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Carbon sequestration benefits of new native woodland expansion in Scotland

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ABSTRACT

Native woodland expansion is a key objective in the Scottish Forest Strategy with a specific intent of enhancing the contribution of forestry to climate change mitigation. The Scottish Forest Alliance has established fourteen sites, with long-term sustainable management plans, for native woodland creation. A primary objective is to yield information on site specific changes in carbon, as woodlands develop, through research driven monitoring that provides robust data for the enumeration of changes in carbon stocks in vegetation and soils.

Since 2002 in excess of 3.8 million trees have been established over 3500ha, through a combination of planting and natural regeneration. This effort is predicted to result in woodland capture of 377830 tonnes of carbon (equivalent to nearly 1.4 million tonnes of CO_2) over the first 100 years of the project, and deliver a verifiable carbon offset of 220000 tonnes of carbon. This equates to an average carbon abatement of around 50 t C ha^{-1} of newly established forest over 100 years.

KEYWORDS
afforestation, woodland, carbon, sequestration, abatement

INTRODUCTION

Forests play a significant role in the global carbon cycle through dynamic exchange of CO_2 with the atmosphere. The management of such terrestrial forest carbon stocks can deliver a significant component to national climate change abatement strategies (Read *et* al. 2009, Anon 2010). Therefore, land-based carbon stocks and their rates of accumulation are of scientific, economic and political interest (e.g. Watson *et al.* 2000*,* Pacala *et al.* 2001). However, the values of land-based carbon exchange (flux) and changes in pools and stocks are poorly known and need to be quantified in the context of the requirements of the Kyoto Protocol (Article 6: UNFCCC, 1997) and wider scientific interests (e.g. IPCC 1999). In order to accurately measure carbon sequestration benefits, it is first necessary to establish a carbon baseline from which additional carbon benefits can be measured and monitored. Carbon may be stored or sequestered in the key components of forest ecosystems and their associated carbon pools and as such newly planted forests offer the potential to offset CO_2 emissions by taking up and storing carbon in forest biomass and soils (Black *et al.* 2008). Land-use change, *i.e.* afforestation, can result in dramatic changes in soil carbon stocks, with, for example, conversion of agricultural crop land to forest plantation having a positive effect and pasture to forest plantation having a negative effect on soil carbon (Guo and Gifford, 2002). Other reviews (Polglase *et al*., 2000; Paul *et al*., 2002) have found that changes in soil carbon after afforestation were limited. Currently the impacts of afforestation on site carbon balance, specifically the effects of cultivation on soil carbon, are poorly defined and understood (Mason *et al.* 2009). Soil carbon can represent a significant proportion of the total forest carbon pool (up to 97% in some Scottish Forest Alliance sites) any management practices that affect forest soils could significantly alter carbon stocks.

In the UK changes in land use through forestry activities are registered on official planning documentation held by the Forestry Commission and, if within the reporting requirements of LULUCF ARD activities, accounted for in the estimation of removals by sinks in the National GHG Inventory. There is also interest in forest offsets from carbon buyers in the voluntary market, where a wish to offset a portion of personal or business emissions whilst supporting projects with multiple social and environmental benefits is met. This unregulated market is currently being addressed in the UK by development of a Code of Good Practice for Forest Carbon Projects by the Forestry Commission, on behalf of the forest industry.

In this context the large-scale afforestation programme developed under the Scottish Forest Alliance and funded by BP is not designed primarily to generate carbon value, but carbon credits which may accrue are held by BP. These efforts also accrue significant additional social, environmental and economic value as part of the lasting legacy from the native woodland expansion (Smith *et al.* 2010, Shorthall *et al.* 2010). In this paper we describe the underpinning scientific protocols and methods for estimating the carbon sequestration and abatement potential provided by this programme of native woodland expansion and discuss them in the wider context of forest abatement strategies.

MATERIALS & METHODS

The Alliance instigated the development of a robust scientific assessment of site carbon which was underpinned by the creation of a Carbon Working Group. Membership of the Group was drawn from each of the Alliance member organisations and drew upon external scientific expertise and advice. This ensured a thorough understanding of the issues with respect to carbon stocks and the assessment of impacts from Alliance activities.

