An economic analysis of the establishment of forest plantations in the United Kingdom to mitigate climatic change

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ABSTRACT

This paper addresses the economic dimensions of climate change mitigation by afforestation in the UK and the necessity of reconciling sustainable development with carbon sequestration forest policy initiatives. Present value costs per tonne of carbon sequestration through the creation of new forests are estimated, and results of a static comparative analysis, aiming to show the influence of key variables on the costs, are presented and discussed. The paper provides empirical evidence of the cost effectiveness of the establishment of forest plantations for climate change mitigation in different locations in the UK, identifying also the importance of placing forestry for carbon sequestration in the general context of rural land use, where significant policy reforms can be anticipated. The evidence from this research suggests that the choice of location for forestry development, and of appropriate species and management regimes to be applied, are important factors in determining economic costs. Afforestation with relatively fast growing tree species (e.g. Sitka spruce) on low grade agricultural land (e.g. currently used for sheep grazing) may be a cost effective option. The general conclusion is that there is a case for forestry in the UK to contribute to climate mitigation, that woodlands expansion is likely competitive with other means of removing carbon from the atmosphere, and that in certain cases and locations, afforestation projects may provide relatively low cost options for carbon sequestration.

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1. Introduction

In the light of the Kyoto Protocol to the United Framework Convention on Climate Change (UNFCCC), the Parties committed themselves to stabilising atmospheric greenhouse gas (GHG) concentrations, including those of CO₂.¹ The commitment of the UK under the EU burden-sharing target is 12.5% GHG emissions reduction for 2008–2012, relative to the base year.² The target is to be achieved by both reducing emissions (sources) and removing GHG from the atmosphere (enhancement of sinks). Since the COP-7 in 2001, afforestation, reforestation, forest management and soil carbon have become eligible strategies (Read et al., 2009).

The UK has one of the lowest percentages of wooded land (12%) in Europe, but it has significantly expanded its wooded cover in the last hundred years (FC, 2010). The maximum rate at which the forests expanded during the 20th century was about 40 000 ha yr⁻¹ in the early 1970s (Cannell, 2003). However, the rate of forest expansion has fallen to an average of about 10 000 ha yr⁻¹ (FC, 2011). Currently, about 4 million tonnes of carbon is sequestered annually in forests in the UK, with 0.5 million tonnes of carbon from trees planted since 1990. Terrestrial carbon sequestration is considered important in the postponement or reduction of climate change, as it allows time for adaption, learning and technological innovation. Read et al. (2009) suggested a UK planting target of 23 000 ha yr⁻¹ and this, over 40 years, would involve changing the use of only 4% of the UK’s land, producing substantial carbon reductions.

Forestry development in the UK is supported by financial instruments which vary across the territory. For example, in England, the Forestry Commission (FCE) administers the English Woodland Grant Scheme (FCE, 2011). Grants and annual Farm Woodland Payments also encourage farmers to convert productive land into forest (FCE, 2011). In Scotland, as part of the Scottish Rural Development Programme (SRDP), new grants have been introduced bringing together a range of...
Rollinson, 2007; Tipper et al., 2004; Valatin, 2011; Valatin, 2012a; Moran et al., 2008; Morison et al., 2012; Price, 2008; Read et al., 2009; Rollinson, 2007; Tipper et al., 2004; Valatin, 2011; Valatin, 2012a; Valatin, 2012b; Stern (2006) explored the economic impacts of climate change and the cost of stabilising GHGs in the global atmosphere. Numerous studies carried out worldwide have addressed the cost effectiveness of afforestation/reforestation for carbon sequestration (Brainard et al., 2009; Newell and Stavins, 2000; Nijink, 2005; Nijink and Bizikova, 2008; Slangen et al., 1997; Stavins and Richards, 2005). van Kooten et al. (2004) carried out a meta-analysis of 68 such studies, with a total of 1047 observations, and identified substantial variability in marginal costs in different countries and in different settings. The analysis showed that carbon sequestration through the establishment of new forests could be costly, particularly in EU countries, but that it often compares well with the cost of technologies for carbon capture and storage (which is in the order of US$150 per tonne C). Also, it was shown that in some regions, marginal cost estimates from carbon mitigation by forests can be compared well with market prices of carbon (e.g. prices in the EU’s Emissions Trading Scheme (ETS)) stand at around €55.5 per tonne C.4 Point Carbon, 2011).5 A pilot evaluation of the cost effectiveness of forest establishment in the UK for carbon sequestration was published in the Final Report to the Committee on Climate Change (Moran et al., 2008). A national assessment of the potential of the UK forestry to mitigate climate change coordinated by the Forestry Commission (FC) was published in Read et al. (2009). In their contribution to these reports, the authors of the current paper showed that the mitigative role of new forests is mediated by externalities and uncertainties, and shaped by environmental, economic and policy drivers, market signals, institutions and governance, and public attitudes and behavioural patterns, at various scales (Nijink et al., 2009a). It was stressed that there is a need for further research on the cost effectiveness of climate change mitigation forestry opportunities for the UK, with identification of projects which will be coherent, effective, efficient, widely accepted by the public, and consistent with other aspects of policy for sustainable development (Nijink et al., 2009b).

