THE UNIVERSITY of EDINBURGH
Global Academy of
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The Comparative Profitability of Afforestation for Carbon Sequestration versus Existing Farm Production on UK Agricultural Land

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Abstract

In response to recent agricultural land purchases by corporations and investment firms expressly for purposes of afforestation, this dissertation sets out to explore the motive behind such purchases by assessing the current state of UK carbon markets and attempting to determine the price at which it becomes more profitable to sell carbon offsets through afforestation than to produce food on UK agricultural land.

One of the key drivers of recent land purchases is found to stem from an increase in the government targeted rates of afforestation in the UK, the justification for which is partially attributed to carbon sequestration for use as emissions offsets in achieving "Net Zero" ambitions. Though regulation of the creation of carbon offset units in the UK seems robust, regulation governing the transparency of the nascent market for trading those units seems less comprehensive. This lack of transparency has created a highly speculative market, with publicly reported sale prices for *ex-ante* units ranging from £10 to £40. This variation seems to be largely driven by limits on market knowledge, and has a considerable impact on the profitability of, and incentivisation for, afforestation projects, with those few in possession of greater market knowledge able to make bolder investment decisions such as land purchases. Currently, only a small portion of total emissions are capable of being offset through carbon units in the UK, however, the IPCC has recently stated that limiting global warming to 1.5 $°C$ cannot be achieved without carbon removals, and the framework governing international trade of carbon offsets, Article 6 of the Paris Agreement, was finally agreed at COP26 in 2021. Both events suggest a near-term proliferation in both domestic and global carbon markets, with implications on farm profitability, land use change, tenant farming, and food security. Since the objective of carbon markets is to maximise carbon removals, not profit, there is a need for greater transparency in the operation of these markets to encourage competition and to ensure that opportunities can be equally realised by all.

This work finds that, although an estimate of the price at which it becomes more

profitable to grow trees than food can be made using publicly available secondary data - around £50/unit in the Scottish Highlands and £100/unit in the South of England at current farm income levels - the considerable uncertainty surrounding input variables limits confidence in these results, and it is expected that primary data would vastly improve the accuracy of the calculations.

Declaration

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# Acknowledgements

This RMarkdown document is based on the guide and example provided here:

http://rosannavanhespenresearch.wordpress.com

Alfy said it is often nice to acknowledge your supervisor…

Glossary

BECCS Bioenergy with Carbon Capture and Storage (5.2)

CCC Committee on Climate Change (1)

CCS Carbon Capture and Storage (5.2)

CDM Clean Development Mechanism (2)

COP Conference of the Parties (2)

DACCS Direct Air Carbon Capture and Storage (5.2)

NDC Nationally Determined Contribution

NUTS Nomenclature of Territorial Units for Statistics (3.2)

PIU Pending Issuance Unit (**??**)

TIFF Total Income From Farming (3.3)

WCC Woodland Carbon Code (**??**)

WCU Woodland Carbon Unit (**??**)

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1 Introduction

Achieving "Net Zero", commonly used to mean a balancing of anthropogenic carbon emissions and removals over a set period (IPCC, 2018) though lacking an internationally agreed definition (Climate Partner, 2020; Carbon Trust, 2022), is increasingly cited as an aspirational target to be met by 2050. At least 100 national governments (van Soest, den Elzen and van Vuuren, 2021), including the UK (DBEIS, 2021); 826 cities and 1,565 companies (NCI and DDEL, 2020), including 60 of the 100 largest companies in the UK (edie, 2021); industry bodies (NFU, 2020); and even a University of Edinburgh lecturer (Weston, 2021) have either set or are considering the goal of Net Zero, and obtaining the right to emit carbon by paying others to reduce or remove it, otherwise known as carbon offsetting, is proposed to be one of the key pathways to achieving it. Though 91% of countries, 79% of cities and 48% of companies fail to declare if offsets will be used in their Net Zero strategies (Hale, 2022), 308 companies, 54 cities, and 28 countries have stated they will, based on data collected by Net Zero Tracker (2022). Mark Carney's *Taskforce for Scaling Voluntary Carbon Markets* has gone further, and is calling on organisations to commit not just to becomming 'Net Zero' by 2050, but to fully neutralize all emissions on the path to 'Net Zero' through carbon reductions and removals (2021), and Working Group III of the IPCC have stated "rapid deployment of [land-based sequestration] measures is essential in all pathways staying within the limits of the... 1.5 $°C$ target" (IPCC, 2022). Offsetting is particularly consequential for the agricultural sector, both due to the difficulty of eliminating many sources of carbon emissions in the necessary time frame (e.g., methane emissions from ruminant livestock), and because of the extent of land available to the sector for carbon removal. The UK Committee on Climate Change (CCC) *Sector Summary for Agriculture and Land Use, Land Use Change and Forestry* (LULUCF) from their Sixth Carbon Budget (CCC, 2020) states that in order to approach Net Zero in the UK by 2050, rates of afforestation must reach 30,000 ha/year by 2025 (a target the government has already committed to (DEFRA, 2020), despite reaching just 29% of their 5,000 ha planting target in

2019 (Harvey, 2019)) and 50,000 ha/year by 2035. This includes the integration of trees on 10% of farmland by 2050, up from an estimated 1% in 2020 (CCC, 2020). If these targets are achieved, combined emissions from the UK's LULUCF sector could fall to 16 MtCO2e by 2050, compared to 67.4 MtCO2e in 2018; this represents positive agricultural emissions of 35 MtCO2e and removal of 19 MtCO2e through nature-based sequestration.

The NFU's Achieving NET ZERO plan (2020) also calls for increased on-farm afforestation (among other commitments) if farming is to reach net zero. It estimates agricultural GHG savings of up to 9 MtCO2e/year through on-farm carbon sequestration alone. Both of these plans (CCC, 2020; NFU, 2020) appear to assume that all emissions sequestered by the UK LULUCF sector will be counted against the sector's own considerable irreducible emissions, as evidenced by neither document mentioning carbon trading. More explicitly, the CCC have opposed inclusion of "land-based GHG removals like afforestation" in carbon trading schemes from a fear that these "solutions might not be available to offset emissions sources which are truly expensive and/or diffcult to decarbonise" (CCC, 2019); Mark Carney, ex-govenor of the Bank of England, has stated that offsets must be limited to residual emissions (Treloar and Taraldsen, 2021), and the IPCC have stated that land-based sequestration "cannot be used to compensate for delayed emission reductions in other sectors" (IPCC, 2022). The UK Government, however, appears to be encouraging land owners (including farmers) to sell this captured carbon through voluntary carbon markets (types of carbon market are explained in Section 2.2.2). For example, the Woodland Carbon Guarantee, states that it is designed to "accelerate woodland planting rates and develop the domestic market for woodland carbon" (DEFRA, 2021); the Woodland Carbon Code, the government-backed woodland certification scheme, states that "we believe all companies should have the opportunity to compensate for their emissions" (WCC, 2022c); and as the UK's Basic Payment subsidy scheme is replaced by the Environmental Land Management payment system, the UK Government stated a desire to place a greater reliance on private money in agricultural subsidy, in part through "growing markets for the sale of carbon or biodiversity credits" (DEFRA, 2022a).

Seemingly in response to these government schemes and encouragement, headlines are being made by investment firms buying land with the explicit intention of afforestation (Garside and Wyn, 2021; Debbie James, 2021; Case, 2022), and the Scottish Land Comission, a government body concerned with land rights, has found that non-farming actors, including corporations and investment firms, have purchased over 40% of UK land since 2017, and over 50% of Scottish land in 2021 alone, resulting in $> 30\%$ year-on-year increase in average per/acre land value, and $> 60\%$ in "poor livestock land" and "plantable hill ground", driven in large part by a perceived "potential for carbon offsetting and developing carbon credits at large scales" (Scottish Land Comission, 2022).

With these land purchases in mind, and the scientific warning against misuse of carbon trading, this dissertation sets out to explore the motive behind such purchases by assessing the current state of UK carbon markets and attempts to determine the price at which it becomes more profitable to sell carbon units through afforestation than to produce food on UK agricultural land.

2 Literature Review

There are two key reasons that it has not been possible to conduct a traditional systematic literature review for this project. First, the majority of publications on this topic fall within the classification of 'grey literature' and are not listed in academic databases; they primarily comprise of news articles and government, NGO, company, or charity reports. Secondly, in the words of Sir Dieter Helm, Professor of Energy Policy at the University of Oxford and author of multiple, well-respected books including "Net Zero" and "The Carbon Crunch", states that "a huge amount of guff is talked about carbon offsetting", which makes filtering out the cite-worthy sources something of a challenge (Scottish Land and Estates, 2021).

Instead, Policy Commons, an indexed database of "uncatalogued, undiscoverable, uncitable, prone to link rot, and likely to disappear" sources, was used in a non systematic way to search relevant grey literature (Coherent Digital, 2022), and perhaps too great a reliance was placed on the editorial teams of news outlets such as Project Syndicate, The Financial Times and The Guardian, and on the algorithmic search engine DuckDuckGo. All of these sources will have introduced bias to the selection of publications included, but it is isn't clear how else the search could have been conducted given the novelty, and guff-content, of publications in the field.

2.1 A Brief History of International Carbon Markets

In 1992, 140 countries collectively agreed to attempt to limit the impact of anthropogenic GHG emissions on the climate. By 1997, this collective had developed the Kyoto Protocol (de Chazournes, 1997), a collection of legally binding emissions targets that applied to the wealthiest 39 industrialised countries (referred to as Annex I Parties) and permitted these Parties to offset their emissions through (among other things) land based sequestration. All other countries, though not legally required to reduce their own emissions, could engage in similar projects with the option of trading their emissions reductions to Annex I Parties under the Clean Development

Mechanism (CDM) (Orlando and et al., 2002). To expand the number of countries included under emissions reductions targets and to overcome "often contentious negotiations" over the legally binding nature of these targets (Bodansky, 2015), the 2015 Paris Agreement opted to adopt the 2009 Copenhagen Accord's bottom-up approach to climate policy and replaced the top-down, prescriptive emissions targets of the Kyoto Protocol with 'Nationally Determined Contributions' (NDCs), a country-specific collection of targets that are set and periodically refined by each country individually and that have received "virtually universal acceptance" (Bodansky, 2015). Although the 2015 Paris Agreement laid out an intention to allow for the international trade of offsets, as was permitted under the Kyoto Protocol's CDM, the heterogeneity of regionally specific NDCs meant that final agreement on Article 6 of the Paris Agreement, a regulatory framework in part designed to avoid double counting during trading (two or more parties claiming the same emissions offset), was not achieved until COP26 in 2021 (Oeko Institut, 2021). In their Sixth Assessment Report, Working Group III of the IPCC have stated that "the rapid deployment of [Agriculture, Forestry and Other Land Use sequestration] measures is essential in all pathways staying within the limits of the remaining [emissions] budget for a 1.5 $\circ$ C target" (IPCC, 2022), and the recent agreement of Article 6 suggests that such measures won't be limited to offsetting domestic emissions for much longer, in turn suggesting an expansion in the international market for carbon offsets (previously, offsets could be sold internationally through private transactions, but could not be counted towards a country's NDCs).

2.2 What are Carbon Credits and Markets?

2.2.1 Carbon Credits

Carbon credits, representing the avoidance, reduction or removal of one metric tonne of carbon dioxide, are traded through carbon markets as carbon offsets. Both carbon credits and carbon markets come in multiple forms:

The Oxford Principles for Net Zero Aligned Carbon Offsetting (2020) outlines five types of carbon credit:

1. **Avoided Emissions**
   - e.g. Renewable energy
2. **Short-Lived Reduced Emissions**
   - e.g. Prevention of environmental degradation
3. **Long-Lived Reduced Emissions**
   - e.g. Carbon Capture and Storage (CCS) (of point-source emissions)
4. **Short-Lived Removed Emissions**
   - e.g. Afforestation
5. **Long-Lived Removed Emissions**
   - e.g. Direct Air Carbon Capture and Storage (DACCS) (of nonpoint-source emissions)

Where 'short-lived' is on the order of decades, and 'long-lived', centuries or millennia.

2.2.2 Carbon Markets

Carbon markets come in two main forms: voluntary and compliance markets.

Participants of a compliance market are legally required to limit their emissions and face punitive measures if they don't. Carbon taxes are a form of compliance market, as are 'cap and trade' systems, where a national government sets a maximum limit on sectoral emissions (the cap) and allocates tradable emissions permits to organisations within the sector, allowing high emitting actors to trade permits with low emitting actors (the trade), benefiting both but maintaining the emissions ceiling (DEFRA, 2022b). Typically, the total permissible amount of emission falls each year, incentivising organisations to reduce their emissions. The method of allocating permits within cap and trade systems is subject to some controversy (Helm, 2021a). The UK and EU Emissions Trading Schemes (ETS) are examples of compliance markets, as is the Clean Development Mechanism (CDM) established under the 1997

Kyoto Protocol.

Currently, the UK ETS covers one third of national emissions and levys a fine of £100 per tonne for exceeding the allowance (Ng, 2021). Three sectors are covered by the UK ETS: power generation, heavy industry and aviation (HM Treasury, 2021). Compliance markets in New Zealand and South Korea include additional sectors, such as heating, transport, waste, and agriculture & forestry, covering 50% and 70% of emissions respectively (HM Treasury, 2021). The EU has proposed to expand their ETS scheme to cover around 85% of regional emissions (HM Treasury, 2021).

Voluntary markets exist in addition to legally mandated emissions reductions. Actors within the voluntary market are incentivised by either moral or commercial objectives to purchase carbon credits and voluntarily offset emissions produced within their organisation or supply chain.

2.3 Criticisms of Carbon Markets

Though there a wide variety of criticisms of carbon markets, specifics for the majority of which have been removed due to space limitations, they generally highlight specific faults in implementation, rather than critiquing the idea of trading carbon directly. A number of studies have found that the design of carbon markets and the certification of carbon credits requires strong and robust oversight and standards, without which perverse incentives are allowed to flourish [Morton, Climate and editor (2021); Mendelsohn, Litan and Fleming (2021); Calel *et al.* (2021); reyesCarbonTradingHow2010; Streck (2021); Mathews (2008)], and additionality is not ensured (additionality being a certification that the carbon removed would not have occurred without the financial incentive of carbon trading) (Mendelsohn, Litan and Fleming, 2021).

Not so easily dismissed criticisms centre around the idea that offsetting is being used as excuse not to reduce emissions (Fairlie, 2021); the idea that the money could be better spent [Grant *et al.* (2021); dasguptaHoldTreePlanting2021]; and that paying for reduced emissions "crowds out civic norms" and should be incentivised morally, not financially (Mark Carney, 2020).