Assessment of Carbon Baseline

Measurement of carbon stocks requires, at the start of a project, that a baseline assessment is obtained against which to monitor the effects of project activities. An assessment of potential non-project activities resulted in a decision to assume a static baseline scenario on Alliance sites, where it was assumed that no significant carbon sequestration would occur at the sites in the absence of the project. This was based on brief analysis of historic land use trends and reflected the decline in the rate of new native woodland afforestation in Scotland. For carbon offset projects the baseline reflects changes in carbon stocks that would have occurred if there was no project intervention. Only additional carbon sequestered as a result of project activities should then be accounted for in calculating carbon offset.

Soils & Vegetation Assessments

In 2002 a detailed site baseline carbon study was conducted at Glen Quey. The existing vegetation was predominantly grassland and bracken with some soils, particularly on the upper slopes of Glen Quey, being highly organic with peat present. Glen Quey comprises 383 hectares of former hill-grazing located on predominantly steep hillside in the Ochils (NGR NN 980030). The assessment at Glen Quey tehn underpinned the development of a stratification and site sampling strategy for subsequent sites in which sampling locations were determined using a 1:25,000 soil survey map with stratified random sampling within soil categories using distance as a variable to ensure spatial independence of sample cores. The sampling regime was then applied across other sites after nominating the remaining sites into priority and complementary ones, based on scheme size. The work programme required that priority sites should be sampled so that a change of 20% mean detectable difference or less could be detected in the future; the minimum detectable change at the complementary sites was set at 30% (*cf.* Conen *et al.* 2005). This approach follows recommended standard statistical sampling practice, as described by MacDicken (1997). The MDD corresponds to the size of the difference required between the means of different samples in order for the difference to be statistically significant.

At each sample point both vegetation and soil samples were taken. At the sample location, the litter was removed and collected before a soil sample tube with an internal diameter of 5.7 cm and containing an internal plastic liner (Giddings Machine Company, Fort Collins, CO, USA) was driven to > 30 cm into the soil perpendicular to the slope using a 7.26 kg sliding hammer. The sample was then divided into two sections organic (O) and mineral (A).

Once roots and stones (>2mm) were removed and weighed, the sample was reweighed and sub-samples of soil were analysed using an elemental analyser (Carlo Erba, 1106). Root samples for each horizon were bulked and analysed separately.

The pools of carbon that will be subject to change on SFA sites as a result of project activities are soil, above ground vegetation, and below ground vegetation (trees and herbaceous plants). These pools will change at different rates and at different scales. These pools are divided into a number of components which will require measurement or extrapolation (using conversion factors) to ensurew a robust monitoring scheme and verifiable detection of change (Table 1).

Table 1 Pools and components

Biomass Pool	Component	Assessment Frequency	Method of measurement
Above ground	Tree stems	5, 10, 20, 30, 40, 50…	Sample
Above ground	Tree branches and foliage	-	Sample or conversion factor[1]
Above ground	Deadwood	-	Sample or conversion factor
Above ground	Shrubs	5, 10, 20, 30, 40, 50…	Sample
Above ground	Herbaceous layer	10, 20, 30, 40, 50…	Sample
Above ground	Leaf litter	-	Sample or conversion factor
Soil	Organic soil carbon	20, 40…	Sample
Soil	Inorganic soil carbon	20, 40…	Sample
Below ground	Roots	-	Sample or conversion factors from stem biomass
Off site	Harvested timber	5, 10, 20, 30, 40, 50…	Inventory/Records (this is considered leakage under CDM)

[Mark] Conversion factors are more commonly referred to as allometric biomass regression equations or co-efficients

Forest Carbon Sequestration Potential

In addition to establishing an evidence-based carbon baseline for SFA sites, it was also necessary to predict the net carbon benefits that will result from the afforestation activities.

An estimate was obtained by application of a bespoke empirical forest carbon model. The model approach was to estimate the carbon sequestered by an area of woodland into the carbon pools contained in tree biomass including on-site biomass (including stemwood, crownwood, foliage and large roots) and off-site biomass (including thinnings and timber products arising from management). The gains in carbon for each of the carbon pools through time were estimated separately for each species. Appropriate native species were selected based on site soils and silvicultural knowledge, with areas assigned National Vegetation Classification (NVC) woodland types (Rodwell 1991) based on an Ecological Site Classification (ESC) assessment (Pyatt *et al.* 2001). Standing and thinned timber volumes, taken from Forestry Commission yield tables (Edwards and Christie 1981) were then used to predict per hectare carbon storage at five year intervals, using an area-based single-species approach. Data on wood density were then used to calculate the quantity of carbon stored in woody material (Lavers 1983). The volume of branches was determined from the standing timber volume. The volume of branch wood left in the forest after thinning and the volume of timber used in forest products was determined from the thinning volume. The carbon content of foliage, fine roots and litter was calculated using parameters derived from the literature (Cannell and Milne 1995). The application of the model allowed for both forest carbon sequestration and a verifiable offset to be calculated over a 100 year time horizon following the method for reconciling emission and sequestration processes, proposed by Tipper and de Jong (1998).