The current paper extends work done previously on the economics of afforestation for carbon sequestration in the UK and internationally (e.g. Adger et al., 1997; Huang and Kronrad, 2001; Nijink et al., 2009b; Pajot, 2008). It modifies some of the earlier assumptions made by the authors and expands the scope of the analysis. The aim is to explore the economic justification for afforestation in the UK to mitigate climate change and to provide benchmarks for possible cross comparison analysis of different carbon sequestration options. The paper first presents the research methodology. Next, carbon sequestration rates and the potential of climate change mitigation through afforestation in the UK are analysed. Present value costs per tonne of carbon sequestration in new forests are estimated to provide empirical evidence of cost effectiveness. The paper takes into account various initial land uses and discount rates, spatial dimensions, various yield classes and regional timber prices of 2010. Results of a static comparative analysis showing the influence of key variables on cost are also shown and discussed. The paper concludes by offering some insights into the feasibility of climate change mitigation through afforestation and by providing ideas for future research.

2. Methodology

2.1. Key approaches available

The IPCC (2007) identified the following measures to increase the forestry contribution to carbon sequestration:

1. afforestation of abandoned and marginal agricultural land;
2. forest management to increase carbon density at the stand and landscape levels (e.g. maintaining forest cover, minimising forest soil losses, increasing rotation lengths, increasing growth and managing drainage);
3. increasing off site carbon stocks in wood products;
4. enhancing product and fuel substitution.

The current paper analyses the cost effectiveness of the first policy measure identified. Stavins and Richards (2005) distinguish three methodologies to analyse the economics of carbon sequestration through afforestation: econometric studies; sectoral optimisation models and a ‘bottom up’ approach. The ‘bottom up’ approach (Valatin, 2012a) is considered as the most straightforward way to carry out cost effectiveness analysis relevant to our research objectives and is used in this paper.

2.2. Baselines and carbon sequestration potential

Consideration of the UK carbon sequestration potential of afforestation was based on targets for planting set by the devolved forestry administrations. Thomson and van Oijen (2008) have developed three scenarios for forestry in the UK until the year 2020, in which the Tier 3 carbon accounting model CFLOW was used and annual planting statistics and management practices, including thinning regimes and rotation lengths, were considered (CEH, 2009). A high emissions scenario did not take into account any new planting. A second scenario projected the 2005 planting rate to occur every year until 2020. This is the mid emissions scenario which is considered as the baseline for afforestation. The third scenario projects a high planting rate of 30 000 ha yr−1. It is described as the low emissions scenario.

6 Carbon fixation alone has a one time effect, and eventually, through the decay of wood all the above ground carbon is released to the atmosphere. However, when trees are usually cut after they reach mean annual increment the carbon stored in wood products is an addition to the terrestrial carbon sink.

7 Wood received can be used as a substitute for fossil fuels, or timber used in wood products can later get burned. If energy required for harvesting and processing of wood is not taken into account, the use of timber as a substitute for fossil fuel is carbon neutral. The net gain here is the amount of CO2 that would have been released by burning fossil fuel if not replacing it with wood.

8 As shown by van Kooten (2004) on examples, particularly of forests in British Columbia, the social benefits of carbon capture and storage, and substitution effects, under wood product and bio energy scenarios are repeatable over rotations, and therefore expected to be considerably higher than under the strategy of carbon fixation alone.

9 It compares forestry and farming incomes and climate benefits (carbon sequestration in trees).
1. The Flow Summation approach consists of summing annual carbon sequestration patterns (i.e. fast growing versus slow growing plantations or projects aiming at sequestering carbon in the biomass versus projects aiming at sequestering carbon in soils). They are also suitable for considering the use of wood in wood products or as a substitute for fossil fuel. The discounting of both benefits and costs explained below (using the method applied e.g. in Nijnik, 2005; Nijnik and Bizikova, 2008) makes economic analysis, with a comparison of different mitigation options, more practical.

2. The Average Storage (stock) approach averages the carbon stocks over a given number of years. The project’s benefits are estimated, as follows:

\[ B = S_{m1} - S_{m2} \]  

(2)

where:

- \( B \) describes the benefits of the project;
- \( S_{m1} \) is the average stock produced by the first project;
- \( S_{m2} \) is the average stock produced by the second project.

The average stocks are calculated according to the following equation:

\[ S_{mi} = \frac{1}{T} \sum_{t=0}^{T} S_i(t) \]  

(3)

where:

- \( S_{mi} \) is the average stock produced by each of the two projects compared;
- \( i \) is either 1 or 2 of the projects.

Projects ‘one’ and ‘two’ are general cases considered by Richards and Stokes (2004). Our case presumes conversion of marginal agricultural land to forestry. Therefore, our case takes project 1 as afforestation, and project 2 as maintaining agriculture. The use of \( T \) is the rotation length; and \( S_i(t) \) is the carbon stock at time \( t \) by project \( i \).