2.4 In Defense of Carbon Markets

No more reliable source than the IPCC is needed to back the claim that "rapid deployment of [land-based sequestration] measures is essential in all pathways staying within the limits of the... 1.5 $°C$ target" (IPCC, 2022), however, all of these organisations agree (Nargi, 2020; Griscom, 2021; Matthews *et al.*, 2022; Carbon Offset Guide, no date). That said, one should not conflate land based sequestration with carbon trading, the latter is justified as a funding mechanism for the underfunded former. This dissertation is not an endorsement for or against carbon trading. Instead, since carbon markets are rapidly growing in the UK, this dissertation seeks to objectively assess the current state of these markets.

2.5 Funding of Afforestation

As mentioned in Section 2.4, land-based sequestration is limited by funding and carbon trading is seen as a means to introduce private funding streams - "privatizing natural capital and ecosystem services... enlists self-interest and the profit motive in the cause of the environment." (Chichilnisky and Heal, 1998; Boccaletti, 2022). DEFRA believes that "our goals can only be met through greater investment by the private sector in woodland creation" (DEFRA, 2021), and the UK Government's £50 million Woodland Carbon Guarantee "helps accelerate woodland planting rates and develop the domestic market for woodland carbon by giving landowners the option to sell their captured carbon in the form of verified carbon credits" (DEFRA, 2021). This statement is reiterated in the UK Government's Net Zero Strategy: "Our Key Commitments: [to] mobilise private investment into tree planting, including through the Woodland Carbon Code (see Section 2.6), with the support of government's Woodland Carbon Guarantee..." (DBEIS, 2021).

2.6 The Woodland Carbon Code

For the full details of the Woodland Carbon Code (WCC), see the 'Standard and Guidance' page of the WCC website (2021). What follows is a brief summary of the information contained there.

The Woodland Carbon Code (WCC) is a Government backed quality assurance standard for woodland creation projects in the UK. It was developed to support independent verification of carbon units, sometimes called carbon credits by other systems. Under the Woodland Carbon Code, carbon units come in two forms: Pending Issuance Units (PIUs) and Woodland Carbon Units (WCUs). A PIU represents an expectation that 1 tonne of CO_2 will be sequestered by a given project at some time in the future. A WCU represents a guarantee that 1 tCO_2 has already been sequestered by a given project. Only WCUs, not PIUs, can be used to offset emissions, however, PIUs can be sold *ex-ante* as an unguaranteed promise of a project's offset potential. Since a WCU represents a tangible current offset, and a PIU represents a promise to deliver a future offset, WCUs are generally worth more than PIUs. The sale value of PIUs and WCUs is not currently regulated or systematically recorded and is agreed between the seller and buyer for each transaction. To certify a project through the WCC, all proposed projects must initially be *validated* by an accredited independent body, typically within 3 years of the first tree being planted (the project start date). During *validation*, the total number of PIUs that are expected to be generated by the project is calculated and issued to the project owner, after which they are listed on the UK Land Carbon Registry, where they can be viewed and purchased. Each PIU belongs to a 'vintage', or time period during which it is expected to mature, meaning that the unit will transition from representing potential to actual sequestration (i.e., from a PIU to a WCU). To make this transition the unit must be *verified*, again by an accredited independent body, at which time the PIU is cancelled and the WCU issued. All projects last a maximum of 100 years; less if the intention is to harvest the timber, and the first vintage period ends 5 years after the project start date. For a 100 year project, each subsequent vintage lasts 10 years, until the final vintage, which lasts 5 years again. It is important to note that not all PIU are allocated to the project owner for sale. Version 2.0 of the Woodland Carbon Code stipulates that 20% of a project's units must be allocated to a communal 'buffer' account, owned by Scottish Forestry, to guarantee against unanticipated losses of stored carbon (for example, through forest fires). To demonstrate the concept of vintage periods and buffer accounts, an example project, taken from (WCC, 2021), is provided in Table 2.1.

Table 2.1: Vitage periods and unit allocation of a hypothetical project estimated to sequester 50,000 tCO2e under the the Woodland Carbon Code.

Vintage Length (years)	Vintage Start	Vintage End	Total PIU	PIU to Buffer	PIU to Project
5	2013	2018	500	100	400
10	2018	2028	4,651	930	3,721
10	2028	2038	14,378	2,876	11,502
10	2038	2048	11,779	2,356	9,423
10	2048	2058	6,758	1,352	5,406
10	2058	2068	4,439	888	3,551
10	2068	2078	2,379	476	1,903
10	2078	2088	1,550	310	1,240
10	2088	2098	1,457	291	1,166
10	2098	2108	1,699	340	1,359
5	2108	2113	412	82	328
TOTAL	–	–	50,000	10,000	40,000

2.7 The Limits of Nature Based Solutions

There is only a limited amount of carbon that can be offset through sequestration in the biosphere (and a limited amount of time for me to write this properly, sorry).

- "There are significant difficulties in exceeding 60-70 MtCO2/yr of removals in 2050 with land based [sequestration]" (UK Centre for Ecology and Hydrology and Element Energy, 2021)
- "The Royal Society is more optimistic, aiming for 10 Mt per year through soil carbon capture. To put this into context, the UK's current carbon emissions total 350 Mt" (Fairlie, 2021)
- At a global level: "...large-scale afforestation and reforestation efforts could

remove between 40 and 100 GtC from the atmosphere once forests reach maturity (Lewis et al., 2019a; Veldman et al., 2019) – an impressive quantity that nonetheless represents only a decade's worth of anthropogenic emissions at current rates." (Waring *et al.*, 2020)

- "it would take "fifty acres of trees planted in tropical areas, to absorb the emissions produced by an average American in her lifetime." [@(Fairlie, 2021)]

There has been only a limited increase in Savanna carbon stocks despite decades of fire suppression (Zhou *et al.*, 2022).

2.8 Carbon Markets in Theory

Those thinking carefully about carbon markets want credits to be reserved for unavoidable emissions.

- "if land-based GHG removals like afforestation… were included in an ETS, the upper bound of what is desirable in terms of take-up… could be quickly reached, meaning that land-based solutions might not be available to offset emissions sources which are truly expensive and/or difficult to decarbonise in the long-run" (CCC, 2019)
- "Carbon Dioxide Removal (CDR) is necessary to achieve net zero CO2 and GHG emissions both globally and nationally, counterbalancing 'hard-to-abate' residual emissions. CDR is also an essential element of scenarios that limit warming to 1.5°C or likely below 2°C by 2100, regardless of whether global emissions reach near zero, net zero or net negative levels." (IPCC, 2022)
- Mark Carney agrees that offsets should be limited to "residual emissions" (Treloar and Taraldsen, 2021)

2.9 Carbon Markets in Practice

Currently, those implementing carbon markets (government) are not restricting the sale of credits by emission source, as suggested by the IPCC and UK CCC (Section 2.8).

- "We believe all companies should have the opportunity to compensate for their emissions" (WCC, 2022c)
- The Woodland Carbon Guarantee, states that it is designed to "accelerate woodland planting rates and develop the domestic market for woodland carbon" (DEFRA, 2021)
- The UK Government has stated a desire to place a greater reliance on private money in agricultural subsidies, in part through "growing markets for the sale of carbon or biodiversity credits" (DEFRA, 2022a)
- "The UK government has made clear its intention to use voluntary carbon markets to scale up land-based emissions reduction and carbon sequestration. . . " (Green Alliance, 2022b)

2.10 Exploitation

- People seem to be beginning to exploit carbon markets:
- BP, through the Scottish Forest Alliance, own around 37% of Woodland Carbon Code units (Green Alliance, 2022a).
  - BP initiated the "Scottish Forest Alliance" to "use a small proportion of its revenue from North Sea oil operations to put something back, by creating new forests in Scotland." (Scottish Forest Alliance, 2010)
  - "BP took a bold decision: to step out of line with the rest of the oil industry and acknowledge that climate change was happening and the burning of fossil fuels was at least partly responsible. This was a brave admission, both within the oil and gas industry and within the company."

(Scottish Forest Alliance, 2010)
    - It isn't clear if BP is selling units, but they've claimed them, so if not selling will likely use them to offset own emissions, which seems to go against their professed philanthropic incentive for creating the woodlands.

- Investment firms are buying up land for afforestation projects
    - (Debbie James, 2021)
    - (Garside and Wyn, 2021)
    - (Case, 2022)

- The Scottish Land Comission, a government body concerned with land rights, has found that non-farming actors, including corporations and investment firms, have purchased over 40% of UK land since 2017, and over 50% of Scottish land in 2021 alone, resulting in $> 30\%$ year-on-year increase in average per/acre land value, and $> 60\%$ in "poor livestock land" and "plantable hill ground", driven in large part by a perceived "potential for carbon offsetting and developing carbon credits at large scales" (Scottish Land Comission, 2022).

2.11 Warnings

Organisation and individuals are trying to get farmers to increase on-farm sequestration but also prevent them from misusing the system:

- Deiter Helm, Professor of Energy Policy at the University of Oxford, is trying to appeal to farmers to engage in afforestation but to not just take the money, asking them to sell credits only to sources of truly irreducible emissions (Scottish Land and Estates, 2021)

- "We conclude that farmers should be wary of selling carbon offset credits to buyers upfront as this could harm their own decarbonisation efforts" (Green Alliance, 2022b)

2.12 Profit

Trading carbon credits promises be a highly lucrative income stream in the future:

- "Today's UK ETS prices are [already] sufficient to maintain farm incomes in the Fens without growing food." (Green Alliance, 2022a)
- "It is cost effective to plant lots and lots of woodlands in the British uplands at much less than £30/tonne of CO2" (Farming Today, 2022b)
- DEFRA radio advert: "If you're a farmer or land manager you could recieve over £10,000 for every hectare of woodland you create and you don't need to take your best agricultural land out of use, because when you plant trees, you plant the future." (Farming Today, 2022a; Farmers Weekly, 2022)
- "Research by UCL and Trove Research suggests voluntary carbon market prices will need to reach 30 to 50 USD per tonne (£23-38) but could reach up to 100 USD per tonne (£76) for some projects [to be viable]" (Green Alliance, 2022b)
- Globally, the size of global voluntary carbon markets exceeded 1 billion USD in 2021 (Ecosystem Marketplace, 2021) and are predicted by some to reach 50 billion by 2030 (Blaufelder *et al.*, 2021)
- "It is likely that net zero targets and net zero compliance will tighten up and increase the demand for carbon offsets." (Helm, 2021b)
- "With a vast and growing demand chasing a scarce, poorly defined supply, the conditions are ripe for a bubble" (Boccaletti, 2022)

But no one seems to have provided a calculation for profitability of afforestation versus existing farm practices. That is what this dissertation sets out to achieve.

3 Materials and Methods

Every figure, plot and table in this document is an original visualisation of publicly available secondary data, or estimations and calculations based on that data. All have been created using the programming language *R* (R Core Team, 2021) and the software *RStudio* (RStudio Team, 2021), though the data analysis and calculation has been performed using a mix of R and Microsoft Excel (Microsoft Corporation, 2022). To maximise legibility for the colourblind, the R package Viridis (Garnier *et al.*, 2021) has been used for all coloured plots, and to maximise transparency and reproducibility, the text of this dissertation has been produced as a single rmarkdown document (`.rmd`) with the code for calculations, figures, plots and tables inserted throughout. A full list of R packages used can be found in Appendix A.1. Where Excel has been used, the output of analysis has been saved as a `.csv` file and imported to R. All `.csv` input data files, the Excel `.xlsx` spreadsheet and the full `.rmd` text file can be found at:

https://github.com/Dylan-Edgar/Profitability_of_Afforestation/

3.1 The Profitability of Afforestation

Calculating the price received per tonne of CO_2 sequestered at which it becomes more profitable to plant trees than to continue with the current agricultural production system requires first that the price at which the two systems are equally profitable be calculated (referred to here as the transition price). Calculating an exact transition price, however, is not possible without primary data for several reasons: first, the amount of carbon sequestered per unit area is highly variable, as shown if Table 4.1; second, the exact profitability of the farm is not known, giving nothing but the regional average to compare the profitability of afforestation to; and third, the costs of afforestation vary greatly depending on the requirements of the project. However, by using publicly available secondary data, a range within which the transition price for any given farm is likely to occur can be estimated.

3.1.1 The Transition Price

The transition price represents the price received per tonne of CO_2 sequestered through afforestation (i.e., the carbon price) at which the estimated profitability of farming (ζ) equals the estimated profitability of afforestation (η) over a given period,

$$\zeta = \eta \tag{1}$$

Where estimated profitability of farming (ζ) is equal to Total Income from Farming (θ) (see Section 3.3 for details) multiplied by the total project area (ι) and project period (κ),

$$\zeta = \theta \times \iota \times \kappa \tag{2}$$

Estimated profitability of afforestation (η) is equal to the total profits from afforestation minus the total costs, i.e., the combined income from carbon sales (λ) and woodland creation grants (μ) (Section 3.5), minus the combined costs of establishment (ν) (3.6), management (π) (3.6.3), and maintenance (ρ) (3.6.2),

$$\eta = (\lambda + \mu) - (\nu + \pi + \rho) \tag{3}$$

And income from carbon sales (λ) is equal to the average rate of sequestration (σ) (3.4) multiplied by project area (ι), project period (κ) and the carbon price (τ), then further multiplied by 0.8 to reflect that 20% of units are issued to a communal buffer account (2.6),

$$\lambda = \sigma \times \iota \times \kappa \times \tau \times 0.8 \tag{4}$$

Equation (1) can therefore be rewritten as,

$$\theta \times \iota \times \kappa = ((\sigma \times \iota \times \kappa \times \tau \times 0.8) + \mu) - (\nu + \pi + \rho) \tag{5}$$

As laid out in the methods below, all other information in this equation can be estimated using publicly available secondary data, meaning the equation can be rearranged to calculate the transition price (τ) for any given set of inputs,

$$\tau = \frac{((\theta \times \iota \times \kappa) + (\nu + \pi + \rho)) - \mu}{\sigma \times \iota \times \kappa \times 0.8} \tag{6}$$

The results of this calculation are recorded in Section 4.3.

3.2 Nomenclature of Territorial Units for Statistics

UK farm profitability data is provided in accordance with the Nomenclature of Territorial Units for Statistics (NUTS), a three-tiered hierarchical system used to divide the economic territories of the EU and the UK (EUROSTAT, 2021). Shapefiles for each of the three NUTS levels are provided by the Office for National Statistics (ONS, 2019a, 2019b, 2019c) and have been used to produce all maps. These three shapefiles are plotted in Figure 3.1.