In addition a repeatable sampling and reporting structure for gains in above ground carbon sequestration, directly attributable to the development of native woodlands across Scottish Forest Alliance sites has been developed and will allow, over the 200 year lifetime of this unique partnership, permanent and verifiable gains in woodland carbon sequestration.

Potentially Damaging Operations

Within the sustainable forest management plan for each SFA site a series of potentially (carbon) damaging operations was noted for managers to report against. These include silvicultural management activities (e.g. tree removal, ground disturbance, thinning), changes in livestock (e.g. sheep grazing area, deer) and site management activities (e.g. drainage, prescribed burning). From area estimates a total carbon impact can then be calculated using literature values (*cf.* Mason *et al*. 2009, Matthews and Broadmeadow 2009).

RESULTS

Detailed baseline site assessments and modelling of potential forest growth have occurred for twelve SFA sites (Figure 1) excluding Loch Katrine in the Trossachs and Drumbow in Falkirk region.

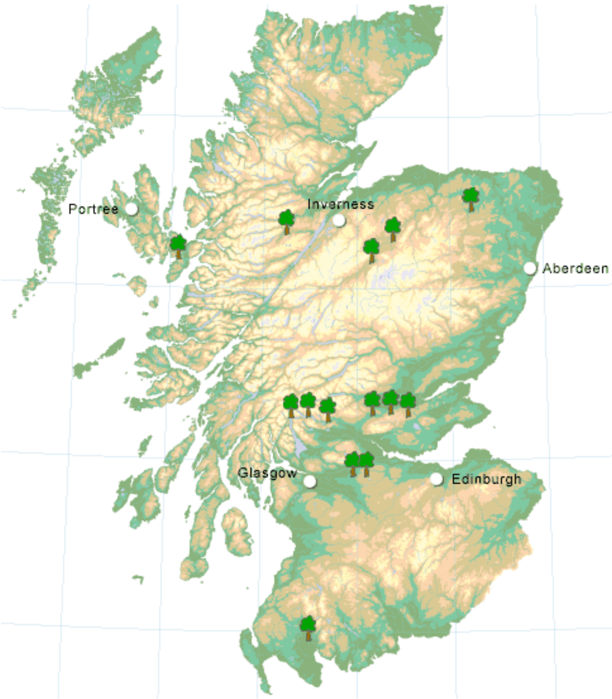

Figure 1. Geographical location of all fourteen Scottish Forest Alliance sites.

In total the management area across the fourteen sites is 13323 ha with plans for afforestation with new native woodland across 6468 ha. For the twelve sites that have been assessed for a baseline carbon audit the modelled potential gain is 377830 t C sequestered over a 100 year period, with a verified offset potential of 220549 t C, equivalent to 808753 t CO_2eq (Table 1). Across the sites between 93 and 98% of all site carbon was assessed to be contained within the soil as evidenced from the baseline assessment sampling and analysis (Table 1). The mean offset (*i.e.* abatement) potential was estimated to be 53.9 tC ha^{-1} (equivalent to 197.7t t CO_2eq ha^{-1}) over the first 100 years of the project. The average carbon sequestration potential per year from native woodland creation was estimated to be 0.54 tC ha^{-1} y^{-1}.

The soil assessment methodology was estimated to provide a mean detectable difference from 14% to 23% across the twelve sites (Table 1). At Glen Quay, where more intensive assessments were conducted the large sample size allowed total carbon storage to be estimated, with soil found to contain 67504 t C and vegetation 740 t C, respectively.

