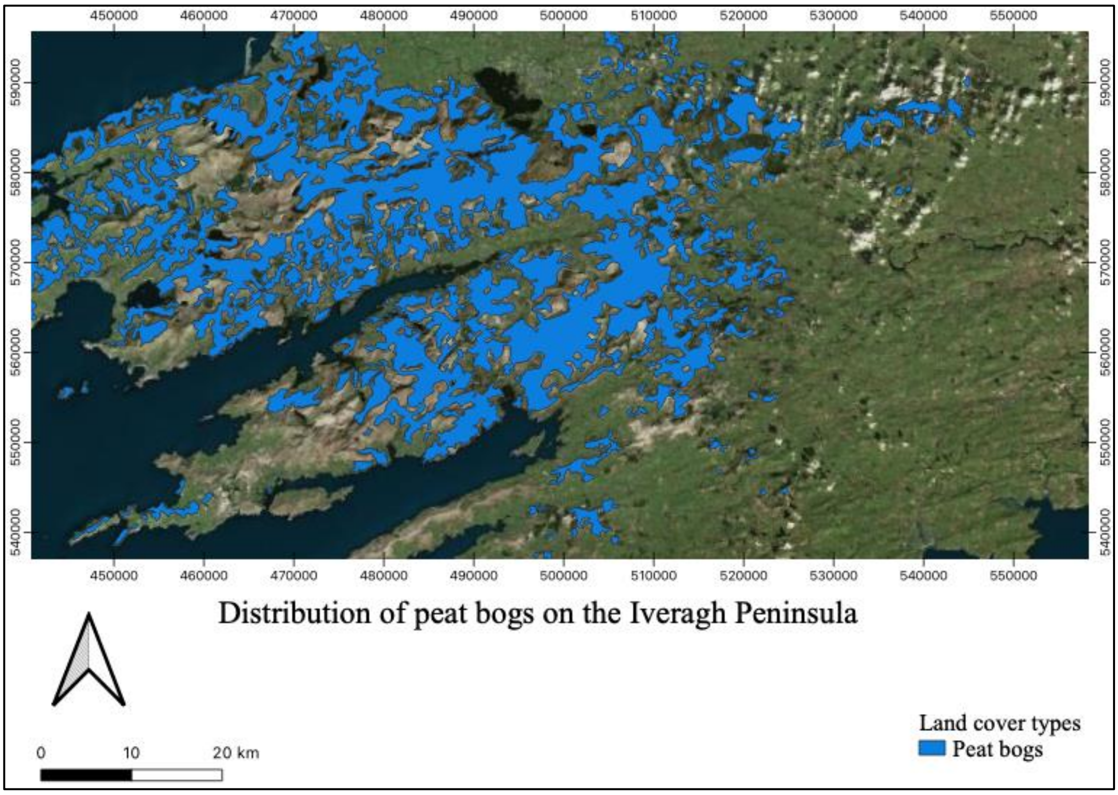

Figure 37. Distribution of peat bogs on the Iveragh peninsula, based on Corine land cover types (2018).

Soils also displayed consistent differences in water content between mainland areas and islands. This is explained by differences in vegetative composition. No tree growth was present in any of the mainland areas sampled, and the soil samples taken were heavier, wetter, and more compacted than those taken from any of the islands. This is despite the proximity of the islands to mainland areas, with the island on Barfinnihy Lough located less than fifty metres from shore. Therefore, one can infer that the differences in soil water content, both visually and during laboratory analysis, are not due to factors such as rainfall, but are instead a result of differences in vegetation. Broadleaf woodland canopies intercept 10-25% of rainfall (Confederation of Forest Industries, 2020), thus reducing the volume of water that reaches the soil. This is observed in the difference in water content between island and mainland soils, with the island soils containing approximately 10% less water than those on the mainland adjacent. Overgrazed upland areas are prone to experiencing waterlogged, saturated soils (O'Rourke & Kramm, 2009), that are unable to absorb excess water, resulting in rapid overland flow (Pattison & Lane, 2012), and thus a heightened risk of flooding. This is a growing concern, as Ireland is predicted to receive an increase in winter precipitation and streamflow, with more intense rainfall events likely to result in flooding, particularly in the southwest of the country (Steele-Dunne *et al.* 2008). Changes in land use management are critical for reducing the risk of flooding, particularly in upland areas, with few trees and highly saturated soils. An increase in woodland cover in these regions would result in reduced run-off and flood risk, with a study in the UK finding that a strip of trees can reduce flood peaks by up to 40% in upland agricultural areas (Jackson *et al.* 2008). Tree shelter belts planted on permanent pastures have been found to greatly increase the infiltration of rainfall into soil, within two to six years of planting, thus having positive impacts on soil erosion and run off rates (Carroll *et al.* 2004).

4.11 Conclusion

Sheep farming across the Irish uplands is in a precarious position, and the continued provision of subsidies to this sector is at the detriment of the range of ecosystem services uplands have the potential to provide through the restoration of native woodland. With mature native woodland and its associated ground level flora having the potential to store 119,000kg of carbon per hectare, there are clear arguments for encouraging regrowth in abandoned, unused and degraded upland regions. Soils under woodland growth also show increased carbon storage potential and contain approximately 10% less water than soils in overgrazed grassland areas. The reduced water content, and less saturated soils of woodland areas show increased ability to cope with the heavy rainfall events that are predicted to become more frequent as climate change progresses. Predicting which areas are likely to see natural regeneration if livestock grazing is removed, is a valuable tool for determining how much carbon can be sequestered over time. Realistic calculations of the amount of woodland that can regenerate, and the volume of carbon this can subsequently sequester, is necessary for understanding where Ireland can meet its' climate targets. The studies of woodland regeneration in Scotland do not provide a realistic estimate of what regrowth might occur over the short and medium term. Understanding which factors influence tree growth and thus where trees will grow, allows policy makers to concentrate intervention planting efforts in places where tree growth is unlikely to occur naturally, and therefore maximise native regrowth and carbon sequestration potential in the future.

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