FORSEE Project

A network of pilot zones to test and improve the indicators of the sustainable forest management at the regional level on the Atlantic Europe area

Regional Final Report
Ireland

PART 4: SCIENTIFIC REGIONAL STUDY ON CRITERION 1

May 2006

Carly Green
(FORSEE Lead Scientist, University College Dublin)

FORSEE Project (20) *www.iefc.net*

Project co-financed by the European Union
A community initiative
ERDF - INTERREG IIIB *Atlantic Area*

The following paper will be submitted for publication as a result of research funded by the FORSEE project;

Green C, Tobin B, Conway M, and Farrell EP. Carbon stock changes in young conifer plantations afforested on blanket peat. To be submitted to Forest Ecology and Management following internal review.

Table of Contents

1. Objectives

Estimates of forest biomass stock are an important indicator of sustainable forestry, being a gauge for forest health and economic vitality. Although biomass estimates have long been a measure of forest productivity, the inclusion of land use change and forestry activities as mitigation measures in global climate change policy has placed new emphasis on developing such estimates. Areas of human induced afforestation since 1990 are recognised as potential carbon (C) sinks under Article 3.3 of the Kyoto Protocol (KP) (UNFCCC 1997). As such, under the terms of the KP rulebook, known as the Marrakech Accords (MA), C measured as an increase due to a human induced land use change can be accounted against national greenhouse gas (GHG) emissions from other sectors during the KPs first commitment period (2008-2012).

Although Ireland has a relatively small area of forest cover by European standards, it has one of the highest annual rates of land use change to forestry (FRA 2000). Over 3.2% of the national land area was converted to forest between 1990 and 2003, the majority planted along the countries western seaboard (Anon 2005). Ireland now has the largest potential forest area in the European Union eligible for Article 3.3 reporting to the Kyoto Protocol. Consequently, its potential contribution to the migation of the nations ever increasing GHG emissions (Howley and O'Gallachoir 2005) is enshrined in national policy (Anon 2000).

C stock estimates on lands afforested since 1990 must be inclusive of five C pools to be eligible for reporting to the KP. Estimates of these pools, namely the above- and belowground biomass, litter, deadwood, and soil organic carbon (SOC), must be developed in a transparent and verifiable manner in accordance with the International Panel for Climate Change (IPCC) good practice guidance for the Land Use, Land Use Change and Forestry Sector (GPG LULUCF) (Penman et al. 2004). This requires that nationally specific activity data and emission factors and models be used to ensure estimates with the lowest possible uncertainty.

As such, there is increased interest in collecting data and development of models that are representative of the specific forestry conditions found where levels of afforestation are high. Focusing research in these areas will ensure that the C sequestration potential of forests is fully understood and that estimates with the lowest possible uncertainty will be achieved and subsequently that the mitigation potential of these areas will be fully acknowledged in the national GHG accounting methodology.

Therefore the objectives of this study were to;

1. Develop biomass functions to estimate above and belowground biomass in typical forest

areas found in the region

2. Investigate the potential contribution of understorey biomass to the total forest C stock in forest planted post 1990

3. Develop a regional C stock estimate, with uncertainty, in accordance with IPCC good practice methodology, with a view as a template for developing national C stock estimates.

2. Material and Methods

C stock estimates were developed within a selected pilot zone in accordance with the IPCC GPG LULUCF (Penman et al. 2004). These estimates were inclusive of the five identified forest C pools and were developed using data from the national forest inventory (NFI) in conjunction with regionally specific models, which were developed as part of this project.

2.1 Pilot zone Description

This study was undertaken with the administrative boundary of county Mayo, located along the western seaboard of Ireland. The pilot zone area was defined as North Mayo (Figure 1) encompassing an area of 243,000 ha of which 37,350ha is classified as forest land. Within this region the landscape ranges from relatively flat farmed fields in the east to quartzite peaks along the Atlantic coastline.

The pilot zone, as with the majority of the west coast of Ireland, experiences annual rainfall in excess of 1140mm per year, and mean temperatures in January of 5.7 °C and in July of 14 °C (Collins and Cummins 1996). The predominant soil type is classified as Histosol.

By definition, a forest in Ireland is described as an area greater than 0.1 ha with a minimum width of 20 m. Crown cover must be in excess of 20% and the forest must consisit of trees that have the potential to reach 5 m in height and includes recently clearfelled areas.

Trees grown for fruit or flowers and woody species such as furze (*Ulex europeaus*) and rhododendron are excluded (Hendrick, E. personal communication, 29th October, 2005)[1]. Area estimated from NFI grid plots in the region indicate 35 600 ha of forestry, or 14.6% of the total pilot zone area. Of this, 12 800 ha or 36% has been planted post 1990. Natural forest cover stands at less than 1% within the county and is representative of the rest of the country (Anon 2003). North Mayo has a long agricultural tradition. Average area of holdings is 22 ha (Crowley

[1] This definition varies only on the specification of minimum area (and width) from definitions historically reported to the FAO (TBFRA 2000) The reduction in area from 0.5 ha is primarily associated with administration of forest areas in Ireland with the minimum area eligible for forest establishment grants and ongoing premiums is 0.1 ha.