However, early sequestration could be considered as having a greater value than late sequestration (for example, when biological sequestration is seen as a means to buy time, while waiting for climate-friendly technologies). Discounting techniques for carbon benefits can be used (van Kooten, 2004) to take this into account. In addition, they allow us to compare projects that exhibit different sequestration patterns (i.e. fast growing versus slow growing plantations or projects aiming at sequestering carbon in the biomass versus projects aiming at sequestering carbon in soils). They are also suitable for considering the use of wood in wood products or as a substitute for fossil fuel. The discounting of both benefits and costs explained below (using the method applied e.g. in Nijnik, 2005; Nijnik and Bizikova, 2008) makes economic analysis, with a comparison of different mitigation options, more practical.

3. The benefits can then be calculated using the Discounting Approach, as:

\[ B = \int_{0}^{T_1} S(t)e^{-rt} \, dt - \int_{0}^{T_2} S(t)e^{-rt} \, dt \]  

(4)

where:

- \( B \) describes the benefits of the project over time \( t \);
- \( S' \) describes annual carbon flow (change in carbon);
- \( T_1 \) is the rotation length implemented in the first project; and
- \( T_2 \) is the rotation length implemented in the second project.

\[ \text{Table 1} \]

UK carbon sequestration potential of afforestation, thousand tonnes C yr\(^{-1}\).

Source: authors’ computations based on Thomson and van Oijen (2008).

<table>
<thead>
<tr>
<th>Year</th>
<th>Carbon sequestration from forest land</th>
<th>Additional carbon sequestration potential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>Abatement</td>
</tr>
<tr>
<td>2007</td>
<td>3909</td>
<td>3867</td>
</tr>
<tr>
<td>2008</td>
<td>3761</td>
<td>3711</td>
</tr>
<tr>
<td>2009</td>
<td>3528</td>
<td>3495</td>
</tr>
<tr>
<td>2010</td>
<td>2939</td>
<td>2949</td>
</tr>
<tr>
<td>2011</td>
<td>2921</td>
<td>2991</td>
</tr>
<tr>
<td>2012</td>
<td>2715</td>
<td>2853</td>
</tr>
<tr>
<td>2013</td>
<td>2444</td>
<td>2648</td>
</tr>
<tr>
<td>2014</td>
<td>2331</td>
<td>2598</td>
</tr>
<tr>
<td>2015</td>
<td>2137</td>
<td>2464</td>
</tr>
<tr>
<td>2016</td>
<td>2107</td>
<td>2489</td>
</tr>
<tr>
<td>2017</td>
<td>2113</td>
<td>2548</td>
</tr>
<tr>
<td>2018</td>
<td>2114</td>
<td>2599</td>
</tr>
<tr>
<td>2019</td>
<td>1851</td>
<td>2386</td>
</tr>
<tr>
<td>2020</td>
<td>1376</td>
<td>1960</td>
</tr>
</tbody>
</table>

Sign ‘−’ indicates carbon removals.

and is taken as our abatement option for afforestation.\(^{10,11}\) Abatement potential was therefore determined relative to a business as usual baseline. Table 1 shows the additional carbon sequestration potential resulting from the greater rate of afforestation under the abatement option.

The emissions caused by soil disturbance occur in the first years after planting.\(^{12}\) Because of emissions from soil, the additional carbon sequestration potential becomes positive several years after planting and then progressively rises as carbon stocks increase in the biomass offset carbon emissions from soils.

2.3. Assessing the benefits of carbon sequestration

Three major groups of approaches briefly presented below have been suggested by Richards and Stokes (2004) to evaluate the carbon sequestration benefits of afforestation.

1. The Flow Summation approach consists of summing annual carbon flows over a given number of years (where the choice of end dates can be arbitrary and has a substantial impact on the results). The projected benefits are estimated, as follows:

\[ B = \int_{0}^{T_1} S(t) \, dt - \int_{0}^{T_2} S(t) \, dt \]  

(1)

where:

- \( B \) describes the benefits of the project over time \( t \);
- \( S' \) describes annual carbon flow (change in carbon);
- \( T_1 \) is the rotation length implemented in the first project; and
- \( T_2 \) is the rotation length implemented in the second project.

\(^{10}\) We note that in the absence of new planting, the current carbon sink function of the land use sector (strongly influenced by carbon sequestration in forests) will be altered. Land could even become a net carbon emitter.

\(^{11}\) For further consideration of the model and its projections see Thomson and van Oijen (2008) and for the way the projections were adopted by Pajot to analyse climate mitigation options for forestry, see Moran et al. (2008).