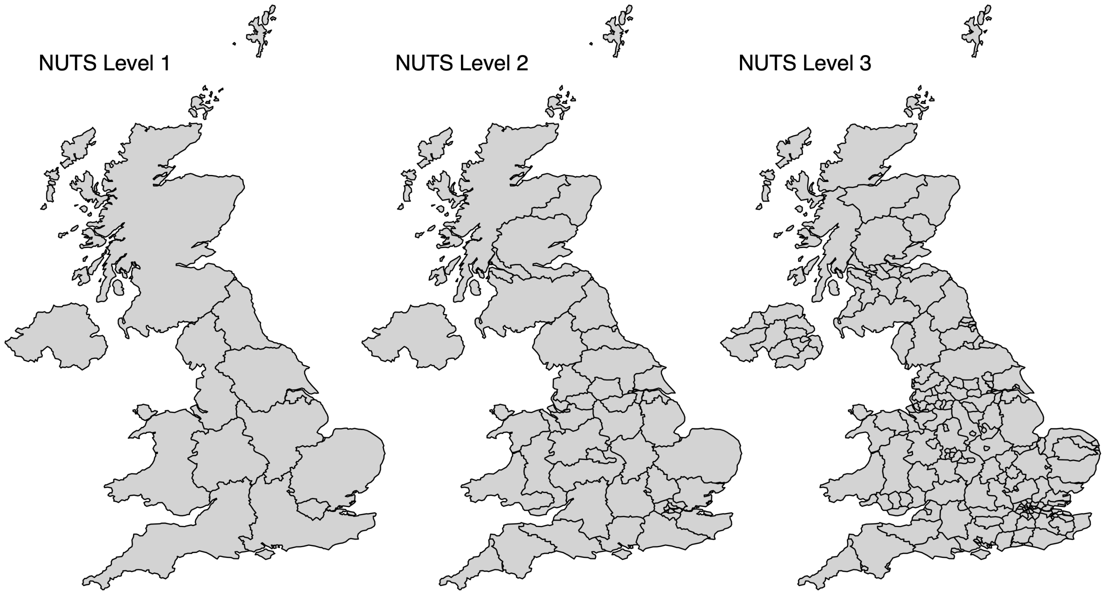

Figure 3.1: Plot of all three NUTS boundary levels (ONS 2019a,b,c)

3.3 Total Income From Farming

Total Income from Farming (TIFF) is a government sourced estimate of farm profitability including costs, profits and subsidies, and broken down by NUTS region. Multiple sources were needed to gather TIFF data for the whole of the UK. TIFF data for England is provided at a resolution corresponding to NUTS level 3 by DEFRA (2022c). NUTS Level 2 TIFF data is provided for Scotland by the Scottish Government in their 2019 'Total Income from Farming Estimates' publication (Scottish Government, 2019), but not in their 2021 revision (Scottish Government, 2021), where NUTS Level 1 data is provided instead. It was decided to maximise spacial rather than temporal accuracy so data for Scotland has been extracted from the older, but higher resolution, 2019 document (Scottish Government, 2019). TIFF data for Wales and Northern Ireland could not be found published by their respective governments, however, the Scottish Government includes NUTS Level 1 estimates for both regions in their 2021 TIFF publication (Scottish Government, 2021).

To enable all regional data to be plotted on the same map, all values were converted to conform to the NUTS level 2 boundaries. Northern Ireland is treated as a single region at NUTS level 2, meaning that Level 1 data was suitable, however, Wales is divided into East and West subregions Due to time constraints, Wales has been treated as though it were a single NUTS level 2 region and identical TIFF values have been assigned to East and West Wales, meaning data for Wales should be interpreted as though it were a single region, not as it is represented in the Figure 4.1 as two regions.

Conversion between boundaries was achieved using a lookup table sourced through correspondence with the Office of National Statistics (REFRENCE), a small section of which is provided in Table 3.1 (and is provided in full in the GitHub repository).

Table 3.1: UK NUTS Region lookup table, Levels 1, 2, 3

NUTS1 Official Name	NUTS2 Official Name	NUTS3 Official Name
North East (England)	Tees Valley and Durham	Hartlepool and Stockton-on-Tees
North East (England)	Tees Valley and Durham	South Teesside
North East (England)	Tees Valley and Durham	Darlington
North East (England)	Tees Valley and Durham	Durham CC
North East (England)	Northumberland and Tyne and Wear	Northumberland
North East (England)	Northumberland and Tyne and Wear	Tyneside
North East (England)	Northumberland and Tyne and Wear	Sunderland
North West (England)	Cumbria	West Cumbria
North West (England)	Cumbria	East Cumbria
North West (England)	Greater Manchester	Manchester
North West (England)	Greater Manchester	Greater Manchester South West
North West (England)	Greater Manchester	Greater Manchester South East
North West (England)	Greater Manchester	Greater Manchester North West
North West (England)	Greater Manchester	Greater Manchester North East
...	...	...

Note:
A section of the full lookup table which can be found in this document's GitHub repository.

This lookup table was used to calculate the mean TIFF for each NUTS Level 2 region based on data for associated NUTS Level 3 subregions. An example calculation is shown in 3.2. A full table of collected and calculated NUTS level 2 TIFF values can be found in Table A.2; a plot of which can be found in Figure 4.1.

Table 3.2: Calculated TIFF and area for the NUTS Level 2 Region 'Tees Valley and Durham' based on corresponding Level 3 subregions.

NUTS 3 Subregion	TIFF (£/ha)	Area (ha)
Hartlepool and Stockton-on-Tees	237	13,027
South Teesside	117	12,743
Darlington	463	14,268
Durham CC	196	157,916
Tees Valley and Durham	253	197,954

3.4 Sequestration Rates

Natural England estimates an average rate of sequestration for English broadleaf woodland of 7 tCO2/ha/year, with an expected range of 2 to 13 tCO2/ha/year (Natural England, 2021). Since this rate of sequestration only applies to broadleaf woodlands in England, however, it was necessary to find rates of sequestration applicable to Scotland (which were expected to also more closely apply to the uplands of Wales).

3.4.1 Sequestration Rates in Scotland

Under the Woodland Carbon Code (WCC), all PIUs are publicly listed on the UK Land Carbon Registry (managed by IHS Markit (2022b)), meaning that the exact number of issued Units and the amount of land associated with each project can be extracted. Since each PIU represents an expectation that 1 tCO2 will be sequestered, and since the project length and area are known, it is possible to calculated the average sequestration rate for every WCC project, as in Equation (7),

$$\alpha = \beta_i / \delta_i \tag{7}$$

where α is equal to the average rate of sequestration (tCO_2e/ha) for the project, β is equal to the project's total expected sequestration (tCO_2e), and δ is equal to total project area (ha). Results for the 16 projects are recorded in Table 4.1.

For the purposes of this dissertation, it was decided to focus on WCC certified projects owned by the Scottish Forest Alliance, a partnership formed in the late 1990s between BP Exploration Operating Company Limited, Forestry Commission Scotland, RSPB Scotland and Woodland Trust Scotland (Scottish Forest Alliance, 2010).

3.5 Sources of Funding

Each of the four constituent countries of the UK provide their own woodland creation grant schemes. Due to time limitations, only the Scottish Forestry Grant Scheme was included in the profitability calculations, and all regional calculations have used these grant income values. This will introduce an unknown error to the regions of England, Wales and Northern Ireland, although it is expected that all grant schemes will provide broadly similar levels of funding.

Information for the four woodland creation grants schemes can be found below.

- Scotland - Forestry Grant Scheme (Scottish Government, 2022)
- England - Woodland Creation Offer (Forestry Commission, 2022)
- Wales - Glastir Woodland Creation (Welsh Government, 2021)
- Northern Ireland - DAERA Forestry Grants (DAERA, 2022)

An example section of the Scottish Forestry Grant Scheme payment data is recorded in Table 3.3.

Table 3.3: Grant payment rates for differing woodland types under the Scottish Forestry Grant Scheme.

Woodland Type	Initial Payment (£/ha)	Annual Maintenance (£/ha)	Total Maintenance (Over 5 years) (£/ha)
Conifer	1920	208	1040
Diverse Conifer	2160	336	1680
Broadleaves	2880	528	2640
Native Scots Pine	1840	272	1360
Native Upland Birch	1840	128	640
Native Broadleaves	1840	272	1360
Native Low-density Broadleaves	560	96	480
Small or Farm Woodland	2400	400	2000
Native Broadleaves in Northern and Western Isles	3600	624	3120

Source: Scottish Government, 2022

Note: [1] Payment rates displayed here relate to woodland projects of under 300ha in 'Standard Areas' that do not plough the land during establishment. Different rates apply to projects outside of these parameters.

3.6 Costs of Afforestation

3.6.1 Establishment Costs

Estimated costs of woodland establishment were sourced from the John Nix Pocketbook (Redman, 2021) and are displayed in Table 3.4.

Table 3.4: Afforestation establishment costs.

	Estimated Cost Range		
Metric	min	max	Unit
Broadleaf tree stock	400.00	650.0	£ / 1000
Conifer tree stock	400.00	500.0	£ / 1000
Fencing - Rabbit	4.40	6.3	£ / m
Fencing - Stock	4.35	5.4	£ / m
Fencing - Deer	6.80	8.9	£ / m
Fencing - Deer + Rabbit	8.40	11.0	£ / m
Fencing - Split Post + Rail	5.70	8.9	£ / m
Tree Guard - Spiral + Cane	40.00	45.0	£ / 100
Tree Guard - Plastic Tube	140.00	190.0	£ / 100
Tree Guard - Softwood Stakes	75.00	100.0	£ / 100
Spot spraying	60.00	90.0	£ / 1000
Hand Planting - Broadleaf	600.00	900.0	£ / 1000
Hand Planting - Conifer	600.00	900.0	£ / 1000
Machine Planting	110.00	215.0	£ / 1000
Beating up - labour	115.00	210.0	£ / ha
Beating up - stock	95.00	160.0	£ / ha
Herbicide	75.00	135.0	£ / ha
Inter-row Mowing	75.00	210.0	£ / ha
Upland - Ploughing	140.00	220.0	£ / ha
Upland - Moulding	290.00	405.0	£ / ha
Upland - Drainage	90.00	115.0	£ / ha
Upland - Scrub Clearance	300.00	400.0	£ / ha
Upland - Fertilising	132.00	297.0	£ / ha
Lowland - Ploughing	70.00	105.0	£ / ha
Lowland - Moulding	290.00	405.0	£ / ha
Lowland - Drainage	0.00	0.0	£ / ha
Lowland - Scrub Clearance	250.00	350.0	£ / ha
Lowland - Fertilising	0.00	0.0	£ / ha
Access road	13500.00	33000.0	£ / km

Source: Redman, 2021.

There is some difficulty in estimating costs without knowing the specific requirements of a project. For example, fencing is one of the primary costs but the length of fencing required can vary greatly; for the purposes of this dissertation, projects are assumed to be perfectly square with a continuous perimeter fence equal to four times the square root of the area. In reality, this is highly unlikely, since few landowners are likely to have either the space or inclination to allow for perfectly square projects, and regular shapes are forbidden under the conditions of establishment grants (Scottish Forestry, 2010). Other cost inputs are subject to similar levels of uncertainty.

3.6.2 Maintenance Costs

Establishing ongoing maintenance costs is also difficult. The John Nix Pocketbook (Redman, 2021) provides an estimated range for maintenance costs of up to £30/ha/year for sporting and amenity woodland, and £600-900/ha/year for timber production. It is expected that woodland for carbon capture would fall towards the lower end of this spectrum but correspondence with a representative of the UK Forestry Commission revealed that, due the number of variables, including soil type, local climate, local biodiversity, tree species mix, and past management, it is not possible to give an average estimate of typical maintenance costs. To simplify the calculation, maintenance costs of £100/ha/year have been used (sourced from a document detailing “Indicative Green Infrastructure Costs” provided by Worcestershire County Council (2016)), however, it is important to note that it is not known how close this value is to the true average cost.

3.6.3 Management Costs

Management costs also needed to be considered. The only such cost included here was that of ascertaining certification under the Woodland Carbon Code. The SRUC Farm Management Handbook suggests that these costs could range from £3,875 to £9,900 (SRUC, 2021). SRUC provides these values as rough estimates, so a value of £7,000, close to the mid point, was chosen. It is not know how accurate this value represents the true cost.

3.7 How to Tax a Woodland

The relationship between tax and woodlands in the UK is quite complex and has not been considered in this dissertation.

3.8 Net Present Value (NPV)

Some consideration was given to the inclusion of Net Present Value (NPV) calculations, however, due to time constraints and the fact that the two competing land uses being considered, agriculture and afforestation, would be considered over the same time period, 100 years, it was assumed that there is a good chance the NPV affects would cancel out - so I skipped it.

4 Results

4.1 Total Income from Farming

Total Income from Farming (TIFF) values were collected and calculated according to Section 3.3 and are plotted according to Section 3.2 in Figure 4.1. See Table A.2 for tabular results.

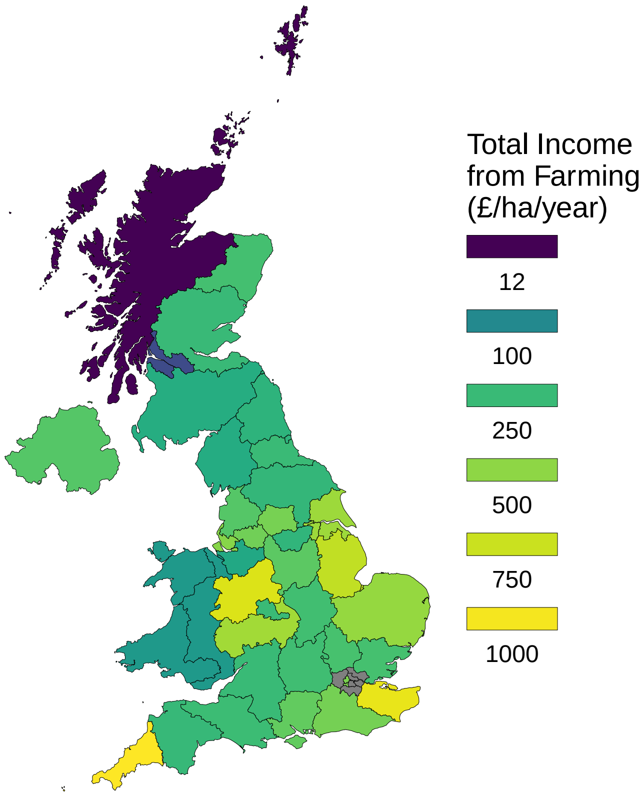

Figure 4.1: Total Income From Farming (TIFF) for UK NUTS level 2 regions.