et al. 2004). Sheep and cattle grazing typify land use prior to afforestation. Diversification by

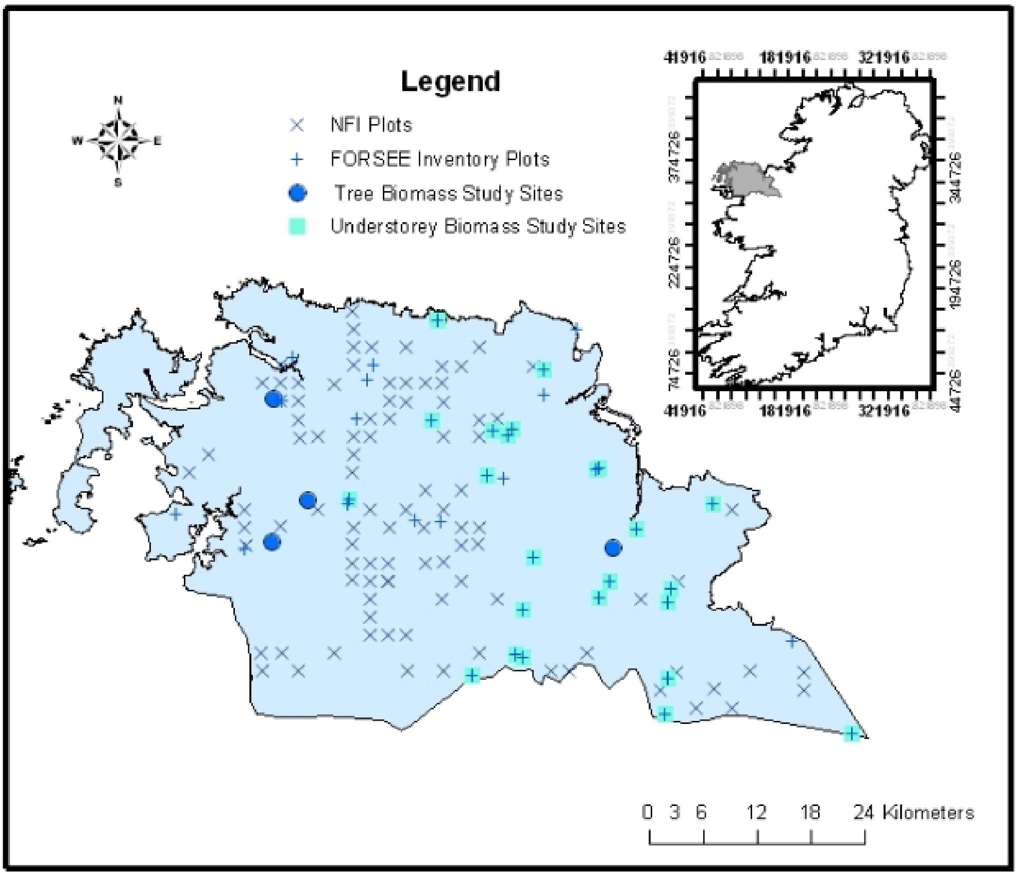

Figure 1: North Mayo Pilot zone boundary and location of dedicated research sites and NFI plots.

farmers in the area has resulted in the majority (75%) of post 1990 plantations being in private ownership, with an average area of 9 ha. These plantations primarily consist of pure stands of Sitka spruce (*Picea sitchensis* (Bong.) Carr) and lodgepole pine (*Pinus contorta* Douglas ex. Loud.) or intimate mixtures of both species. Few broadleaf plantations are found due to the unfavourable soil conditions in the region.

2.2 Model Development

Measurements and samples were taken of tree and understorey biomass at dedicated research sites (Figure 1b) to develop models for the estimation of above- and belowground biomass. A total of 31 research sites were used, five in the development of biomass functions for both Sitka spruce and lodgepole pine and a further 26 in the development of models linking tree attributes to understorey biomass stock. Estimates of the C stock in the litter, deadwood and SOC pools were developed through the application of emission factors based on both national research and expert judgement. All models and emission factor applied in the development of C stock estimates are listed in Tables 1and 2. For more detail on model development and emission factor selection see Appendix B and (Green et al. 2006a).

2.3 Regional C Stock Estimate

C stock estimates in post 1990 forests within the pilot zone were developed using data from national forest inventory (NFI) plots (Figure 1c), which was collected in the region in 2005. Total area estimates were generated on the 2 x 2 km NFI grid basis using simple area of proportions methodology with NFI data from each plot being representative of 400ha. The appropriate models and emissions factors were applied to develop a C stock at each plot which was then upscaled to 400 ha and all plots aggregated to produce an estimate for the pilot zone (Green et al. 2006a).

2.4 Current C increment

The C stock estimate at each plot was divided by the stock to allocate an average C increment over the age of the stand. This was then used to produce a C increment map for the pilot zone. Areas of high and low C increment within the pilot zone were then identified.

2.5 Uncertainty Analysis

Uncertainty analysis was undertaken using a Monte Carlo simulation software package known as Crystal Ball (Decisioneering 2005). Monte Carlo analysis randomly generates C stock estimates from the uncertain parameters using an iterative process. Each time the program selects a new value from each parameter's defined probability density function (PDF) until the procedure stabilises toward a smooth frequency distribution. From this distribution the mean stock and overall uncertainty is determined. For a more detailed explanation of the Monte Carlo approach to estimating uncertainty see Winiwarter and Rypdal (2001) and Monni et al. (2004) and Green et al. (2006a).