\(^{12}\) Thuille and Schulze (2006) showed that despite the comparatively larger amount of carbon stored in the growing trees, afforestation should also aim at the preservation/increase of carbon in the mineral soil regarding its greater stability compared with stocks in biomass and humus layers. If grassland afforestation is planned, suitable management options and a sufficient rotation length should be chosen to achieve these objectives. Maintenance of grass cover reduces the initial loss. Estimates of carbon losses from the afforested soils by Hargreaves et al. (2003) suggest that long term losses from afforested peatlands are about 0.3 tonne C per ha yr\(^{-1}\) thirty years after afforestation. The Forestry Commission has therefore implemented a policy prohibiting tree planting on peat lands.

The current paper is largely designed to provide benchmarks for possible comparison of the costs of climate change mitigation, and under the specific requirements of the UK Government (Moran...
et al., 2008) and in consideration of intergenerational equity, all carbon benefits in this paper are valued equally whenever captured. Therefore, carbon uptake benefits are not discounted, and the average storage (stock) approach (method 2 above) is primarily used. The exception is brief theoretical considerations about discounting and some final calculations showing the effect of using different discount settings on the results provided in Section 3.5.

2.4. Carbon sequestration rates

Carbon sequestration rates by forests vary depending on the tree species’ ability to grow and lock up carbon. A widely held assumption is that a tree approaches carbon saturation at maturity, and when it reaches saturation, carbon sequestration equals carbon loss through respiration and leaching (van Kooten, 2004). This current paper builds upon the work done by Bateman and Lovett (2000) that combines data from the FC Yield tables (Edwards and Christie, 1981) describing timber volumes and data on carbon storage in trees.

Sitka spruce (Picea sitchensis) is the most common species in UK forests (FC, 2010), and the study covers a range of Yield Classes (YC) between 12 and 24. The following function ($u_{TWCS}$) of total carbon storage in unthinned wood, by Bateman and Lovett (2000), for example, describes carbon storage of an unthinned Sitka spruce stand ($SS$) of YC 12:

$$u_{TWCS_{SS,12}} = 0.43727t + 0.10747t^2 - 0.0010267t^3$$

where:

$$t = \text{years from planting (} t = 0, 1, 2, \ldots, \text{)}.$$ 

A generalised function $u_{TWCS_{YC}}$ by Bateman and Lovett (2000) as considered in this paper for $i = SS$ (Sitka spruce stands) of any YC is:

$$u_{TWCS_{SS,YC}} = A_{SS,YC}u_{TWCS_{SS,12}}$$

By Bateman and Lovett (2000), carbon storage varies linearly across YC, and $A$ is the factor allowing for an approximate switching from the YC12 to any other Sitka spruce stand.

$$A_{SS,YC} = 0.08333YC$$

Further, a thinning factor allowed consideration of the impact of thinning on carbon stocks. A similar approach (functions) by the same authors is available and was applied in the current research paper for broadleaves. The results for thinned and unthinned stands for Sitka spruce and beech ($Fagus sylvatica$) based upon the Bateman and Lovett (2000) functions are summarised in Table 2.

The carbon sequestration rate for the new plantations was averaged over the length of the rotation and is, for example, 2.8 tonne C per ha (Sitka spruce, YC12, thinned). This is in the range of other estimates for UK (c.f. Broadmeadow and Matthews, 2003) and comparable or even slightly better than those in some other countries in Europe (Nijnik and Bizikova, 2008). Carbon sequestration rates between the tree species are shown in Table 2 for purposes of comparison. Although the demand for multiple ecosystem services from UK forestry will likely mandate a mix of coniferous and broadleaved species to be planted, this research addresses the establishment of tree plantations for climate change mitigation alone. Therefore, the planting of Sitka spruce was considered, for which the upper limit for carbon sequestration is comparatively high (c.f. Thomson and van Oijen, 2008). For the reason that sequestration rates for beech are lower, the option of afforesting land with beech for the purpose of carbon sequestration alone has not been considered further. It was assumed that all newly established forests will have the same growth characteristics as Sitka spruce under an intermediate thinning management regime. Further, because in this paper the tree-planting for carbon sequestration is considered, and carbon sequestration rates positively correlate with the growth rates of trees, we do not think about lower yield classes than 12.

2.5. An economic analysis of afforestation for carbon sequestration

The costs per tonne of carbon sequestration are computed by dividing the opportunity costs of land conversion to forests (Newell and Stavins, 2000) by the tonnes of carbon sequestered, Eq. (8). According to Stavins and Richards (2005), an important element affecting the costs of carbon sequestration through afforestation in the UK is the revenue that is foregone by diverting land from other (current) uses in order to establish a carbon sink.

$$CE = \frac{NPV_{Forestry} - NPV_{Farming}}{\Delta C}$$

where:

$CE$ is the cost effectiveness of carbon sequestration;

$NPV_{Forestry}$ is the NPV of forestry;

$NPV_{Farming}$ is the NPV of farming.

13 Discounting at a positive rate assigns insignificant present values even to considerable far away future damages/losses, consequently, advocating little immediate action as to climate change alleviation. Therefore, for decision making to favour the resilience to climatic changes: the more rapidly CO$_2$ concentrations in the atmosphere are projected to be increasing in time (and could lead to considerable future damages/losses), the less future carbon benefits should be discounted. Overall, largely because of uncertainties an important question that arises while employing economic analysis of planting trees to mitigate climate change is that of carbon discounting (Nijnik, 2002).