Across the SFA sites upland nutrient poor soils predominated, with NVC woodland type selections focused on planting of Birch-oak woodland (W17), Pine-birch-rowan woodland (W18) and on more fertile and moist soils Oak-birch woodland (W11), Ash-alder woodland (W7) and Aspen-birch (W9b) on moist fertile soils at lower elevations. In waterlogged ‘boggy’ areas W4 willow-birch is also suitable.

The contribution of each NVC woodland type to the model-based prediction of long-term carbon benefit were calculated using an area based single-species approach. This results in estimated figures of, for example, 90 t C sequestered per hectare for W11 Oak-Birch Oxalis woodland, providing 56t C offset at Clashindarroch over an area of 110 hectares.

Table 1. Summary of Scottish Forestry Alliance site afforestation projected net benefits.

Site	Location	SFA project area (ha)	New woodland (ha)	Year of work	Veg Baseline (mean carbon content) (gCm^{-2})	Soil Baseline (mean carbon content) (gCm^{-2})	Woodland Carbon Sequestration (tC)	Woodland Offset potential (tC)	Mean Offset potential per hectare (tC/ha)	Resultant MDD
Glen Quey	Ochil Hills	383	303	2002	185*	16897*	30023	19511	64.4	7%
Glen Sherup	Ochil Hills	605	421	2003	474	15811	33372	21105	50.1	18.75%
Abernethy	Strathspey	1868	1254	2003	1089	16253	130625	58,431	46.5	16.3%
Darrochwids (Clashindarroch)	Huntly	500	388	2003			32779			
▪ Old Meldrum			{ 84}		365	9486	{21379}	4191	49.8	22.5%
▪ Blackmiddens			{ 62}			11957	{ 4477}	2674	42.8	17.3%
▪ Coynachie			{242}			6706	{ 6923}	12953	53.5	15.9%
Drumbow	Falkirk	65	39	2004	257	11362	2134	1705	43.9	22%
Kinloch	Skye	3661	1083	2004	722	6928	91331	62781	57.9	27%
Glen Finglas	Trossachs	231	154	2005	429	8646	11266	8363	54.3	19%
Glenmore	Strathspey	1445	15 [potential = 115]	2005	298/421	17245/15988	1527	603	50.3 [45.4]	17% / 19% 21% / 22%
Geordies Wood	Ochil Hills	246	124	2005	343	17007	12012	7831	63.8	18%
Garrisons (Inversnaid)	Loch Lomond	443	250	2005	363	9034	779	510	86.6	18% [^{3}14%]
Barclye Farm	Dumfries & Galloway	371	233	2006	407	12782	12659	8447	40.9	20%
Corrimony	Central Highlands	1531	230	2006	510	16413	19323	11444	49.8	20%
Crossrig	Falkirk	124	124	2005	data pending survey & analysis					
Loch Katrine	Trossachs	1850	1850	2009	data pending survey & analysis					
TOTAL [incl. Loch Katrine & Crossrig]		11349 [13323]	4494 [6468]				377830	220549		

DISCUSSION

The forestry sector has a huge potential to contribute to the mitigation of climate change (Malhi *et al.* 2002). In a recent UK review Read *et al.* (2009) highlighted that forestry can make a significant and cost-effective contribution to meeting the UK's challenging emissions reduction targets.

However, best choice management evaluations are hampered by both considerable uncertainty and difficulty in analysing net carbon balances (Cathcart and Delaney 2006). Globally there is about three times as much carbon in soils as in vegetation, with the largest proportions in the northern temperate and boreal forests (Roy *et al.* 2001). Carbon stocks in soil can often exceed those in vegetation by *c*2:1 in northern temperate forests to over 5:1 in boreal forests (Schlesinger, 1997). Whilst changes in soil carbon stocks can be determined many samples are required to achieve adequate precision over short (decadal) periods (Conen *et al*., 2005). To date studies of forest carbon balance and carbon flux, in the UK, have focussed on high carbon content (peat) soils where afforestation could cause significant initial carbon loss from the soil if drainage and ploughing occur (Hargreaves *et al*. 2003; Zerva and Mencuccini, 2005a). This potential loss has been estimated at up to about 20–25% of the total carbon in the peat (Harrison *et al*., 1997; Jones *et al*., 2000). Reynolds (2007) analysed four upland UK afforestation sites by modelling of biomass carbon accumulation and showed that, despite a loss from the peat (soil) of 0.5 tC ha^{-1} year^{-1}, the forest stand net ecosystem productivity was around 45 tC ha^{-1} over a 26-year period (1.72 tCO$_2$eq ha^{-1} year^{-1}). Zerva and Mencuccini (2005b), assessed a peaty-gley site in northern England, and found the first 40-year rotation resulted in a decrease in soil carbon of 3.4 tC ha^{-1} year^{-1}. They attributed this decline to accelerated decomposition caused by drainage and cultivation. Subsequently, in the second rotation there was a recovery of soil carbon. However, the estimates from these studies have a large degree of variation associated with them (*cf.* Conen *et al*., 2005). Across the Alliance sites there is a mosaic of NVC woodland types, and corresponding variation in soil types. As such the baseline assessment provides a comparative investigation of initial site carbon stocks and will, over time, enable investigation of tree-soil interactions on site carbon capture.