In this study 10,000 iterations were used and uncertainties given as the upper and lower bounds of the 95% confidence interval, expressed as a percent relative to the mean value. Uncertainty associated with activity data and emissions factors (Tables 1 and 2) were allocated based on domestic and international literature, expert judgement, and/or recommendations by the IPCC.

The same software package was used to conduct a sensitivity analysis to determine the contribution of each input parameter to the overall uncertainty estimate, leading to the identification of possible areas of future research.

Table 1: List emission factors used for each carbon pool in the development of regional C stock estimates. Taken from (Green et al. 2006a)

Input	**Value**	**PDF**	**min/5%[a]**	**Max/95%[b]**	**Source**
SOC_{ref} - $SOC_{NonForestLand}$ ($t\ C\ ha^{-1}\ yr^{-1}$)[b]	0.7	Normal	0.57	0.83	(Green 2006b)
$EF_{Drainage}$	-1.0	Uniform	-0.60	-1.4	Adapted from (Byrne and Farrell 2005)
ΔC_{LTt} ($t\ C\ ha^{-1}\ yr^{-1}$)[c]					
Coniferous	0.25	Normal	0.15	0.35	(Green 2006b)
Broadleaf	0.8	Normal	0.25	1.55	IPCC Table 3.2.1

a. Probability distribution function

b. max and min refers to the extreme values used in uniform PDF. 5 and 95% are extreme values used in normal and lognorm PDF

c. The default transition time period of 20 years was applied as specified in Penman et al, 2004.

Table 2: Biomass functions, root:shoot ratios (R) and associated uncertainty applied to the NFI plot data in development of tree carbon stock estimates. Taken from (Green et al. 2006a)

Species	Form[1]	a	b	c	Reference	Uncertainty (%)
Picea sitchensis (small[1])[ab]	aln(H)+b	2.876	0.442		(Green et al. 2006b)	5.1
Pinus contorta (small)[ab]	aln(H)+b	2.876	0.442		(Green et al. 2006b)	5.1
Picea sitchensis[ab]	$A(DBH(H))^b$	0.140	1.23		(Black et al. 2006)	8
Pinus contorta (stem)[+]	aD^b	0.049	2.429		(Gholz et al. 1979)	23
Pinus contorta (foliage)[+]	aD^b	0.024	1.836		(Gholz et al. 1979)	48
Pinus contorta (branches)[+]	aD^b	0.009	2.353		(Gholz et al. 1979)	49
Picea abies (small)[+]	$aD^2+b(D-c)$	200.37	99.36	25	(Braekke 1986)	30
Picea abies[+]	aD^b	0.272	2.104		(Jokela et al. 1986)	15
Larix sp.[+]	aD^b	0.095	2.357		(Ker 1980)	14
Fraxinus excelsior[*]	a+b(lnD)	-2.460	2.488		(Bunce 1968)	30
Salix sp.[*]	aD^b	0.062	2.509		(Perola and Alban 1994)	30
Understorey vegetation	$a\exp^{(bH)}$	18.96	-0.65		(Green et al. 2006b)	48

1. Small trees are defined as being below merchantable timber volume (i.e. DBH < 7 cm)

ab indicates that above and belowground are incorporated in the equation

+ Root:Shoot ratio of 0.46 (±111%) applied taken form IPCC Table 3A1.8

*Root:Shoot ratio of 0.43 (±91%) taken from IPCC Table 3A.1.8

3. Results and Discussion

Within the pilot zone a total of 124 NFI plots were identified of which 32 were located in post 1990 forests (Figure 1). The distribution of the plots indicate the non-continuous nature of forest land in the pilot zone, a result of numerous private owners with relatively small forest holdings by European standards (FRA 2000). For ease of discussion these plots were categorised into three main areas, Northern, Central and Eastern. Forest age was found to be evenly distributed between the three zones. As expected, the main two species were Sitka spruce and Lodgepole pine, the main soil type organic and most stands were in private ownership (See Appendix A).

3.1 Regional C Stock Estimate

C stock estimates for each pool were calculated for the year 2004 (Table 3). The above- and belowground C pool was the largest contributor to the total forest C stock in the pilot zone. The contribution of the understorey biomass to the estimates for the above- and belowground biomass pool was almost 11%. Previous stock estimates for forestlands in Ireland do not take into consideration the C stock in the understorey (Gallagher et al. 2004). The results of this study indicate that its contribution in post 1990 forests is comparable with that measured in the litter C pool (Table 3).

Table 3: Pilot zone carbon stock estimate for each forest pool estimated from 2004 NFI plot data.

Carbon Pool	2004 Stock Estimate (t C)[a]	Uncertainty (%)
Above- and Belowground	**-265271**	**13**
Trees	-237114	14
Understorey	-28157	23
Litter	**-29400**	**49**
Soil Organic Carbon	**106040**	**19**
Total	**-188631**	**11**

a. Negative numbers represent C uptake (sink) and positive numbers C release (source).