14 The model reported fits the data extremely well ($R^2 = 99.9$). All parameter estimates are statistically significant (a significance level of $P = 0.05$) and coefficients have expected signs and magnitudes. Figures in brackets are of t-statistics.

15 Yield class affects not just the rate of carbon accumulation, but the profile through time. However, in this paper, it was not analysed.

16 The main idea behind is that after thinning operations total tree carbon storage falls progressively below what is predicted by $u_{TWCS}$. Using data by Matthews (1991 and 1993), this proportion can be measured as the thinning factor and is provided in Bateman and Lovett (2000).

17 See, for example, Thuille and Schulze (2006) who explored carbon dynamics in Norway spruce (Picea abies) stands in Thuringia and the Alps.

18 An assumption was made of the tree species suitability to grow in 2050 and 2080, and e.g. climate and other drivers of changes were omitted from this pilot analysis.
NPV_{farming} is the NPV of farming; and
ΔC is the carbon stock gain over one rotation (i.e. ‘benefits’ of the project).

Forestry generates timber sales income through thinning and clear fell harvesting. We assess the benefits of forestry over one rotation, i.e. the ‘Fisher (single) rotation’ (van Kooten, 2004), seeing forestry as a temporary solution that enables society to buy time while waiting for low carbon technologies. A simplified form of the net present value (NPV_{forestry}) is:

\[
NPV_{\text{forestry}} = -c + p v e^{-rt} 
\]

where:
- \( p \) is the timber price;
- \( c \) is the plantation cost;
- \( v \) is the timber volume;
- \( T \) is a temporal variable;
- \( r \) is the discount rate.

Since there is no accurate measure of mean net farming incomes per unit area of farmland (NPV_{farming}), the revenues that are foregone by diverting land from other uses can be approximated by gross margins from current farming activities. Previous studies carried out in the UK used this approach (Moran et al., 2008; Nijnik et al., 2009b). However, considering that the use of gross margins likely overestimates the costs of carbon sequestration, since it only deducts variable costs (i.e. labour, fuel and fertiliser application) from the farm gross earnings, an approach based on land market values has been applied in this paper.

3. Results

The marginal costs vary with initial land use and also spatially for a given option (for example, because of variations in growing conditions and in the price of land). The discounting protocol also impacts on the costs of carbon sequestration. A static comparative analysis aiming to show the influence of these key variables on the costs has been carried out. It focused on the land use on which afforestation takes place, yield classes, locations and discount rates.

3.1. Opportunity costs of land

The costs of carbon sequestration through afforestation are analysed for various initial land uses and discount rates. Spatial dimensions of UK forestry, multiple yield classes and timber regional prices are also taken into consideration. Forestry generates income through thinning and clearfell harvesting. The amount of income depends on timber prices, available from the Forestry Commission

For England, Scotland and Wales. Tree planting costs (for example, of £1250 per ha for conifers) are based on data from Radov et al. (2007). As recommended by the HM Treasury (2003), a discount rate of 3.5% is used as a basic one to represent the attitude of a public investor. The private discount rate is higher, so we also considered a rate of 7%.

To account for the opportunity cost of land, we used the land market values (Table 3) which were investigated in the Agricultural Land Market Survey. We analysed the costs of carbon sequestration when low quality, medium quality and good quality land is considered for conversion to forest. The assumption was made that it would first displace uncultivated land with a low agricultural potential, i.e. used for low density sheep grazing.

3.2. Costs of carbon sequestration and initial land uses

The carbon sequestration costs for various initial land uses are presented in Fig. 1 ranking the cheapest places to afforest as low cost options and the most expensive places as high cost options. The example considers plantation of Sitka spruce forest in Scotland, YC 16 under a 3.5% discount rate assumption (only financial variables are discounted at this stage).

As expected, the conversion of the highest graded land to forests generates the highest carbon sequestration costs. The costs range from £15.4 per tonne C for low grade land (poor livestock) in Scotland to £75.7 per tonne C (prime arable), when high quality land is considered, and costs are discounted at 3.5%. The costs of carbon sequestration are lower than in our previous study (Nijnik et al., 2009b) and confirm that the use of gross margins overestimates the costs of carbon sequestration, whereas the use of land values, as in this paper, probably leads to more accurate estimations. However, public sector calculations relating to the implicit opportunity cost of land might still be overestimated.

The results provide empirical evidence in support of prospective afforestation of marginal land currently used for livestock (for instance, low density sheep grazing). The costs of carbon sequestration on poor livestock land and some Grade 3 livestock land may fall below the social value of carbon (approximately £18 per tonne C) proposed by DEFRA (2008). If those measures are undertaken, for example, it is less costly if environmental dis-benefits from initial/former land uses are fully taken into consideration (Valatin, 2012a).