4.2 The Woodland Carbon Code

The Scottish Forest Alliance owns 16 Woodland Carbon Code (WCC) certified projects across Scotland, as shown in Figure 4.2, totalling 4,802 hectares, for which the partnership has been issued 1,210,513 PIUs (excluding 341,572 units issued to the buffer account), collectively representing an expectation that the projects will sequester 1,552,085 tCO_2 (IHS Markit, 2022a).

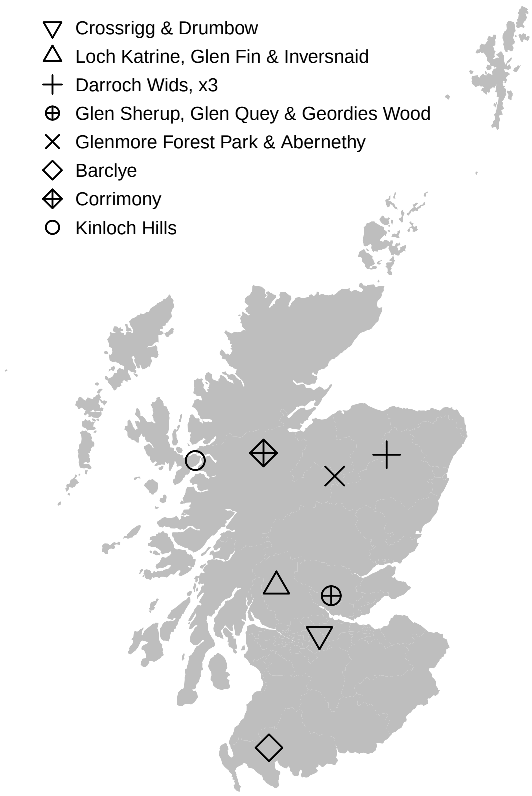

Figure 4.2: Locations of Scottish Forest Alliance projects.

The 16 Scottish Forest Alliance projects represent roughly one quarter off all Units issued under the WCC (1,552,085 of 6,427,819 units (IHS Markit, 2022a)), as shown in Figure 4.3.

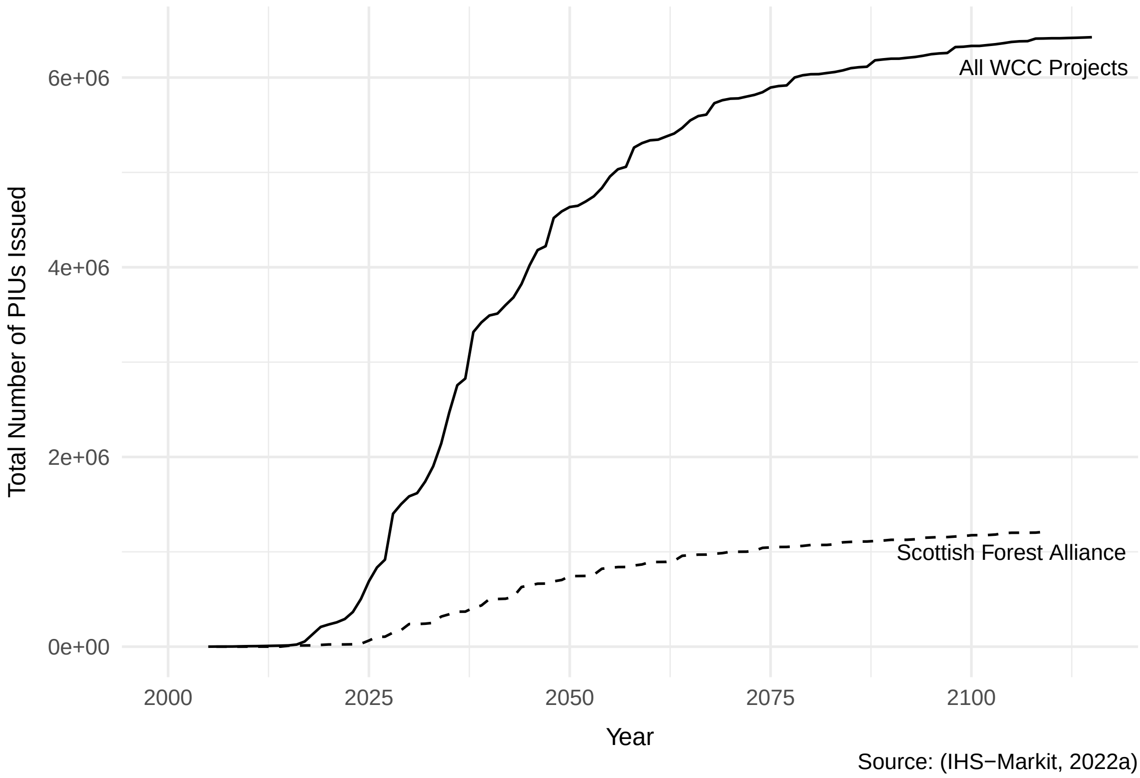

Figure 4.3: All currently issued PIUs under the Woodland Carbon Code and when they become available for use as offsets.

As outlined in Section 3.4, PIUs issued to a project directly correlate to the expected total sequestration, with 1 PIU issued per tonne of CO2 sequestered. For each of the 16 Scottish Forest Alliance projects, total PIUs issued per year were extracted and plotted in Figure 4.4.

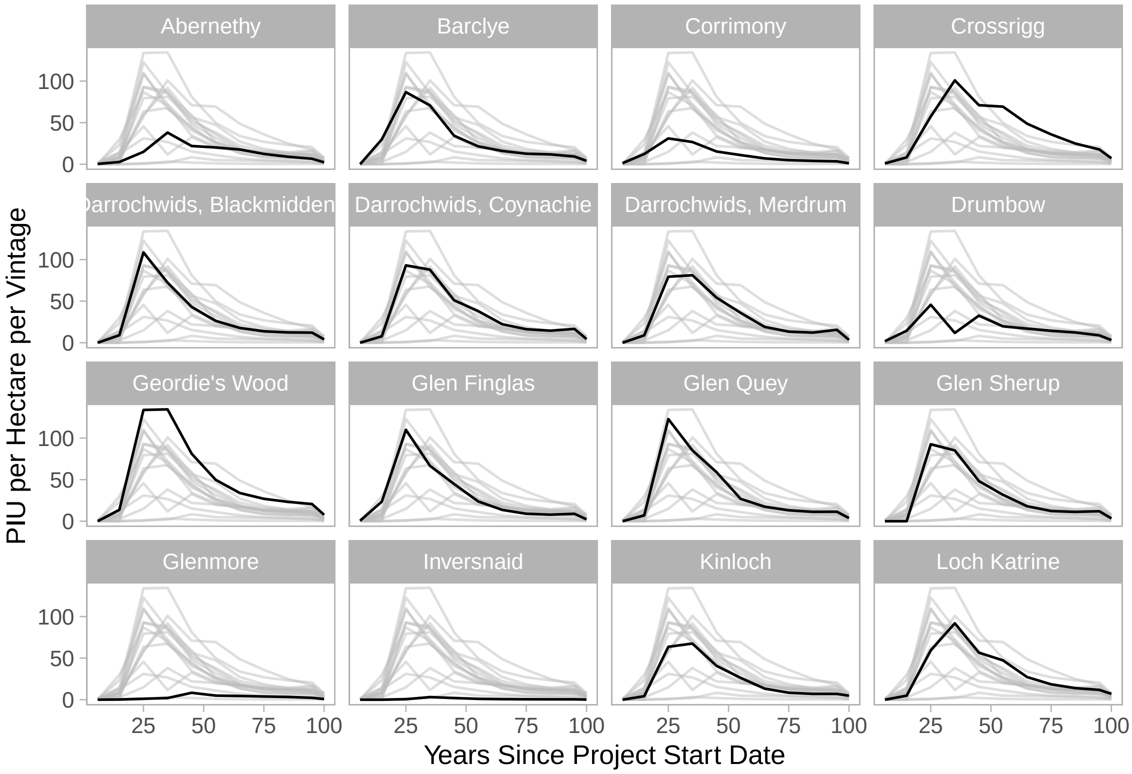

Figure 4.4: example caption

PIU per year was then plotted cumulatively and divided by total project area to give the cumulative PIU per hectare, a more accurate metric for comparing expected rates of sequestration between projects, as shown in Figure 4.5.

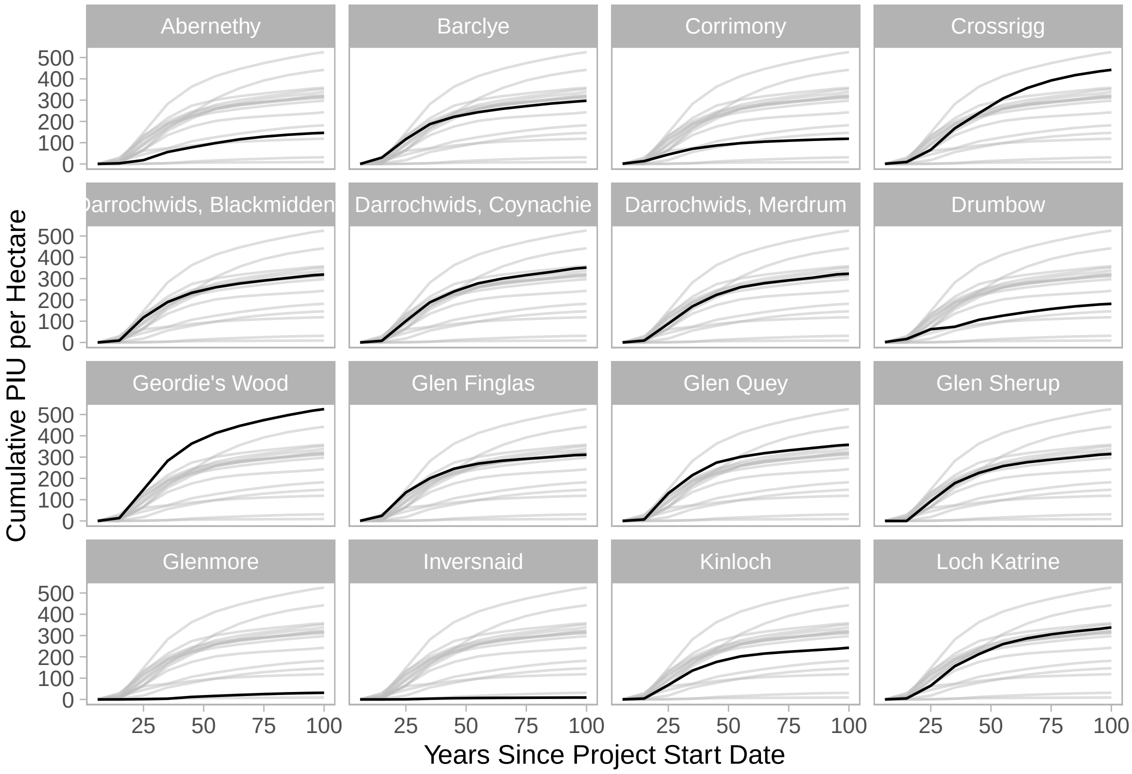

Figure 4.5: example caption

To explore the large variation in expected total sequestration shown in Figure 4.5, cumulative area under each tree species was calculated for each project, shown in Figure 4.6.

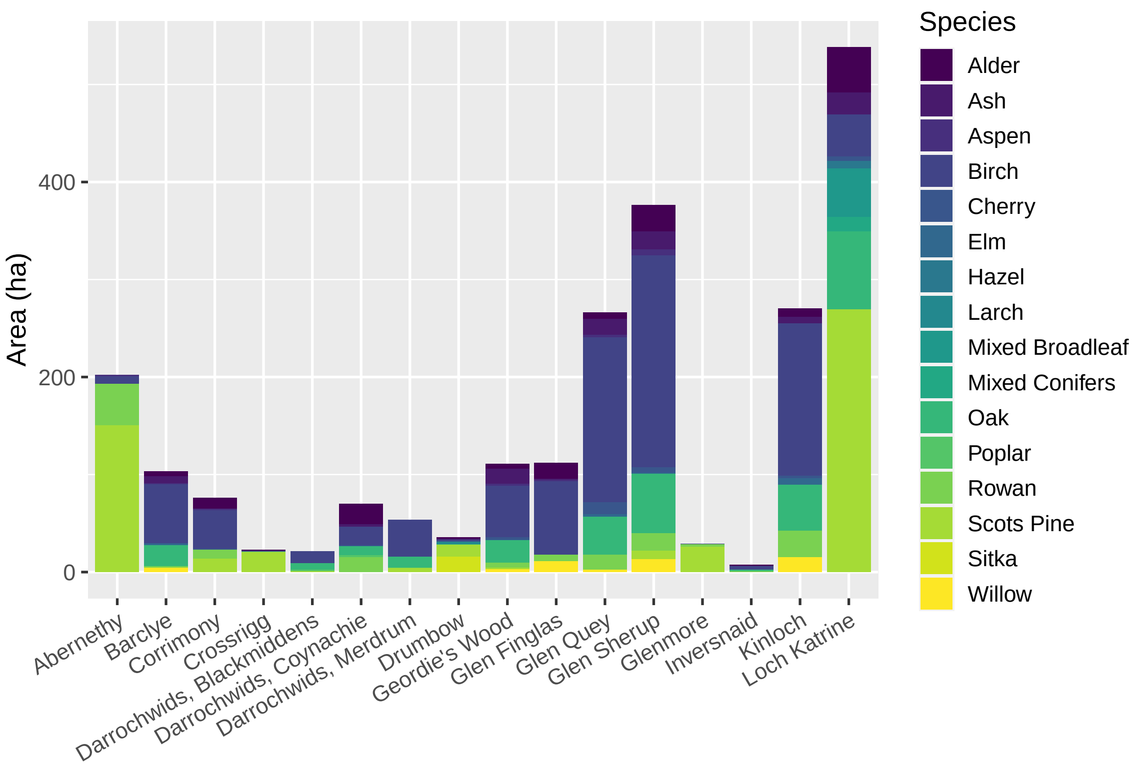

Figure 4.6: example caption

Trees species were then categorised as broadleaf or conifer to test if the ratio of these two types explained the variation in sequestration rate seen in Figure 4.5. The ratio of broadleaf to conifer for each project is plotted in Figure 4.7.