Emissions from the SOC pool were significant to the overall C stock budget as the predominant (i.e. 91%) forest soil type in the pilot zone, identified from NFI data, was organic. The remaining plots were identified as a wet mineral gley. The C emission from afforested organic soils (Table 1) sometimes resulted in the plot estimates (and subsequently its representative forest area) being identified as a source of C. This occurred either where the forest plot was located in stands in the very early establishment phase or in a stand experiencing low productivity (Green et al. 2006b). In both cases tree biomass and therefore C increment in the above- and belowground C pool was lower than 1 t C ha^{-1} yr^{-1}. A total of four plots (or 1600ha) in the region were classified as being a source of C in 2004.

The litter pool contributed 7% to the total C stock and had the highest associated uncertainty. This is largely due to the emission factor being selected from only one national study (Green 2006b) that had not been verified in the region. Although the value compared well with published default values (Penman et al. 2004) more research on litter accumulation in the region would be required to improve on estimates for this C pool.

The total C stock in the pilot zone was estimated as 0.19 Mt C ± 11% (Table 3). Afforestation in the region could offset 1% of the nation's reported annual emission in 2004 (McGettigan et al. 2006) (Box 1). Applying the current trade price for C of €12[2] per ton of CO_2 equivalent, this resource is worth $7.5 million.

3.2 Uncertainty and Sensitivity Analysis

The uncertainty associated with the total C stock in the LULUCF sector was relatively low compared with that reported by other Parties to the KP (Green 2006a). This was the result of the targeted research in key areas undertaken in the pilot zone. A sensitivity analysis of all the parameters used to generate total C stock estimates found that three sources of uncertainty were responsible for over 95% of the total uncertainty (Table 4). The most significant was the variability of tree data collected in the NFI. Such variation is typical of stands in the early establishment phase. This combined with a small NFI plot radius (3 m) and subsequent small sample results in this variability being responsible for over 60% of the total uncertainty.

The total uncertainty would also benefit from improved confidence in the emission factor for organic soils. This would come from increased research to enable modelling of the full C budget for afforested organic soils.

[2] Available at http://blog.carbon-360.com. Last accessed 26th May 2006.

Table 4: Sensitivity of each parameter to the confidence in the overall C stock estimate

Carbon Pool	**Contribution to Overall Uncertainty (%)**	**Source of 95% of the uncertainty**
Above- and Belowground	60.6	NFI plot tree height variance
Soil Organic Carbon	25.4	Confidence in emission factor
Litter	10.9	Confidence in emission factor

3.3 C Incement Map

Annual C increment varied greatly throughout the pilot zone (Figure 2) ranging from a sink of 8 t C ha^{-1} yr^{-1} to a source of 0.5 t C ha^{-1} yr^{-1}. In general the Eastern area experienced considerably higher C increment compared with the other two regions. This supports published productivity maps that indicate conditions in this area are likely to support forests of higher productivity than in the northern and western areas of the pilot zone (Anon 2003).

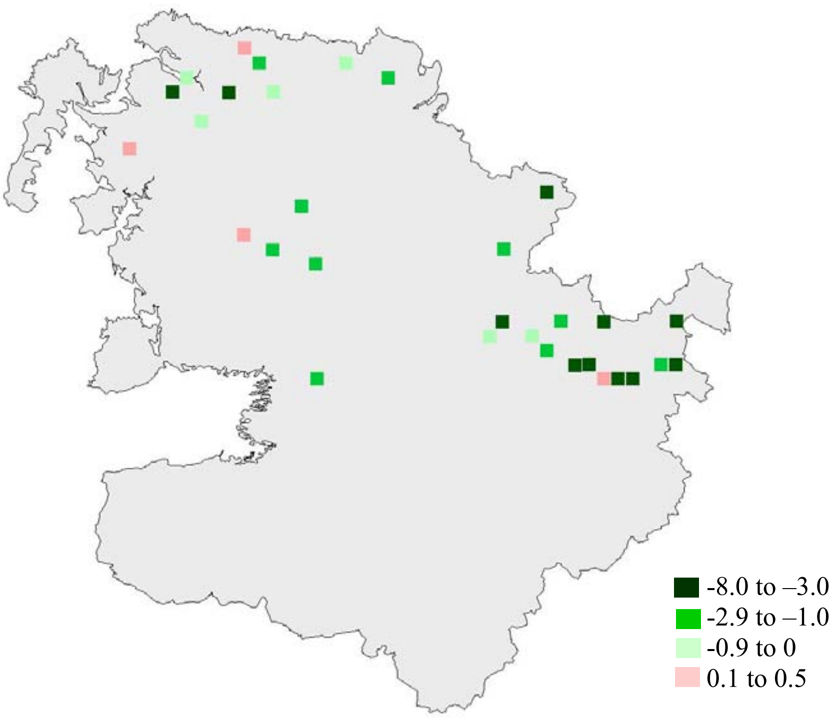

Figure 2: Average carbon increment (t C ha^{-1} yr^{-1}) map for North Mayo Pilot zone 2004. Each point is representative of 400 ha. Negative values represent a C sink, positive a C source.