Table 3

<table>
<thead>
<tr>
<th>UK regions</th>
<th>Prime arable</th>
<th>Grade 3 arable</th>
<th>Grade 3 livestock</th>
<th>Prime dairy</th>
<th>Poor arable</th>
<th>Poor livestock</th>
</tr>
</thead>
<tbody>
<tr>
<td>South East England</td>
<td>14,961</td>
<td>13,903</td>
<td>12,608</td>
<td>14,155</td>
<td>11,413</td>
<td>11,766</td>
</tr>
<tr>
<td>South West England</td>
<td>14,892</td>
<td>13,468</td>
<td>11,309</td>
<td>13,045</td>
<td>-</td>
<td>9,976</td>
</tr>
<tr>
<td>West Midlands</td>
<td>15,423</td>
<td>13,570</td>
<td>12,285</td>
<td>15,257</td>
<td>-</td>
<td>9,883</td>
</tr>
<tr>
<td>East Midlands</td>
<td>12,516</td>
<td>11,748</td>
<td>9,811</td>
<td>10,249</td>
<td>9,336</td>
<td>8,996</td>
</tr>
<tr>
<td>East of England</td>
<td>15,557</td>
<td>14,474</td>
<td>7,413</td>
<td>-</td>
<td>11,486</td>
<td>9,991</td>
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<tr>
<td>North of England</td>
<td>13,695</td>
<td>11,174</td>
<td>9,473</td>
<td>13,079</td>
<td>-</td>
<td>6,021</td>
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<tr>
<td>Wales</td>
<td>10,656</td>
<td>10,110</td>
<td>10,001</td>
<td>11,084</td>
<td>-</td>
<td>7,823</td>
</tr>
<tr>
<td>Scotland</td>
<td>13,501</td>
<td>9,722</td>
<td>4,684</td>
<td>8,323</td>
<td>-</td>
<td>2,871</td>
</tr>
</tbody>
</table>

24 We realise that land price represents a capitalisation of future net benefits and that arrangements for Single Farm Payment affect the private opportunity cost of forestry, representing money accruing other than for the physical product. However, in this pilot study, some assumptions and approximations have been made, including those on our computation of NPV_{forestry}. There is no accurate measure of mean net farming income per unit area of farmland in the UK and the use of gross margins from farming activities as the measure (Nijnik et al., 2009a, 2009b) probably overestimates the costs of carbon sequestration, since it only deducts variable costs from initial/former land uses.

25 For example, it is less costly if environmental dis-benefits from initial/former land uses are fully taken into consideration (Valatin, 2012a).

See for example Valatin (2011) for more information.
they will benefit society. However, in order to maximise the benefits of afforestation, the economic and climate policy considerations must be reconciled with a more holistic vision of sustainable forestry development, and an economic analysis should be supported by geographic information systems to balance trade-offs (e.g. between bioenergy production and biodiversity conservation, or carbon sequestration/energy generation and food production), and to avoid soil carbon losses.

3.3. Costs of carbon sequestration and yield classes

The analysis shows a negative relationship between yield class and the costs of carbon sequestration; an example of this relationship for low grade land in Scotland under a 3.5% discount rate is shown in Fig. 2 (only financial variables are discounted). This relationship is understandable as high yield classes that sequester more tonnes of carbon equate to higher timber revenues for forest businesses which, in turn, generate a higher NPV, and therefore, a lowering of carbon sequestration costs.

3.4. Costs of carbon sequestration across the location

The cost effectiveness of afforestation varies from region to region across the UK, because of different timber prices and of opportunity costs effects. Fig. 3 shows the example of afforestation of land ranked as “Grade 3 livestock” in various regions under a 3.5% discount rate and YC12 (only financial variables are discounted at this stage). Costs vary considerably, ranging from £26.7 per tonne C in Scotland to £65.3 per tonne C in South East England, where land values are high.

There are two opposite effects of location on the costs of carbon sequestration. On one hand, carbon sequestration is more cost effective when the timber price is higher (i.e. in England compared with Scotland), if other variables are kept constant. Higher timber prices generate a higher NPV of forestry, which then compares favourably with agriculture. On the other hand, carbon sequestration is less cost effective where the opportunity costs of land are high. Generally, this effect is stronger than the “timber price effect” inducing higher carbon sequestration costs in places where land values are the highest.

3.5. Costs of carbon sequestration and discounting protocols

Forestry is a long term activity that generates income over several decades. Therefore the economic analysis of forest plantations is considerably influenced by the discounting protocol used (Nijnik, 2002). Furthermore, the traditional framework of cost–benefit analysis...
(CBA) has been challenged for several reasons (Price, 2005), including that the use of a constant and positive discount rate reduces the weight of future benefits/costs, and intergenerational equity might be overlooked. Therefore, in the example given in Fig. 4, we analyse Sitka spruce plantations for various types of land under several discounting protocols applied (Eq. (8)). In line with Moran et al. (2008), we assume that the private discount rate is 7%, and that the social discount rate is 3.5%.