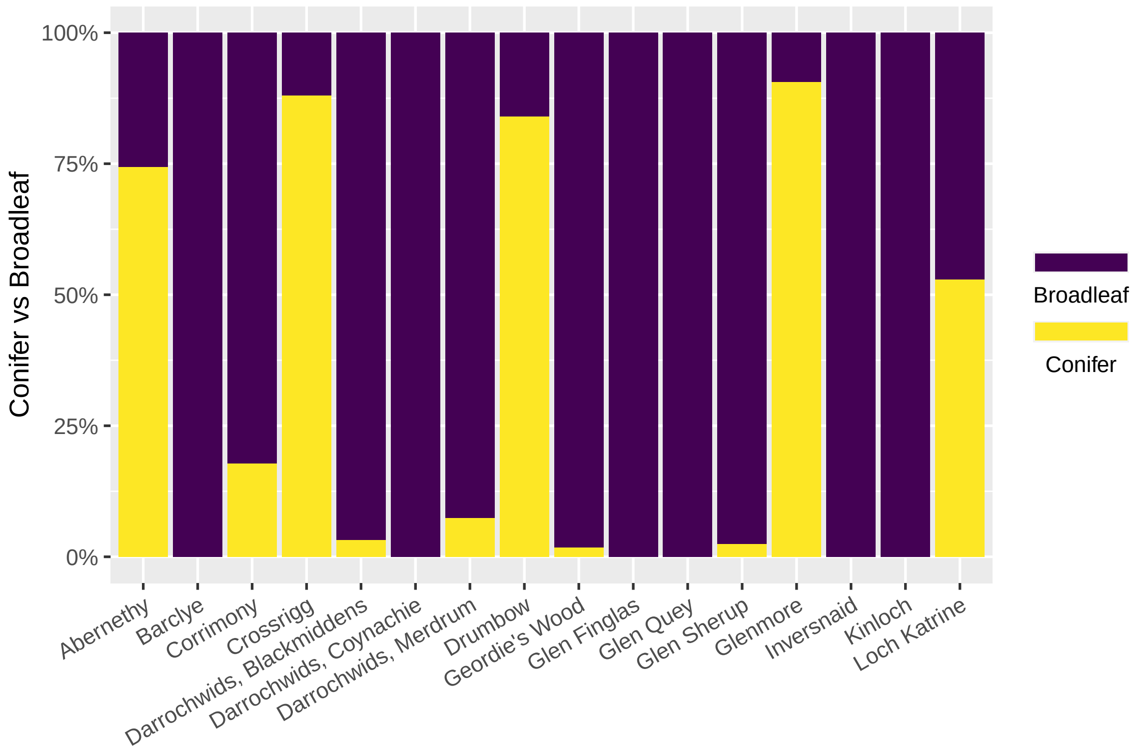

Figure 4.7: example caption

The total number of PIUs issued to the project were then plotted against the ratio of broadleaf to conifer. The large confidence interval suggests that, at least for these projects, broadleaf to conifer ratio is not the primary driver of increased sequestration.

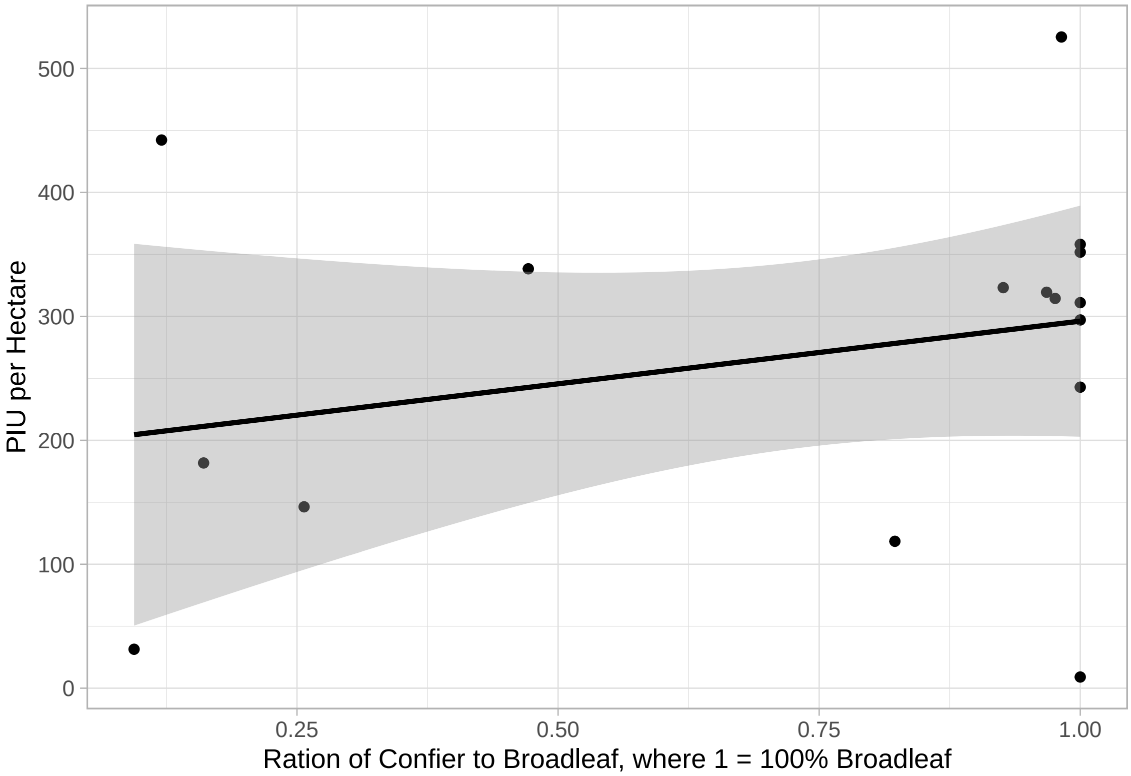

Figure 4.8: example caption

The average rate of sequestration for each project was calculated from total expected sequestration and total area, as in Section 3.4.1. These values, along with broadleaf ratio, previous land use and soil types (sourced from (IHS Markit, 2022a)) were recorded in Table 4.1.

Table 4.1: Project information for the 16 Woodland Carbon Code certified projects owned by the Scottish Forest Alliance.

Project Site	Area (ha)	Total Sequestration (tCO2)	Sequestration per Hectare (tCO2/ha)	Amount of Broadleaf (%)	Previous Landuse	Soil Group
Inversnaid	250	2,252	9	100	Pasture	Organo-mineral
Glenmore	304	9,556	31	9	Semi-natural	Mineral
Corrimony	290	34,385	118	82	Semi-natural	Organo-mineral
Abernethy	558	81,717	146	26	Semi-natural	Organo-mineral
Drumbow	37	6,782	182	16	Pasture	Mineral
Kinloch	754	183,066	243	100	Semi-natural	Organo-mineral
Barclye	200	59,511	297	100	Pasture	Organo-mineral
Glen Finglas	148	45,974	311	100	Pasture	Mineral
Glen Sherup	421	132,491	314	98	Pasture	Organo-mineral
Darrochwids, Blackmiddens	36	11,423	319	97	Pasture	Mineral
Darrochwids, Merdrum	57	18,537	323	93	Pasture	Mineral
Loch Katrine	1,119	378,651	338	47	Semi-natural	Organo-mineral
Darrochwids, Coynachie	161	56,778	352	100	Arable	Mineral
Glen Quey	315	112,957	358	100	Pasture	Organo-mineral
Crossrigg	26	11,302	442	12	Pasture	Mineral
Geordie's Wood	124	65,131	525	98	Pasture	Organo-mineral
AVERAGE	300	75,657	252	74	–	–

Note: Sequestration values refer to the total after 100 years.

Based on this table, it appears that neither broadleaf ratio, previous land use or soil group directly control expected sequestration rate.

4.3 Profitability of Afforestation

Afforestation profitability was calculated in an Excel spreadsheet and includes the option to use any subset of inputs as laid out in the Methods above, including establishment costs, grant incomes, project size and period, species mix, and sequestration rate. A subset of inputs based on an estimated UK average was selected then optimised for profitability: for example, a sequestration rate of 6 tCO_2/ha/year, slightly below the English broadleaf average (see Section 3.4 for details), was selected, along with a grant income based on a 100% broadleaf woodland of <300ha, the maximum grant funding available from the Scottish Forestry Grant Scheme (Table 3.3). These baseline inputs are shown in Table 4.2. A sensitivity analysis was then conducted and subsequent comparative calculations were performed, as laid out in Table 4.3 and Figures 4.10 to 4.15.

Table 4.2: TIFF and Area by NUTS Level 2 region

Metric	Value	Units
Location	Scotland	–
Location Type	Lowland	–
Woodland Type	Broadleaf	–
Project Period	100	years
Project Area	110	ha
Planting Density	2,000.00	stems/ha
Sequestration Rate	6	tCO_2/ha/yr
Grant Received	846,256.38	£
Establishment Costs	626,639.98	£
Management Costs	7,000.00	£
Woodland Maintenance	100	£/ha
Total Maintenance Costs	1,170,950.00	£
PIU to Project	52,800.00	Units
TIFF	100	£/ha
Transition Price	38.98	£

Note: Sequestration rate refers to the 100 year average.

Calculation of the transition price displayed in Table 4.2, based on Equation (6), is shown in Equation (8),

$$38.98 = \frac{((100 \times 110 \times 100) + 626,639.98 + 7,000 + 1,170,950) - 846,256.38}{6 \times 110 \times 100 \times 0.8} \quad (8)$$

This calculation was repeated for a number of TIFF values and plotted in Figure

4.9, showing that, as expected, the greater the profitability of farming, the greater the carbon price required for the profitibility of afforestation to match it.

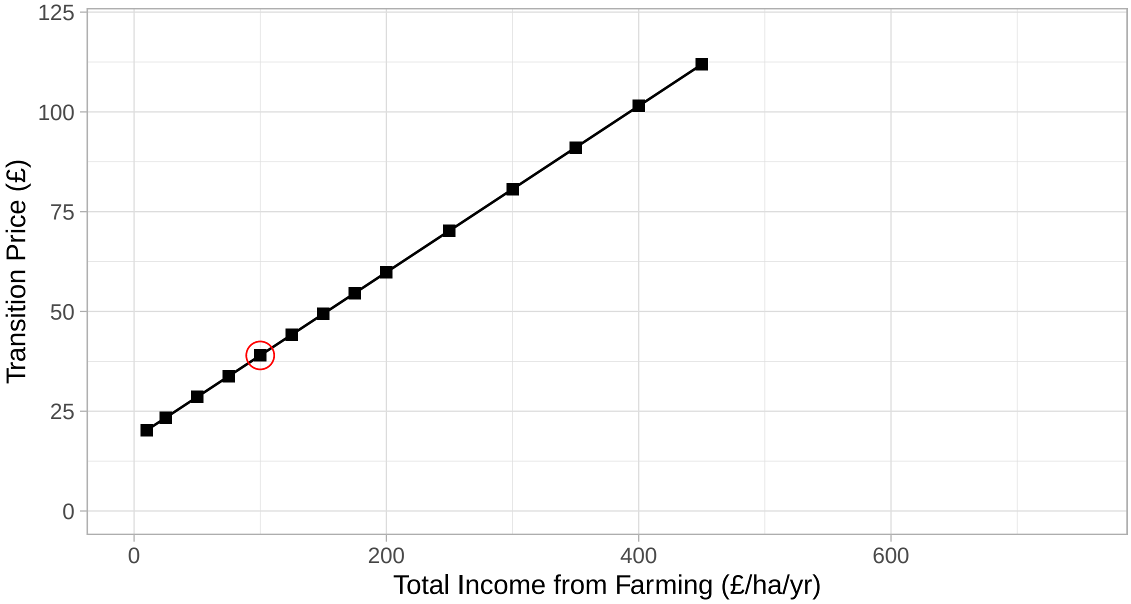

Figure 4.9: Transition price at multiple TIFF levels.

A plot of transition price calculated using Equation 5 and input data from Table 4.3 at multiple Total Income from Farming (TIFF) levels. The value circled in red, for example, represents a hypothetical farm with a TIFF of £100/ha. At that TIFF level, a price recieved per tonne of CO2 sequestered (i.e., carbon price) of £38.98 would be needed for income from afforestation to match that of farming, assuming all other inputs were correct.

A simple, one-at-a-time sensitivity analysis was conducted using the Table 4.2 inputs as a baseline. Each value was independently increased by 1% and the subsequent variation in output was recorded; this allowed for the calculation of variation in output due to a 1% increase in the input, referred to as relative sensitivity. The baseline was then reset and the next input modified. The results of all relative sensitivities greater than 0.1% are recorded in Table 4.3.

Table 4.3: TIFF and Area by NUTS Level 2 region

Metric	Original Input	Original Output	+1% Input	+1% Output	Units	Relative Sensitivity
Sequestration Rate	6.00	38.98	6.06	38.60	tCO2/ha/yr	0.99%
Maintenance Costs	100.00	38.98	101.00	39.19	£/ha/yr	0.53%
Total Income from Farming	100.00	38.98	101.00	39.19	£/ha/yr	0.53%
Broadleaf Establishment Grant	2880.00	38.98	2908.80	38.92	£/ha	0.15%
Tree Guards - Grant	140.00	38.98	141.40	39.04	£/100	0.14%
Broadleaf Planting Rate	2000.00	38.98	2020.00	39.03	Stems/ha	0.12%
Tree Guards - Cost	1.16	38.98	117.00	38.94	£/100	0.11%

Note: Sequestration rate refers to the 100 year average.

Sequestration rate was the primary driver of variation identified during sensitivity analysis, with a relative sensitivity of 0.99%. Sequestration rate also appears to be among the most variable inputs, with a range of 0.09 to 5.25 tCO2/ha/year calculated from Scottish Forest Alliance projects (Table 4.1) and a range of 2 to 13 tCO2/ha/year identified by Natural England (Natural England, 2021).