4. Conclusion

Within the pilot zone 12 800 ha of forest have been planted since 1990 and the C stock in these forest in 2004 was 0.19 Mt C. The large majority of the C stock is associated with the above- and belowground biomass pool, however this is substantially offset by emissions from drained organic soils. Research funded by this project enabled the above- and belowground biomass to be estimated with a relatively high level of confidence. Further research is now required into emission factors for both the soil organic carbon and litter pools to improve the overall C stock estimate.

This C stock within the pilot zone has an important role to play as a GHG mitigation measure. As a C sink the resource has a market value of €7.5 million. Forests within the pilot zone area provide an important contribution to the mitigation of national C emissions at present and will continue to do so into the future.

References

Anon (2000). National Climate Change Strategy Ireland. Dublin, Department of Environment: 14.

Anon (2003). Indicative Forest Strategy for County Mayo. Johnstown Castle Estate, County Wexford, Forest Service, Department of Communications, Marine and Natural Resources: 20.

Anon (2005). National Annual Afforestation Statistics. Johnstown Castle, County Wexford, Forest Service.

Black, K, T Bolger, P Davis, M Nieuwenhuis, B Reidy, G Saiz, B Tobin and B Osborne (2006). Inventory and Eddy Covariance-Based Estimates of Annual Carbon Sequestration in a Sitka Spruce (<I>Picea Sitchensis</I> (Bong.) Carr.) Forest Ecosystem. European Journal of Forest Research: 1-12.

Braekke, FH (1986). Distribution and Yield of Biomass from Young Pinus Sylvestris and Picea Abies Stands on Drained and Fertilised Peatland. Scandinavian Journal of Forest Research 1: 49-66.

Bunce, RGH (1968). Biomass and Production of Trees in a Mixed Deciduous Woodland. I Girth and Height as Parameters for the Estimation of Tree Dry Weight.

Byrne, KA and EP Farrell (2005). The Effect of Afforestation on Soil Carbon Dioxide Emissions in Blanket Peatland in Ireland. Forestry 78(3).

Collins, JF and T Cummins, Eds. (1996). Agroclimatic Atlas of Ireland. Dublin, AGMET.

Crowley, C, D Meredith and J Walsh (2004). Population and Agricultural Change in Rural Ireland - 1991-2002. Rural Development Conference, Dublin, Teagasc.

Decisioneering (2005). Crystal Ball 7.2. Monte Carlo simulation tool for Excel spreadsheet.

FRA (2000). Global Forest Resource Assessment 2000. Main Report, FAO.

Gallagher, G, E Hendrick and KA Byrne (2004). Preliminary Estimates of Biomass Carbon Stocks in Managed Forests in the Republic of Ireland over the Period 1990-2000. Irish Forestry 61(1): 35-46.

Gholz, HL, CC Grier, AG Campbell and AT Brown (1979). Equations for Estimating Biomass and Leaf Area of Plants in the Pacific Northwest. after Ter-Mikaelian, 1997.

Green, C (2006a). Improved Methods for Estimating and Reporting Carbon Stock Changes on Afforested Lands in Accordance with International Climate Change Policy. School of Biological and Environmental Science. Dublin, University College Dublin: 223.

Green, C (2006b). Improved Methods for Estimating and Reporting Carbon Stock Changes on Afforested Lands in Accordance with International Climate Change Policy. School of Biological and Environmental Science. Dublin, University College Dublin: 208.

Green, C, E Farrell and K Byrne (2006a). Kyoto Carbon Budgets for Afforestation Activities Reportable under Article 3.3. Submitted to Climate Policy.

Green, C, B Tobin, EP Farrell and M Nieuwenhuis (2006b). Carbon Stock Changes in Young Conifer Plantations Afforested on Blanket Peat. Submitted to Forest Ecology and Management.

Howley, M and B OGallachoir (2005). Energy in Ireland. Trends, Issues and Indicators. Dublin, Sustainable Energy Ireland: 70.

Jokela, EJ, JP Van Gurp, RD Briggs and EH White (1986). Biomass Estimation Equation for Norway Spruce in New York. Canadian Journal of Forest Research 16: 413-415.

Ker, MF (1980). Tree Biomass Equaitons for 10 Major Spescies in Cumberland County, Nova Scotia. after Ter-Mikaelian, 1997.

McGettigan, M, P Duffy and N Connolly (2006). National Inventory Report 2005. Greenhouse Gas Emissions Reported to the United Nations Framework Convention on Climate Change. Johnstown Castle Estate, Wexford, Ireland, Environmental Protection Agency.

Penman, J, M Gytarsky, T Hiraishi, T Krug, T Kruger, D Pipatti, L Buendia, K Miwa, T Ngara, T Tanabe and F Wagner, Eds. (2004). Ipcc Good Practice Guidance for Land Use, Land Use Change and Forestry. Ipcc National Greenhouse Gases Inventories Programme. Hayama Kanagawa Japan, Institute for Global Environmental Strategies (IGES).

Perola, DA and DH Alban (1994). Allometric Biomass Estimators for Aspen-Donimated Ecosystems in the Upper Great Lakes, US Forest Service Reseach Paper.

UNFCCC (1997). Report of the Conference of the Parties on Its Third Session, Held at Kyoto from 1 To 11 December 1997. Kyoto.