For the declining discount rate protocol in this research, the HM Treasury Guidelines (2003) were followed (Fig. 5) when incomes occurring in the years beyond 30 are discounted at a lower rate. The declining discount rates (DDR) applied to forestry and agricultural flows27 work in favour of forestry (by giving more weight to future financial flows compared to current ones). The declining discount rate protocol thus reduces the costs of carbon sequestration in forestry. This is reflected in calculations.

As discussed in Section 2.2, it is also possible to discount carbon (in physical terms) to take into account the fact that sequestration projects may exhibit various sequestration profiles, which means they are not equivalent in terms of their effects on climate. Whereas all major calculations have been made under the assumption that financial benefits were discounted, results with discounted (average) carbon benefits are now shown in Fig. 4 (black columns). Thus, financial costs can be compared with carbon storage benefits on an identical basis. When carbon fluxes are discounted at the same rate as the economic variables (3.5%), costs are severely impacted. They are almost doubled, as discounting of carbon fluxes reduces carbon benefits (the denominator of Eq. (8)).

### 4. Discussion

Carbon price volatility will remain an important factor to consider in economic analysis of afforestation for carbon sequestration (Nijnik et al., 2009a). EU ETS carbon prices may rise over time (as suggested by Turner et al., 2008). However, the development of a carbon market with an increase in the amount of carbon credits available may on the contrary push the price of carbon credits down. This is also driven by availability of “hot air”28 particularly in transition countries (Nijnik and Bizikova, 2008).29 A large inflow of REDD carbon credits (if it takes place) would mean a lowering of carbon prices across the globe (unless demand were to increase through tighter cap). This is because GHG mitigation through REDD projects is generally thought to be relatively inexpensive (with a reduction potential of 2.65 Gt tonnes at a cost below $14.7 per tonne C, Point Carbon, 2011b). Thus, the economically optimal level of mitigation through forestry, and the actual uptake of mitigation by private forest owners, including those in the UK, will depend on what is assumed about the global price of carbon (years into the future).

Van Kooten and Sohngen (2007) argue that, if the opportunity cost is fully taken into account and emissions reduction credits can be purchased for ca. US$26110 per tonne C, the carbon sequestration through tree planting (and fuel substitution) in tropical and boreal regions will be generally competitive with emissions reductions (Table 4). In Europe, marginal costs of creating carbon offset credits through forestry are much higher.

Results of this research add to the evidence suggesting that an important factor influencing the costs of carbon sequestration through afforestation is the opportunity cost of land, which in the UK is often high. It suggests that afforestation for carbon sequestration should be focused on the less productive land in the UK rather than considering larger scale afforestation. The decline of hill farming may create space for new economic activity on abandoned farmland, among which could be forestry.31

Choice of discounting protocol has a dramatic impact on the economic acceptability of an afforestation project. Higher discount rates reduce the present value of future forest operations. Clear cutting is distant in time, and is more affected by a high discount rate than agricultural annual income flows. This reduces the relative value of

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27 Timber harvesting is distant in time, and is more affected by a high discount rate than annual agricultural flows of income.
28 ‘Hot air’ concerns the amount by which the emissions have been reduced below their target levels.
29 In May 2006, when several countries revealed registries indicating that their industries had been allocated more allowances than they could use, trading prices crashed from about €110.1 per tonne C to €36.7 per tonne C, and (after a slight recovery) declined to below €0.2 per tonne C in December 2007 (Point Carbon, 2011a).
30 In September 2012, 1US$ approximately equals to £0.61, for a more detailed information see: http://www.xe.com/ucc/
31 The issues of institutional changes and future cash flow for and responses of farming enterprises merit attention but are beyond the scope of this paper. Also, shifting to forestry would depend on whether agricultural subsidies continue to hold up land prices and whether cultural values would affect the propensity to develop forest-based activities on private land, including those of tree-planting.

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**Fig. 5.** The long term discount rate based on HM Treasury Guidelines of 2003.

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**Table 4** Marginal costs of creating carbon offset credits through forestry, $ per tonne C. Source: adapted from van Kooten and Sohngen (2007).

<table>
<thead>
<tr>
<th>Activity</th>
<th>Global</th>
<th>Europe</th>
<th>Boreal</th>
<th>Tropics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planting</td>
<td>81–121</td>
<td>580–680</td>
<td>18–470</td>
<td>0–26</td>
</tr>
<tr>
<td>Planting and fuel substitution</td>
<td>0–180</td>
<td>422–686</td>
<td>3.67–330</td>
<td>0–84</td>
</tr>
<tr>
<td>Forest management and fuel substitution</td>
<td>176–283</td>
<td>740–804</td>
<td>161–396</td>
<td>0–184</td>
</tr>
<tr>
<td>Forest conservation</td>
<td>172–716</td>
<td>n.a.</td>
<td>n.a.</td>
<td>95–499</td>
</tr>
</tbody>
</table>

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forestry compared to agriculture and generates higher carbon sequestration costs. The declining discount rates applied to both forestry and agriculture work in favour of forestry (by giving more weight to future financial flows of income compared to current ones). Nevertheless, there are situations when short term benefits could be preferred to long term benefits. For example, climate change is characterised by thresholds beyond which irreversible effects appear. If the threshold is close, we might prefer a strategy sequestering carbon as quickly as possible or drastically reducing emissions. The discounting of carbon stocks changes is also an issue that merits attention, as its influence on the results of economic analysis is substantial (Fig. 4).