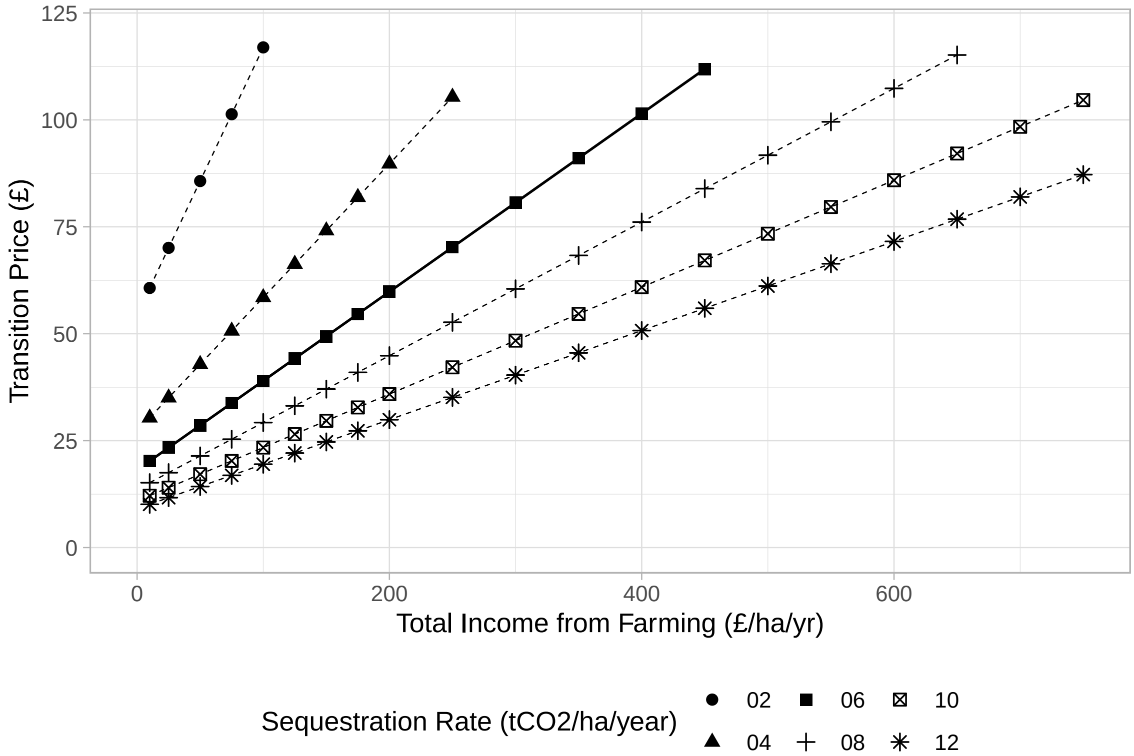

Figure 4.10: Transition price with varied sequestration rate.

A plot of calculated transition price at different TIFF levels using Equation 5 and input data from Table 4.3, with 5 additional calculations using a varied sequestration rate. Each marker corresponds to the transition price at which afforestation becomes equally profitable to farming at the associated TIFF level. The solid line with square markers corresponds to that shown in Figure 4.6.

As highlighted in Table 3.4, the Nix Pocketbook (SOURCE) provides a range for each woodland establishment cost estimate. All calculations in this dissertation have used the minimum cost estimate. Figure 4.11 shows the variation in transition price for a range of sequestration rates using both minimum and maximum establishment cost estimates. Relative sensitivity was not calculated for this variation.

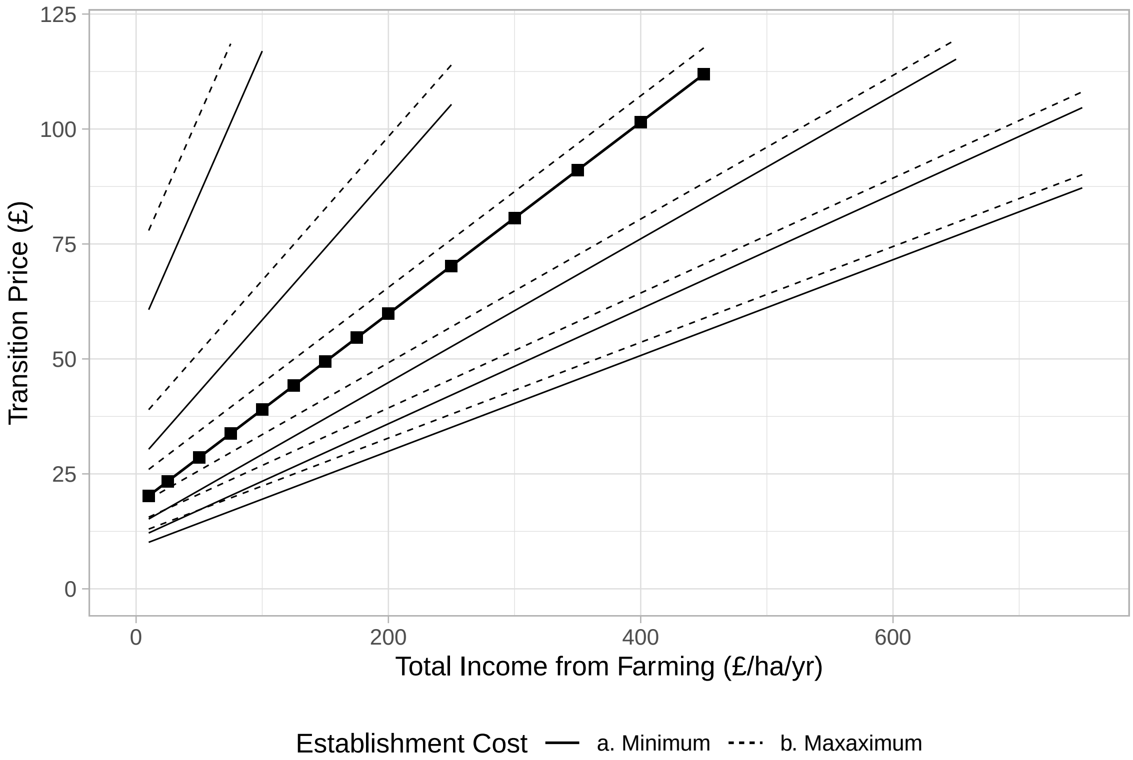

Figure 4.11: Transition price with varied establishment cost.

A plot of calculated transition price at different TIFF levels using Equation 5 and input data from Table 4.3, with 5 additional calculations using a varied sequestration rate, at 2 different establishment cost levels. Each marker corresponds to the transition price at which afforestation becomes equally profitable to farming at the associated TIFF level. The solid line with square markers corresponds to that shown in Figure 4.6.

Variation in maintenance costs was found to be the second most impactful input variable during sensitivity analysis (0.53% relative sensitivity), and is the input subject to the greatest uncertainty. As discussed in Section **??**, the 2022 Nix Pocketbook estimates woodland maintenance costs of <£30 to £900/ha/year depending on intended use. More accurate estimates of this input could strongly impact the interpretation of results.

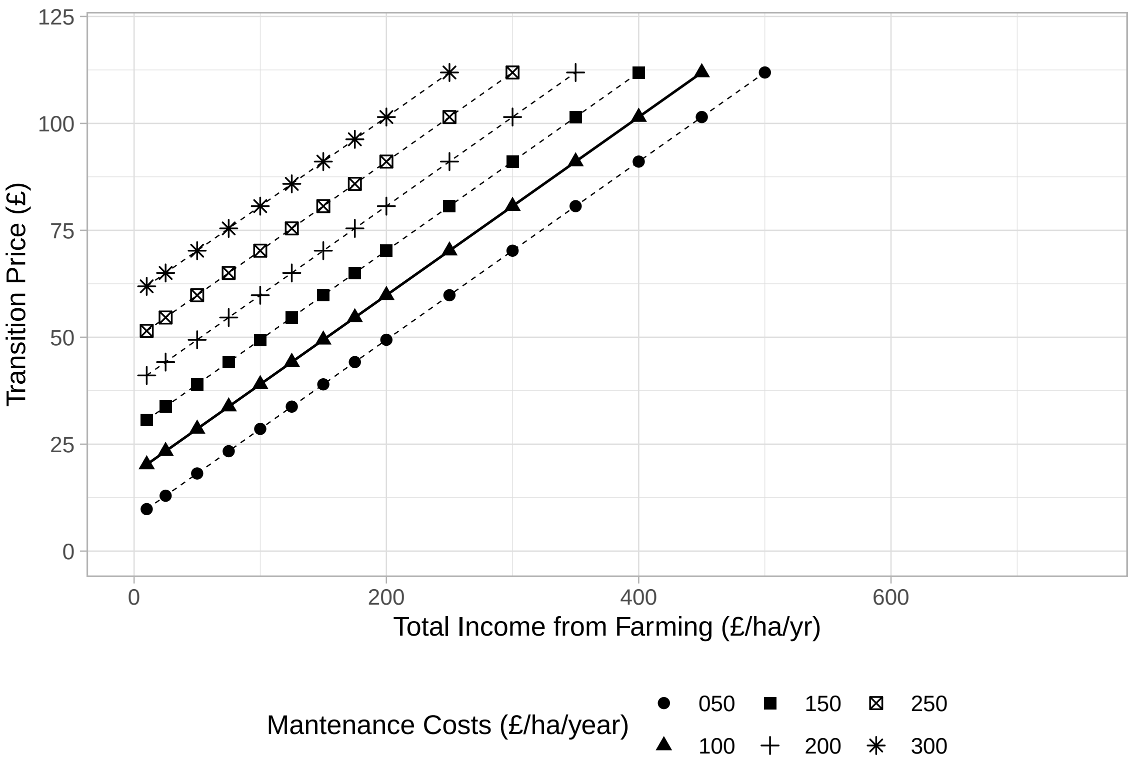

Figure 4.12: Transition price with varied woodland maintenance costs.

A plot of calculated transition price at different TIFF levels using Equation 5 and input data from Table 4.3, with 5 additional calculations using a varied level of maintenance cost. Each marker corresponds to the transition price at which afforestation becomes equally profitable to farming at the associated TIFF level. The solid line with triangle markers corresponds to that shown in Figure 4.6.

Variation in woodland type, though producing the fourth highest relative sensitivity during analysis (0.15%), resulted in a comparatively small variation in estimated transition price when using supplied grant payment rates for different woodland types. Payment rates are largely fixed and based on primary woodland type, with some variation as described in Section 3.5.

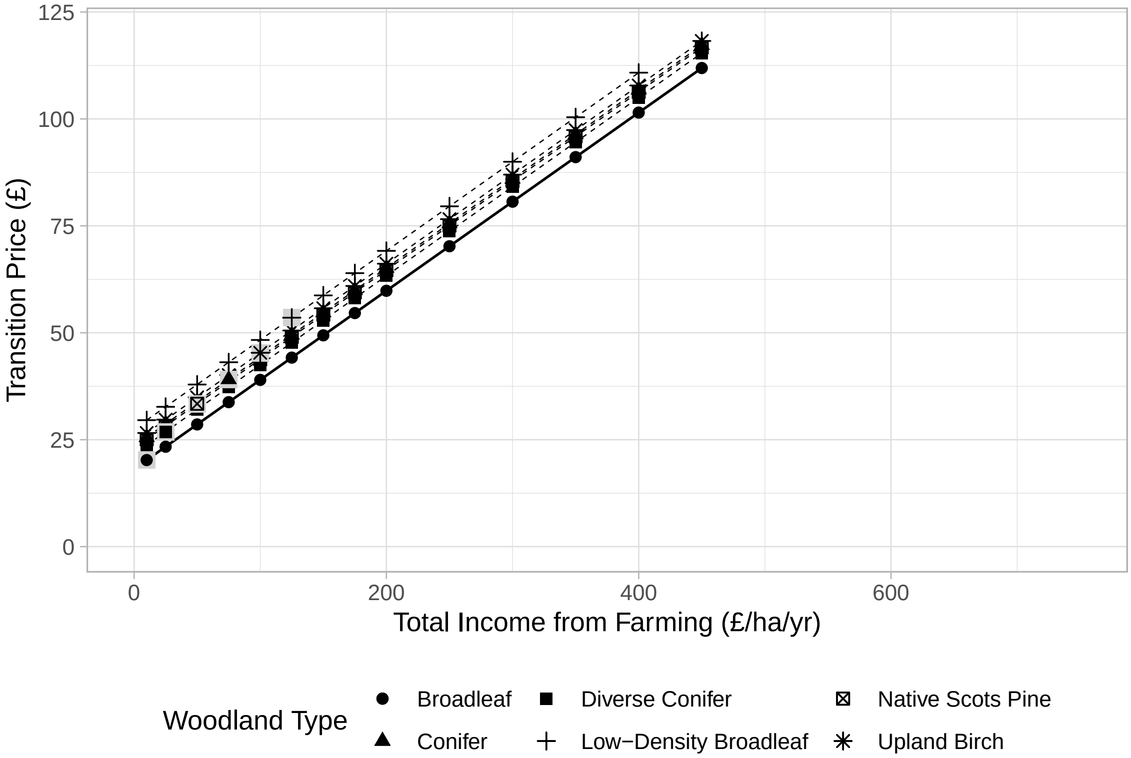

Figure 4.13: Transition price under different types of woodland.

A plot of calculated transition price at different TIFF levels using Equation 5 and input data from Table 4.3, with 5 additional calculations using different woodland type, which impacts the amount of grant money received. Each marker corresponds to the transition price at which afforestation becomes equally profitable to farming at the associated TIFF level. The solid line with circle markers corresponds to that shown in Figure 4.6.

Variation in project period from 25 years, around the time required to reach peak sequestration, to 100 years, the maximum project length permitted under the Woodland Carbon Code, produced a comparatively small impact of the project's estimated transition price. Relative sensitivity was 0.07%.