Appendix I – Data

National Forest Inventory Plot Data – Page 1

Plot No.	X	Y	Plot NFI ID No.	Stand Age	Owner	Soil Type	Species 1	Species 2	Species 3
1	78067.84	326021.54	815	10	Private	Organic	*Picea sitchensis*		
2	84038.37	334006.94	1118	9	Private	Organic	*Picea sitchensis*	*Pinus contorta*	
3	86019.97	335961.92	1226	9	Private	Organic	*Picea sitchensis*	*Pinus contorta*	
4	88011.55	329916.43	1337	13	Private	Organic	*Picea sitchensis*	*Pinus contorta*	
5	91901.91	333932.52	1566	13	Private	Organic	*Pinus contorta*	*Picea sitchensis*	
6	93939.82	313974.65	1670	15	Public	Organic	*Picea sitchensis*	*Pinus contorta*	
7	94056.54	340036.74	1683	15	Private	Organic	*Pinus contorta*	*Picea sitchensis*	
8	96064.39	337995.40	1797	8	Private	Organic	*Picea sitchensis*	*Pinus contorta*	
9	97943.85	311920.49	1909	15	Public	Organic	*Pinus contorta*		
10	98005.95	333953.35	1920	14	Private	Organic	*Picea sitchensis*	*Pinus contorta*	
12	101979.44	318000.96	2172	10	Private	Organic	*Picea sitchensis*		
13	104075.35	294043.74	2299	8	Private	Organic	*Picea sitchensis*		
14	103908.63	309969.40	2307	4	Private	Organic	*Picea sitchensis*		
15	103908.63	309969.40	2449	5	Public	Organic			
16	108092.58	338028.88	2604	3	Private	Organic	*Picea sitchensis*	*Larix sp.*	
19	113968.02	335914.07	3044	7	Private	Mineral	*Picea sitchensis*		
22	128072.71	299914.05	4032	4	Private	Organic	*Fraxinus excelsior*	*Larix sp*	
23	129922.13	301935.43	4168	1	Public	Organic	*Picea sitchensis*		
24	130071.37	312040.75	4173	9	Public	Organic	*Picea sitchensis*		
25	133980.87	299964.41	4444	10	Public	Organic	*Picea sitchensis*		
27	136069.72	297933.02	4587	11	Private	Organic	*Picea sitchensis*		
28	136016.04	319985.47	4598	15	Private	Organic	*Pinus contorta*	*Picea sitchensis*	
29	137980.88	302078.89	4739	14	Private	Organic	*Pinus contorta*	*Salix sp.*	
30	139989.30	295901.10	4883	7	Public	Organic	*Picea sitchensis*	*Salix sp.*	
31	141948.49	295988.32	5031	10	Private	Organic	*Picea sitchensis*	*Salix sp.*	
32	144003.15	294026.29	5178	11	Private	Organic	*Pinus contorta*		
33	143972.29	301906.55	5182	2	Private	Organic	*Picea sitchensis*	*Larix sp.*	
35	145925.18	293980.58	5326	10	Private	Organic	*Picea abies*	*Picea sitchensis*	*Salix sp.*
36	148011.72	294044.67	5475	10	Private	Organic	*Picea sitchensis*		
39	151928.93	295938.96	5777	7	Public	Mineral	*Pinus contorta*	*Picea sitchensis*	*Larix sp.*
40	154031.22	295961.12	5927	5	Public	Mineral	*Picea sitchensis*		
41	154066.90	302080.29	5930	13	Private	Organic	*Picea sitchensis*	*Salix sp.*	

Plot No.	Mean Tree Height (m) Species 1	Species 2	Species 3	Overall Mean Height (m)	Tree Biomass Stock (t C)	Understorey Stock (t C)	Litter Stock (t C)	Soil Organic C (t C)	Total (t C)
815	1.90			1.90	816	1103	1000	-4000	-1081
1118	3.22	2.82		3.04	10594	526	900	-3600	8420
1226	2.10	2.32		2.21	2539	902	900	-3600	740
1337	2.48	3.03		2.70	4460	656	1300	-5200	1215
1566	7.05	4.05		5.44	21112	110	1300	-5200	17322
1670	0.69	0.90		0.69	141	2418	1500	-6000	-1941
1683	1.63	1.97		2.19	1837	913	1500	-6000	-1749
1797	1.63	3.24		2.52	5104	737	800	-3200	3441
1909	8.43			8.43	14590	16	1500	-6000	10105
1920	2.80	2.93		2.88	5852	583	1400	-5600	2236
2172	3.34			3.34	7465	432	1000	-4000	4896
2299	2.72			2.72	5176	649	800	-3200	3424
2307	1.76			1.84	1359	1147	400	-1600	1306
2449					0	3792	500	-2000	2292
2604	1.30	1.35		1.65	411	1297	300	-1200	809
3044	0.78			1.55	148	1385	700	1960	4193
4032	1.60	0.74		1.60	92	1340	400	-1600	232
4168	0.22			0.22	3	3287	100	-400	2990
4173	2.64			2.64	5453	683	900	-3600	3435
4444	4.68			4.68	2905	181	900	-3600	386
4587	3.63			3.63	9487	357	1100	-4400	6544
4598	8.24	3.75		6.74	21701	47	1500	-6000	17249
4739	7.38	1.50		7.38	12316	31	1400	-5600	8147
4883	2.99	1.36		3.43	8205	408	700	-2800	6513
5031	6.91	3.85		6.91	10926	43	1000	-4000	7969
5178	2.13			2.80	298	614	1100	-4400	-2387
5182	0.56	1.20		0.56	53	2640	200	-800	2093
5326	5.16	7.35	3.70	6.25	11653	65	1000	-4000	8718
5475	7.35			7.35	22388	32	1000	-4000	19420
5777	0.97	1.93	2.10	2.30	1101	850	500	1400	3852
5927	2.15			2.20	3417	907	500	1400	6224
5930	10.26	4.66		10.03	45513	6	1300	-5200	41618