This pilot economic analysis considers carbon forestry alone. However, carbon sequestration forestry projects are likely to be implemented if they are consistent with the wider programmes of sustainable rural development (focusing on multiple social, economic and environmental objectives). This particularly concerns remote rural areas where carbon sequestration forestry projects could combine the socio economic objectives with the enhancement of nature and rural landscape. National programmes supporting carbon sequestration forest-based activities in the UK focus largely in rural areas. The effective measures aim for “win–win” situations to benefit rural development, people, the economy and the environment (Rollinson, 2007).

An ecosystem services approach (Millennium Ecosystem Assessment 2005) which is currently widely espoused as a suitable lens through which to explore multifunctional rural land use, fits well for the understanding of UK forestry. The multiple purpose land use considerations would help to prevent potential conflicts between ‘development’ and ‘conservation’ and to manage possible conflicts relating to trade offs, e.g. between biodiversity and carbon sequestration, or between landscape amenity values and those of climate change mitigation. However, there remains much to do to find acknowledged mechanisms for balancing trade-offs and attaining an ‘optimal’ (case specific) solution for appropriate stakeholders. For example, although multipurpose afforestation may result in lower rates of carbon sequestration, it is expected to be more attractive to people, as in the majority of cases, it will provide additional benefits and will promote sustainable rural development (Nijnik and Bizikova, 2008). In the UK, the role of forestry is deemed to be particularly relevant to regions that have a potential for tree planting (as in Scotland), and where cost effectiveness of afforestation, social acceptability of forestry options, challenges of forest development on high carbon soils, using wood for energy and in wood products projects, are important future topics.

Woody biomass is being recognised as a renewable energy source with low GHG emissions (Galbraith et al., 2006; HMG, 2009a; Matthews and Robertson, 2003; Read et al., 2009), and grant aid (e.g. the Energy Crop Schemes in England and Scotland) is available in many parts of the UK (HMG, 2009b). Policy support for renewable energy is likely to increase the demand for wood, as should any differential tax on non-renewable energy (Atanasiu, 2011). The optimum policies tend to link carbon sequestration in forestry with the long-term substitution of wood in renewable energy projects and in construction. The wood products pool in the UK is estimated to be 80 million tonnes of carbon stored (excluding landfill). It is growing at 0.44 million tonnes C yr⁻¹ (Broadmeadow and Matthews, 2003). The building of more timber-rich houses and increasing the service life of wood products are considered by UK policy makers to be valuable contributions to reducing carbon impacts, and particularly in the long perspective, when the land now available for the establishment of forest plantations is exhausted and forest carbon gets stabilised (Sutcliffe et al., 2009).

5. Conclusions

Carbon sequestration in forestry could contribute modestly but significantly to UK emissions reduction (Read et al., 2009). Carbon sequestration rates per unit area of forest in the UK are comparable with those in other countries in Europe (Nijnik and Bizikova, 2008). The carbon sequestration potential of afforestation in the UK is deemed to be substantial. Although this potential is restricted by various factors, including socio economic, the results suggest that forest carbon sequestration is likely to be competitive with other means of removing carbon from the atmosphere. The results provide evidence in support of prospective conversion to forest of some marginal land currently used for low density sheep grazing. About 5.5 million ha of this land type is available in the UK (ADAS, 2007). With an afforestation rate of 30,000 ha yr⁻¹ (i.e. the abatement option used in this study), there would be enough land for tree planting until 2020 (and even until 2200).

The sensitivity analysis shows that carbon sequestration costs vary negatively with yield class and timber prices. Yield class is also an important variable determining the viability of forest based business. It changes considerably across UK territory. Higher yield classes generate higher wood volumes, from thinning and clear cutting operations. Therefore, the present value of forestry is much higher for the upper range of yield classes, which then generates relatively low costs of carbon sequestration (as shown in Fig. 2). Moreover, choosing appropriate tree species and locations for tree planting are important considerations. Afforestation with relatively fast growing tree species (e.g. Sitka spruce) on low grade agricultural land may be a cost effective option, ranking the costs in some regions of the UK below the shadow price of carbon estimated by DEFRA (2008).

Although the current paper is limited to afforestation, future research will go beyond a single rotation and take a longer-term, holistic perspective reflecting on time preference (by discounting of both, costs and benefits of carbon uptake) and taking into account future use of land and wood after timber harvesting. This particularly concerns carbon storage in wood products, the quantities of which are anticipated to be significant.

Acknowledgement

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References


See also Bottcher et al. (2012) who bring in many of the discussion points mentioned for future work and integrate more over other options than just afforestation.

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CEH No. CD1116.