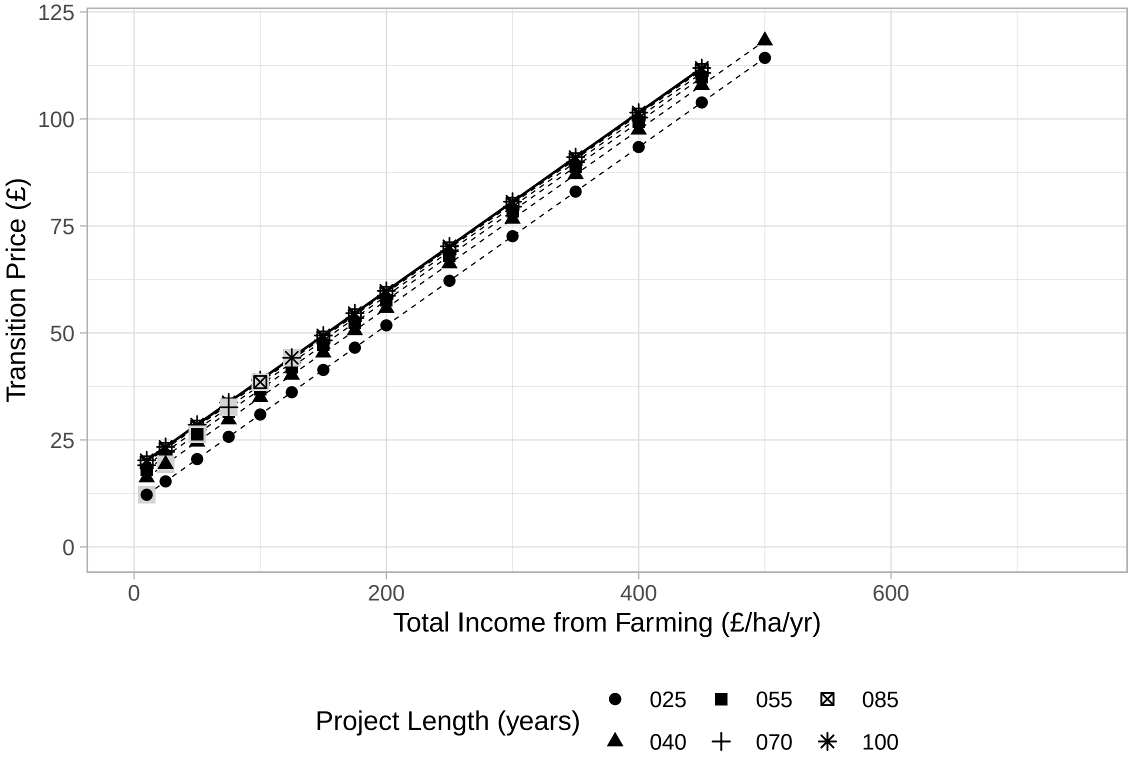

Figure 4.14: Transition price with varied project length.

A plot of calculated transition price at different TIFF levels using Equation 5 and input data from Table 4.3, with 5 additional calculations using a varied project length. Each marker corresponds to the transition price at which afforestation becomes equally profitable to farming at the associated TIFF level. The solid line with star markers corresponds to that shown in Figure 4.6.

As seems intuitive, increasing the size of the project reduces the carbon price required for profitability of afforestation to match that of farming, however, the impact is far smaller than all others ananlysed in this dissertation, with a relative sensitivity of 0.01%.

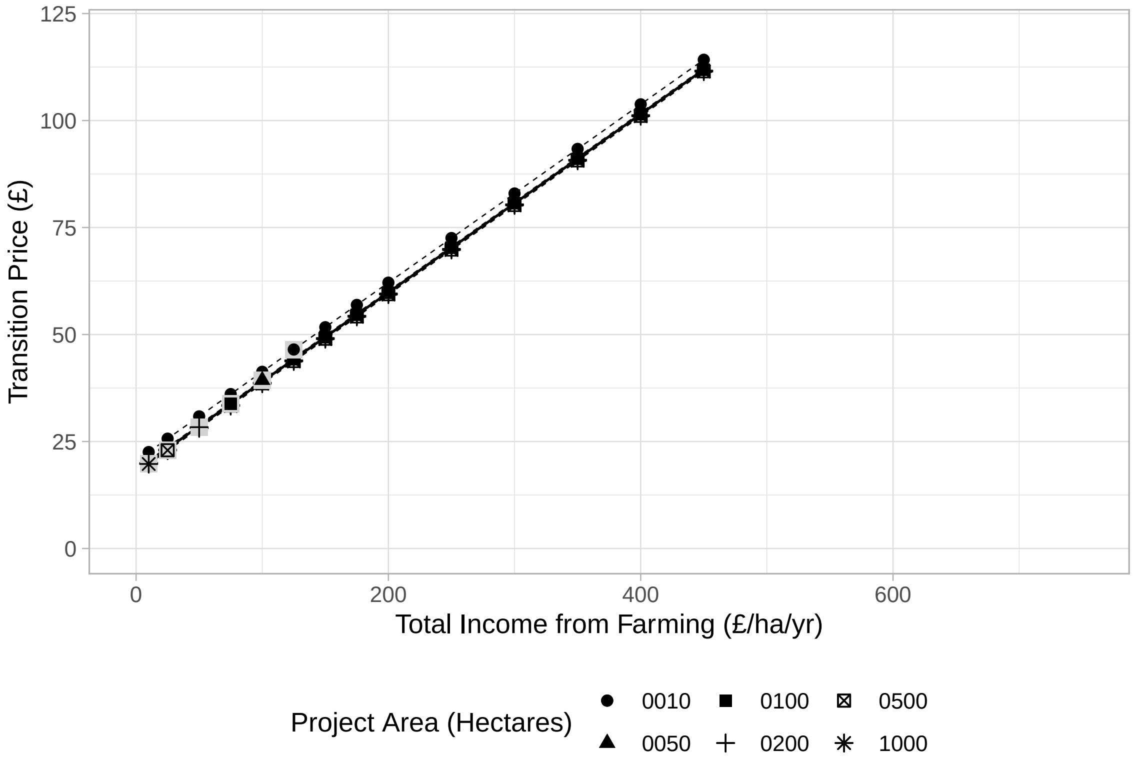

Figure 4.15: Transition price with varied project size.

A plot of calculated transition price at different TIFF levels using Equation 5 and input data from Table 4.3, with 5 additional calculations using a varied project area. Each marker corresponds to the transition price at which afforestation becomes equally profitable to farming at the associated TIFF level. The solid line with square markers corresponds to that shown in Figure 4.6.

Transition prices, based on a range of sequestration rates and inputs from Table 4.2, are provided for each UK NUTS Level 2 region in Table 4.4.

Table 4.4: Transition price by NUTS 2 region at multiple sequestration rates.

		Sequestration Rate (tCO2/ha)					
NUTS Level 2 Subregion	TIFF (£/ha)	1	2.5	5.25	7	10	13
Highlands and Islands	12	123.90	49.56	23.60	17.70	12.39	9.53
West Central Scotland	33	150.15	60.06	28.60	21.45	15.02	11.55
East Wales	134	276.40	110.56	52.65	39.49	27.64	21.26
West Wales	134	276.40	110.56	52.65	39.49	27.64	21.26
Cheshire	176	328.90	131.56	62.65	46.99	32.89	25.30
Cumbria	189	345.15	138.06	65.74	49.31	34.52	26.55
Southern Scotland	194	351.40	140.56	66.93	50.20	35.14	27.03
Northumberland and Tyne and Wear	218	381.40	152.56	72.65	54.49	38.14	29.34
South Yorkshire	228	393.90	157.56	75.03	56.27	39.39	30.30
North Yorkshire	235	402.65	161.06	76.70	57.52	40.27	30.97
Devon	243	412.65	165.06	78.60	58.95	41.27	31.74
Eastern Scotland	249	420.15	168.06	80.03	60.02	42.02	32.32
Gloucestershire, Wiltshire and Bath/Bristol area	251	422.65	169.06	80.51	60.38	42.27	32.51
Tees Valley and Durham	253	425.15	170.06	80.98	60.74	42.52	32.70
West Midlands	253	425.15	170.06	80.98	60.74	42.52	32.70
Dorset and Somerset	260	433.90	173.56	82.65	61.99	43.39	33.38
Berkshire, Buckinghamshire and Oxfordshire	270	446.40	178.56	85.03	63.77	44.64	34.34
Leicestershire, Rutland and Northamptonshire	274	451.40	180.56	85.98	64.49	45.14	34.72
North Eastern Scotland	281	460.15	184.06	87.65	65.74	46.02	35.40
Essex	283	462.65	185.06	88.12	66.09	46.27	35.59
Bedfordshire and Hertfordshire	288	468.90	187.56	89.31	66.99	46.89	36.07
Lancashire	326	516.40	206.56	98.36	73.77	51.64	39.72
Northern Ireland	326	516.40	206.56	98.36	73.77	51.64	39.72
Derbyshire and Nottinghamshire	345	540.15	216.06	102.89	77.16	54.02	41.55
Hampshire and Isle of Wight	363	562.65	225.06	107.17	80.38	56.27	43.28
Greater Manchester	408	618.90	247.56	117.89	88.41	61.89	47.61
Surrey, East and West Sussex	419	632.65	253.06	120.51	90.38	63.27	48.67
West Yorkshire	428	643.90	257.56	122.65	91.99	64.39	49.53
Inner London - West	442	661.40	264.56	125.98	94.49	66.14	50.88
Merseyside	478	706.40	282.56	134.55	100.91	70.64	54.34
East Anglia	528	768.90	307.56	146.46	109.84	76.89	59.15
East Yorkshire and Northern Lincolnshire	555	802.65	321.06	152.89	114.66	80.27	61.74
Herefordshire, Worcestershire and Warwickshire	577	830.15	332.06	158.12	118.59	83.02	63.86
Lincolnshire	709	995.15	398.06	189.55	142.16	99.52	76.55
Shropshire and Staffordshire	844	1,163.90	465.56	221.70	166.27	116.39	89.53
Kent	923	1,262.65	505.06	240.51	180.38	126.27	97.13
Cornwall and Isles of Scilly	1,068	1,443.90	577.56	275.03	206.27	144.39	111.07

Note: Sequestration rate refers to the 100 year average.

5 Discussion

The primary finding of this dissertation is that the publicly available secondary data included here is insufficient to accurately calculate the exact price at which it becomes more profitable to grow trees for carbon sales than to continue with current farming practices on UK agricultural land. The uncertainty of calculation inputs available from publicly available data found during this dissertation, such as costs of establishment, costs of maintenance, expected sequestration rate, and current income from farming, mean that it is only possible to estimate a range of output values within which the true value is likely to fall. As shown in Table 4.4, the price received per unit at which it becomes equally profitable to plant trees and sell carbon credits or to continue with existing farm practices ranges from £9.53 to £123.90 per unit in the Highlands and Islands, depending on the sequestration rate that the farm is able to achieve, and assuming that the TIFF received by the farm matches the 2019 regional average and that all other calculation inputs are identical to those shown in Table 4.2. In practice, there is a large variation in TIFF between farms, as highlighted by SOURCE, and the values for other inputs, such as establishment costs, maintenance costs, species choice and planting density (both of which impact expected sequestration rate), are also likely to vary greatly between projects; for example, between the 16 Scottish Forest Alliance projects, average sequestration rates range from 0.09 to 5.25 tCO2/ha/year (Table 4.1).

Given the range of values provided in Table 4.4, it seems reasonable to assume that some farms in some regions will fall within the complete spectrum of transition prices identified; for example, it is likely that there are farms in the Highlands and Islands whose TIFF is $\leq$ £12/ha/year, and whose sequestration rate is $\geq$ 2.5 tCO2/ha/year (the Kinloch Hills project, located on the Isle of Skye, has an estimated sequestration rate of 2.43 tCO2/ha/year (See Table 4.1). If such a farm does exist, and the other calculation inputs identified in Table 4.2 are broadly similar, that indicates that the transition price for that farm would be around £49.56/unit. So how close is this to the going rate for WCC carbon units?

5.1 The Current Price of Carbon

Knowing the exact sale price of either PCUs or WCUs under the Woodland Carbon Code at any given time is difficult since, unlike the almost all other information about woodland projects, sales prices do not need to be publicly listed. Trading of units currently appears to occur between actors with little knowledge of the wider market: sale prices are not tracked or reported by any official body, can be subject to non-disclosure agreements, and appear to be strongly influenced by imperfect information, perceived co-benefits (biodiversity, social value, etc.), and unit location. As of May 2022, the Woodland Carbon Code advice on buying carbon units states that "companies are paying between £10 and £20" per PIU (WCC, 2022a), however, in April 2022, The Scotsman reported that the Trees for Life project in the Scottish Highlands has sold units for £40 each (Amos, 2022). Given that WCUs take a minimum of 5 years to be issued and that the WCC has only been running for around 10 years, there are comparatively few WCUs currently available to purchase (just 2,700 compared to 1,640,000 PIUs, as of May 2022 (WCC, 2022b)), however, in consideration of the fact that WCUs, unlike PIUs, can be used immediately as carbon offsets, it is likely that WCUs will demand a premium over PIUs, suggesting reported price per PIU can be used as a baseline for either unit type.

Based on a price per unit of £20, as stated by the WCC, only those farms with the highest sequestration rate and lowest TIFF in Table 4.1 are likely to currently be more profitable under woodland than existing production systems - and such farms, with sequestration rates of $\geq$ 7 tCO2/ha/yea but a TIFF of $\leq$ 12 £/ha/year, are unlikely to exist anywhere, since sequestration rate and TIFF positively correlate. However, once the price received per unit rises to £40, the transition to woodland being more profitable begins to look more likely in more locations. For example, the average income of Welsh farms was £134/ha/year in 2021 (Scottish Government, 2021), and the average rate of sequestration for broadleaf woodland in England is 7 tCO2/ha/year (Natural England, 2021). No secondary data on sequestration rates in Wales could be found, but using the English average as an input (and assuming costs etc match those in 4.2), the price required for afforestation to become more profitable than the previous farm system on the average Welsh farm is £39.49/unit - below the £40/unit reported to have been received by Trees for Life (Amos, 2022).

As stated in Section 5, there is a large amount of uncertainty surrounding the inputs to the calculation behind Table 4.4, for example ongoing woodland maintenance costs are very difficult to estimate, however, the fact that the four NUTS 2 regions highlighted by Table 4.1 as the most likely candidates where profitability of afforestation is begin to surpass the profitability of conventional farming, namely the Scottish Highlands and Islands, West Central Scotland, East Wales, and West Wales, are the very same regions where land purchases by non-farm actors expressly for purposes of afforestation are reported to be occurring (Garside and Wyn, 2021; Debbie James, 2021; Case, 2022; Scottish Land Comission, 2022), suggests that the calculations are likely reasonably accurate.

(NOTE: I have also been told of confirmed sales of "well over £60/unit" and rumoured sales of £80/unit, but I didn't get HERC approval so I'm not allowed to tell you that. . .)

5.2 The Future Price of Carbon

Currently, only a small portion of total emissions are capable of being offset through carbon credits in the UK. The WCC has issued a little over 6 million carbon units representing an expectation that 6 million tonnes of CO2 will be sequestered in WCC projects over the next 100 years (WCC, 2022b). This reflects around 5 days worth of the UK's total GHG emissions (DBEIS, 2022). However, Working Group III of the IPCC have stated that limiting global warming to 1.5 $°C$ cannot be achieved without carbon removals (IPCC, 2022), and the framework governing international trade of carbon offsets, Article 6 of the Paris Agreement, was finally agreed at COP26 in

2021 (Carbon Brief, 2019). Both of these events suggest a coming expansion in the use of carbon offsets both nationally and globally, but what can we say about the future price of carbon units?