Appendix II – Submitted Paper

Carbon Stock Changes in Young Conifer Plantations Afforested on Blanket Peat

Carly Green[a], Brian Tobin[b], Marina Conway[c], and Edward P Farrell[a]

[a]*Forest Ecosystem Research Group, School of Biology and Environmental Science, University College Dublin, Belfield, Dublin 4, Ireland*

[b]School of Biology and Environmental Science, University College Dublin, Belfield, Dublin 4, Ireland

[c]Western Forestry Co-Op

ICOS House, Finisklin Road, Sligo

Abstract

Draining peatland areas for forestry leads to increased aeration and the subsequent release of CO_2 to the atmosphere. This can result in such areas being net sources of carbon (C) in the early establishment phase of the plantation as the stand biomass increment does not compensate for the peat soil CO_2 emission. Biomass functions for estimating tree and understorey biomass in conifer plantations afforested on blanket peat in the west of Ireland were developed and combined with organic soil emission factors to develop net C stock change estimates. For typical growth conditions in the region it was found that the forest became a net annual sink of C five years following planting. However regional variations in site growth rates mean that the sites could be sources for as little as three years or as long as 34 years. Significant research on C cycling in peatland forests is required to improve these estimates and to ensure that good practice reporting to the Kyoto Protocol is achieved.

Keywords: Sitka spruce, lodgepole pine, biomass equations, organic soil, understorey vegetation

Introduction

Ireland has a significant area of afforestation since 1990, which is eligible for reporting to the Kyoto Protocol (KP) under Article 3.3. It has been debated that a significant proportion of this area is on peat soils in the west of the country (Byrne and Perks 2000). Such plantation forestry on blanket peat is dominated by two exotic species, namely lodgepole pine (*Pinus contorta* Douglas ex. Loud.) and Sitka spruce (*Picea sitchensis* (Bong.) Carr) (MacCarthy and Keogh 1984).

Estimating carbon (C) stock and stock changes on these afforested lands should be reported as the net result of five C pools; above- and belowground biomass, deadwood, litter and soil organic C (SOC) (Penman et al. 2004). The above- and belowground biomass includes both the tree and the understorey vegetation. Tree C stock estimates are usually developed by applying expansion factors or biomass functions to national forest inventory (NFI) data or yield models (Brown 2002; Cienciala 2005). These expansion tools, data inventories and models are generally based on trees of merchantable timber volume (Brown 2002; Gallagher et al. 2004; Tobin et al. 2005) with small trees (i.e. below 7 cm diameter at breast height (DBH)) omitted. For countries with large-scale post 1990 afforestation such an omission is likely to result in significant uncertainty in estimates of C stock on forest lands (Brown 2002). In recognition of this Ireland has included small tree measurements in its NFI design. Biomass functions, whose range covers trees of less than merchantable timber dimensions, are now required to calculate C stocks with low uncertainty.

Understorey biomass stock has to date been omitted from estimates of C stock and stock changes in Irish forests (Gallagher et al. 2004). In a study of young plantations afforested on peatland areas in Scotland, Hargreaves et al. (2003) reported that understorey biomass makes a significant contribution to the overall C budget in such plantations. So much so that it can offset the comparatively large CO_2 emission from draining peat soils in the early development stages. As the stand matures the influence of the forest biomass stock increment significantly outweighs that of the peat soil emission.

In the understorey species vegetation succession can be caused by differences in light availability (Mitchell et al. 1999; Thysell and Carey 2001) and therefore stand developmental stage may be correlated to understorey biomass stock for modelling purposes.

Draining peat soils for forestry increases the depth of the aerobic layer, leading to increased decomposition and subsequently a greater release of CO_2. The magnitude of this variation varies widely and can be influenced by such factors such as depth to water table, peat soil properties and drainage depth (Minkinnen and Laine 1998; Hargreaves et al. 2003; Byrne and

Farrell 2005). This CO_2 loss is relatively large compared to the biomass increment in young trees and can result in these sites being a net source of C (Hargreaves et al. 2003). The time taken for these sites to become net C sinks is of interest in terms of reporting to the KP during the first, and any subsequent, commitment periods.

The objectives of this study were;

1. To develop improved methods for estimating tree and understorey biomass in forests planted since 1990 on blanket peatland in the west of Ireland, and
2. To estimate the time taken for such sites to become a sink.