The maximum rate of forest growth expected on SFA sites is Yield Class 6-8 Scots pine, Ash and Aspen, Yield Class being the maximum mean annual increment of a crop in cubic metres per hectare (*cf.* Edwards and Christie 1981). In conjunction with the specific gravity of timber, Yield Class can be used to estimate the amount of carbon in a forest. The relatively low yield, compared to productive coniferous forestry in upland UK, evident from such new native woodland planting reflects site conditions, species mix and relatively low stand density targets for such schemes. However the development of these schemes under the principles of sustainable forest ecosystem management aims to provide growing societal demands for forest services and functions beyond economic timber production (Spiecker 2003). These demands include delivery of ecosystem services at the landscape scale for social benefit, biodiversity enhancement and water quality (Smith *et al.* 2010). As such the science underpinning the SFA afforestation effort is providing key methodological developments in the assessment of carbon and a long-term scientific resource for continued investigation of the issues of forest mitigation and adaptation.

In 2007/8 Forestry Commission Scotland approved 1500ha of woodland creation (Forestry Commission 2008), excluding SFA sites, under a specific climate change afforestation programme, and assisted through grant aid planting of 2415ha of new native woodland on private land. The efforts of the Scottish Forest Alliance are considerable with respect to these Scottish national figures. The key milestone for forestry in the Scottish Governments Climate Change Delivery Plan is to increase planting rates to 10,000 -15,000 hectares per year by 2015 and to sustain that rate thereafter to maintain the levels of carbon sequestered annually in trees and soils and maximise the abatement potential of woodland creation in mitigating climate change. There is also a specific recognition that new models for financing the enhanced planting rates are required. Forestry Commission Scotland is actively considering alternative approaches to increase afforestation rates.

Within this wider framework the SFA is a world-leading demonstration of the potential for commercial corporate social responsibility objectives to be met, in part, by collaboration with land-based organisations in the development of woodland generated climate abatement projects. In a recent study Moran *et al.* (2008) estimated the carbon sequestration costs, through woodland creation, were estimated to range from £8 per tCO2 (afforestation of sheep grazing areas) to £48 per tCO2 (for afforestation of agricultural land), using a discount rate of 3.5%, for productive Sitka spruce. In a recent review Nijink *et al.* (2009) identified the major constraints to the inclusion of carbon credits from forestry being ‘leakage’, double-counting and high transaction costs associated with measuring, assessing and monitoring of carbon. Further analysis of native woodland establishment has shown, that as part of an enhanced forest abatement planting strategy, over the longer-term (century) timescale considerable abatement (>1055 tC ha^{-1}) can be achieved whilst also delivering ‘high value’ ecosystem services (conservation, biodiversity) and social value (Matthews and Broadmeadow 2009). Furthermore, for native pine woodland expansion this has been shown to occur at low annual cost when compared against other afforestation types. In addition, it is imperative in the future that a valuation of the forest benefits encompassed by the term ‘ecosystem services’ are accounted for.

The SFA methodology outlined in this paper demonstrates that the use of site-soil stratification and a statistical assessment approach can deliver mean detectable differences of 20-30% in soils where afforestation projects, designed with carbon abatement as a goal, are considered. This is a robust and relatively cost effective method to benchmark the long-term effective net benefit from afforestation and address the question of permanence with respect to delivery of forestry carbon credits, including soils. Whether afforestation for multiple benefits, as with SFA sites, or management focussed on maximising short-term (decadal) forest abatement potential is targeted the overarching methods and knowledge which underpin the SFA assessment protocols are fit-for-purpose.

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