Carbon storage in the biosphere, such as through afforestation, is rivalled by carbon storage outside of the biosphere, primarily through artificial Carbon Capture and Storage (CCS) technologies, such as Direct Air Carbon Capture and Storage (DACCS) and Bioenergy with Carbon Capture and Storage (BECCS). It seems reasonable to posit that if storage within and without the biosphere offer the same solution, removal of CO2 from the atmosphere, the price demanded by both solutions per tonne of CO2 removed will begin to align, meaning the stated aspirational price of CCS technologies could inform where biosphere-based carbon pricing will eventually peak.

In 2019, Stripe, one of the world's largest providers of "secure online payment processing", made a commitment to spend 1 million USD per year purchasing "negative CO_2 emissions [from CCS projects] at any price per tCO_2 [removed]" (Stripe, 2019), in an attempt to kickstart the CCS industry. In 2020, Stripe announced that it had invested in 4 carbon removal projects that had declared an expectation to be able to provide carbon removal at $<$ 100 USD/tCO2 by 2040 (Stripe, 2020); in spring 2021 announced 6 more projects with the same expectation (Stripe, 2021c); and in autumn 2021 announced 3 more projects for which the stated year in which the sub 100 USD target would be met was considered in their funding application (Stripe, 2021a, 2021b, 2021d). Relevant details of these investment are displayed in Table 5.1. In April 2022, Stripe and three other Big-Tech companies announced an intention to spend 925 USD over 8 years on CCS technologies (Meyer, 2022).

While the price per tonne of CO_2 paid to these projects - over 2000 USD/tCO_2 in one case - is far higher than the current price offered by carbon storage in the biosphere, such as through the Woodland Carbon Code, Stripe has stated that it is paying these prices with the explicit intention of being an early adopter in what

Table 5.1: 2020 and 2021 Stripe investments in CCS technologies.

Year	Providing Company	Price Paid ($/tCO2)	Predicted to Reach <100 $/tCO2
2020	Climeworks	775	2040
2020	Project Vesta	75	2040
2020	CarbonCure	100	2040
2020	Charm Industrial	600	2040
2021	CarbonBuilt	260	2040
2021	Heirloom	2054	2040
2021	Running Tide	250	2040
2021	Seachange	1370	2040
2021	Mission Zero	319	2040
2021	The Future Forest Company	200	2040
2021	Ebb Carbon	1950	2031
2021	Eion	500	2025
2021	Sustaera	700	2031

Source: See Stripe sources in text above.

it expects to become "a trillion dollar industry by the end of the century" once the price approaches 100 USD/tCO_2 (Stripe, 2019). A value of 100 USD/tCO_2 also features in other sources. Based on a review of relevant papers, Broehm et al. (2015) estimate that a reasonable long term range for the cost of DACCS is between 40 and 140 USD/tCO_2; the IPCC WG III Sixth Assessment Report (2022) states that anything under USD 100 /tCO2e is "economical"; and the CCC's *Sixth Carbon Budget* expects that carbon removal through new broadleaf woodland will cost £105/tCO2e by 2035 (CCC, 2020).

In an imagined world where TIFF remained fixed over the next 20+ years, selling carbon units at £100/tCO2 at an average sequestration rate of 7 tCO2/ha/yr would mean it were more profitable across much of the UK to plant trees than food, based on the results shown in Table 4.4.

5.3 Implications

The plot below builds on 4.3 and shows the amount of sequestration that will be achieved in 4 milestone years: 2022, 2025, 2030, 2050, 2100.

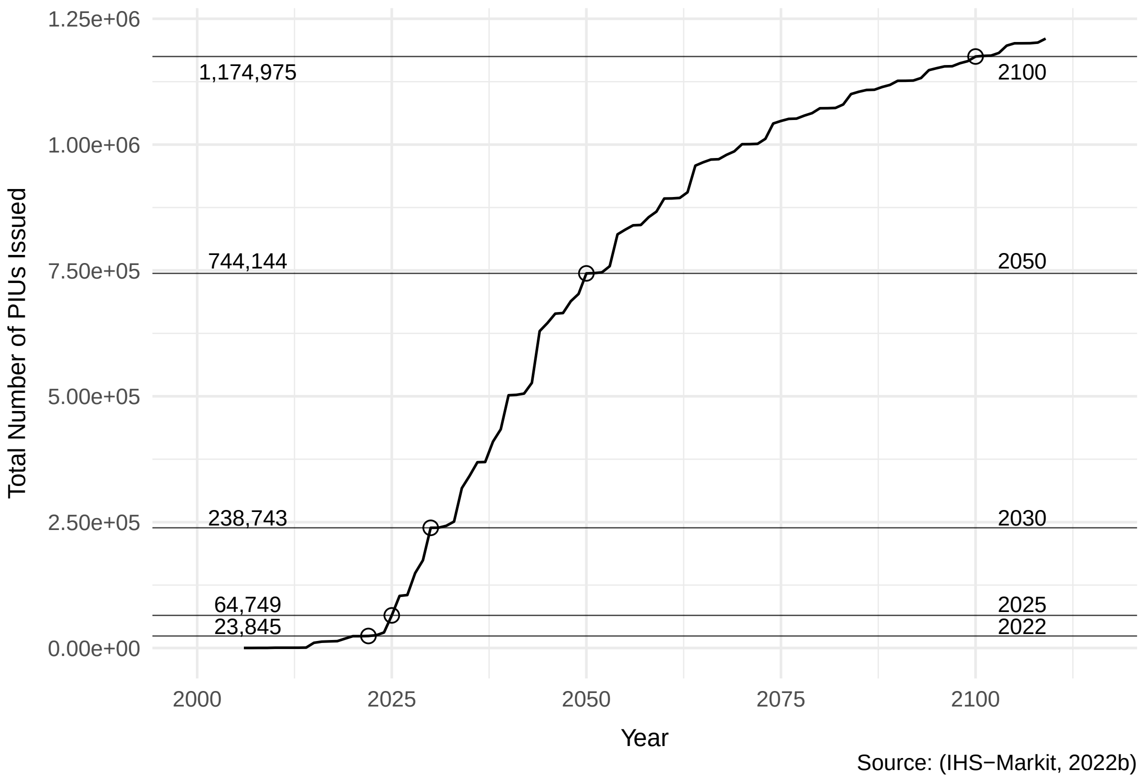

Figure 5.1: example caption

The IPCC have stated that Land-based sequestration "cannot be used to compensate for delayed emission reductions in other sectors" (IPCC, 2022). As explained in Section **??**, PIUs cannot be used as offsests until they mature, meaning the vast majority of this sequestration cannot yet be claimed as an offset. There is still time to regulate the industry further and limit offsets to those industries that cannot reduce their emissions.

Also talk about - the risk to tenant farmers + It isn't just food security that is affected by high carbon prices, but also job security - 30% of farms in wales are run by tenent farmers and already they are concerned about losing their lease to tree planting + "Tenant warning on notices to quit for landlord tree planting" (Debiie James, 2021) - food security implications + if it is more profitable to plant trees than food is there a risk of farmers stopping food production? Presumably market would respond. - Land use change + as above, if it is more profitable to plant trees than food is there a risk of exporting food production to regions with lower environmetal standards. - Own farm net zero ambitions + if farmers plant trees and sell all their C credits, what happens if regulations/market forces change and they need to offset their own emissions but have no on farm capacity to do so?

5.4 Limitations

5.4.1 Maps

A lot of effort was put in to developing a method to plot all results in the format of a map, as in Figure 4.1, since it was initially thought that this would be the most suitable way to convey results. However, since the profitability of afforestation directly corresponds to the profitability of farming, the maps all end up looking identical to Figure 4.1, except with different values displayed in the legend. A number of variant methods for using the map format were considered, but due to time constraints, none have been implemented.

5.4.2 Profitability

Changes in land price between different land use were not considered, although it is expected that land price will fall considerably if land is taken out of agricultural production.

Changes in labour requirement have also not been considered, although it is expected that managing a woodland for 100 years would require considerably less labour than 100 years of farming.

5.4.3 Assumptions

This dissertation assumes that TIFF will be fixed over the next 100 years, which it presumably won't.

This dissertation assumes that there will not be a carbon tax introduced, which may happen, and may limit the profitability of high emitting farm systems, such as ruminant livestock and peatland agricuture (i.e., the Fens).

This dissertation assumes that meat consumption will remain at current levels, although if there is a considerable reduction there may be a dramatic increase in upload areas upon which afforestation will be comparatively profitable.

5.5 Further Questions

This dissertation highlights two key areas to question going forward, one supply side, one demand side.

5.5.1 Supply side

Who is selling the carbon credits and does it matter?

The lack of transparency in carbon markets seems to be disadvantaging actors without extensive market knowledge, primarily farmers. Do we want to maximise cross-benefits of afforestation (erosion protection, biodiversity, etc), if so we need to convince farmers to start planting trees, or do we want to maximise carbon removals to improve our chances of limiting warming to 1.5 degC, regardless of who profits? Are these binary options, or can we have both?

5.5.2 Demand side

Who is buying the credits and does it matter?

As stated in Section 2.8, the IPCC and CCC have said that carbon offsets should be reserved for residual emissions, but the UK Government is encouraging open markets that will sell offsets to anyone. Why has the UK Government taken this approach? How much will this approach impact ambitions to limit warming?

5.6 Conclusion

. . . Sum up the dissertation. . .

Giulio Boccaletti has written that water utilities "are natural monopolies tasked with managing a public good... what is being paid for is not the commodity (water) but the social outcome (water security)." (Boccaletti, 2022). The same is true of organisations paid to remove carbon from our atmosphere, but researching this dissertation has revealed an industry, designed ostensibly to mitigate climate change, but steeped in 'commercial interests' and secrecy. The UK Government is encouraging the exchange of commodities (carbon offsets) with seemingly little regard for the necessary social outcome (mitigation of emissions). We are wasting our offset potential on everyday emissions, when we should be reserving offsets for those few sources that are truly infeasible to eliminate.

One of the highest forms of charity, according to the Jewish philosopher by Maimonides, is to give to an unknown recipient, and to receive from an unknown benefactor (Maimonides, 1180), and we are "the unlucky [generation] who must fix a problem [we] did not entirely cause to help save people [we] will never meet from disasters [we] can scarcely imagine" (Clark, 2022). We can't afford to waste the few oppertunities we have left.

A Appendicies

Appendix 1 - R Packages Used

Package Name	Description	Reference
bookdown	Authoring Books and Technical Documents with R Markdown	(Xie, 2016)
broom	Convert statistical objects into tidy tibbles	(Robinson, Hayes and Couch, 2022)
ggplot2	Elegant graphics for data analysis	(Wickham, 2016)
here	A Simpler Way to Find Your Files	(Müller, 2020)
janitor	Simple tools for examining and cleaning dirty data	(Firke, 2021)
kableExtra	Construct complex table with 'kable' and pipe syntax	(Zhu, 2021)
knitr	A General-Purpose Package for Dynamic Report Generation in R	(Xie, 2022)
plotly	Interactive web-based data visualization with R	(Sievert, 2020)
rgdal	Bindings for the 'geospatial' data abstraction library	(Bivand, Keitt and Rowlingson, 2022)
scales	Scale functions for visualization	(Wickham and Seidel, 2020)
tidyverse	Welcome to the Tidyverse	(Wickham *et al.*, 2019)
viridis	Colorblind-Friendly Color Maps for R	(Garnier *et al.*, 2021)
wordcountaddin	Word counts and readability statistics in R markdown documents	(Marwick, 2022)

Appendix 2 - Total Income From Farming Data

Table A.2 is plotted in Figure 4.1.

Table A.2: TIFF and Area by NUTS Level 2 region

Region	NUTS Level 2 Subregion	TIFF (£/ha)	Area (ha)	Year	Source
England	Cheshire	176	158,841	2,020	a
England	Cumbria	189	508,004	2,020	a
England	Northumberland and Tyne and Wear	218	405,386	2,020	a
England	South Yorkshire	228	82,199	2,020	a
England	North Yorkshire	235	665,750	2,020	a
England	Devon	243	513,683	2,020	a
England	Gloucestershire, Wiltshire and Bath/Bristol area	251	542,332	2,020	a
England	Tees Valley and Durham	253	197,954	2,020	a
England	West Midlands	253	14,259	2,020	a
England	Dorset and Somerset	260	471,513	2,020	a
England	Berkshire, Buckinghamshire and Oxfordshire	270	384,484	2,020	a
England	Leicestershire, Rutland and Northamptonshire	274	371,227	2,020	a
England	Essex	283	248,666	2,020	a
England	Bedfordshire and Hertfordshire	288	173,262	2,020	a
England	Lancashire	326	220,491	2,020	a
England	Derbyshire and Nottinghamshire	345	325,125	2,020	a
England	Hampshire and Isle of Wight	363	235,173	2,020	a
England	Greater Manchester	408	33,110	2,020	a
England	Surrey, East and West Sussex	419	278,495	2,020	a
England	West Yorkshire	428	92,830	2,020	a
England	Inner London - West	442	10,935	2,020	a
England	Merseyside	478	19,113	2,020	a
England	East Anglia	528	975,617	2,020	a
England	East Yorkshire and Northern Lincolnshire	555	274,156	2,020	a
England	Herefordshire, Worcestershire and Warwickshire	577	444,662	2,020	a
England	Lincolnshire	709	507,058	2,020	a
England	Shropshire and Staffordshire	844	473,462	2,020	a
England	Kent	923	229,583	2,020	a
England	Cornwall and Isles of Scilly	1,068	263,253	2,020	a
N Ireland	Northern Ireland	326	1,035,642	2,019	c, e
Scotland	Highlands and Islands	12	2,756,000	2,018	b
Scotland	West Central Scotland	33	107,000	2,018	b
Scotland	Southern Scotland	194	1,163,000	2,018	b
Scotland	Eastern Scotland	249	1,042,000	2,018	b
Scotland	North Eastern Scotland	281	536,000	2,018	b
Wales	East Wales	134	928,700	2,019	c, d
Wales	West Wales	134	928,700	2,019	c, d

Source:
[a] DEFRA, 2022
[b] Scottish Government, 2019
[c] Scottish Government, 2021
[d] Welsh Government, 2019
[e] DAERA, 2021

Appendix 3

Appendix 3 could be a list of transition price by NUTS 3 region in England.

NOTE: Remember to include sessioninfo() somewhere at the end!

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