Biomass functions relating tree and understorey biomass to NFI tree measurements were developed and used in conjunction with NFI data and a nationally specific emission factor for organic soil to provide C stock change estimates for plantations on blanket peat in County Mayo.

Methods

Area Description

A total of 31 sites were used in this study (Figure 1). All sites were post 1990 commercial plantations located within county Mayo along the western seaboard of Ireland. Five sites were used in the development of tree biomass functions and 26 sites used for the understorey biomass component of the study. The area containing these sites experiences an average annual rainfall of approximately 1140mm per year, with mean temperatures in January of 5.7°C and in July of 14°C (Collins and Cummins 1996).

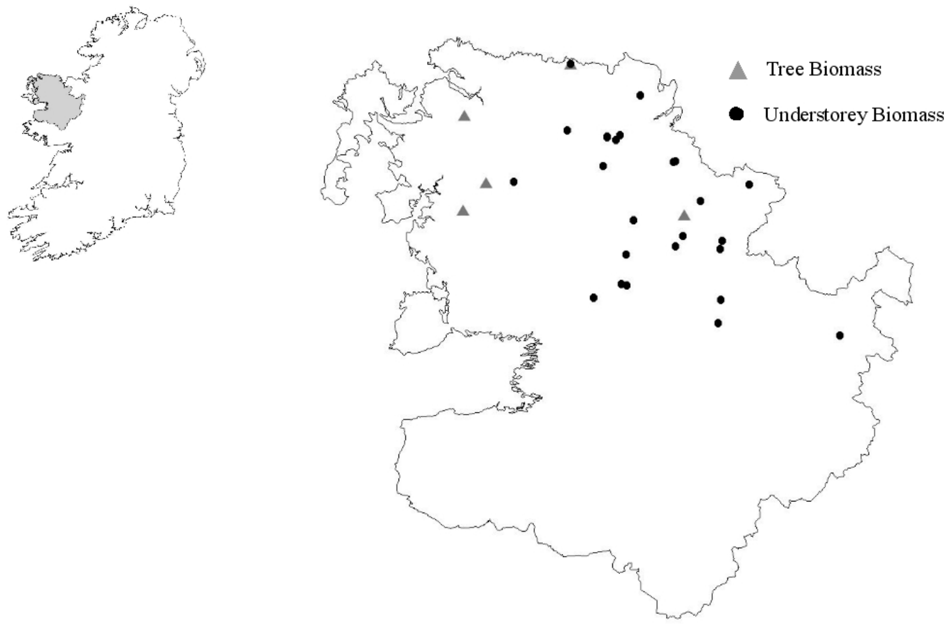

Figure 8.1: Location of plots for tree and understorey biomass collection.

The land use prior to afforestation was typically extensive sheep and cattle grazing. Drainage is a prerequisite to afforestation on peat and as such all sites had undergone ground preparation and the installation of drainage ditches. The most common form of ground preparation in Ireland is mounding. This involves the installation of drainage channels every 8m to a depth of 40-60cm and the distribution of a mound of soil for planting (Anon 2000). No additional removal of existing ground vegetation (i.e. heather, moss and grasses) was undertaken.

The five sites (T1-T5) used in the development of biomass functions ranged in age from 3 – 12 years. All stands consisted of Sitka spruce and lodgepole pine planted in intimate mixtures at 2 m spacing (2500 stems ha^{-1}) on ombrotrophic blanket peat (Table 1). Following planting, phosphorus was applied at the recommended rate of between 350-500 kg ha^{-1}. Refertilisation with phosphorus and/or nitrogen was carried out approximately 7 years following establishment and on extremely poor sites applications have been applied again 2-3 years later in order for the crop to close canopy.

Table 1: Characteristics of *Picea sitchensis* (Bong.) Carr and *Pinus contorta* Douglas ex. Loud. Mean values shown with standard deviation in parenthesis.

Stand No.	Co-Ordinates	Age (yr)	Stocking (stems ha^{-1})	Height (m)	
				Picea sitchensis	Pinus contorta
T1	54° 05´N, 09° 10´W	3	2183	0.94 (0.26)	0.80 (0.24)
T2	54° 13´N, 09° 45´W	5	2400	1.08 (0.43)	1.13 (0.49)
T3	54° 18´N, 09° 30´W	8	2775	1.42 (0.46)	1.97 (0.76)
T4	54° 05´N, 09° 45´W	10	2041	2.11 (0.62)	2.18 (0.66)
T5	54° 07´N, 09° 42´W	12	2600	3.14 (0.93)	2.98 (0.96)

Understorey vegetation was collected from plots located in 26 post 1990 forests (U1-U27), which had the same management prescriptions and site preparation as described previously. Characteristics of these sites are listed in Table 2.

Measurements

At each site tree biomass measurements from two species were treated independently from each other. An inventory of tree height and DBH was undertaken at each location for each of the two species to determine its height distribution and stocking rate.

<u>Above- and Below-ground Tree Biomass</u>

Three trees of each species were selected from the height distribution for destructive sampling from each of the five sites; one of mean height and two others, one standard deviation either side of the mean, resulting in a total of 30 sample trees. From the centre of the stem, a square measuring 2 x 2 metres was marked on the ground and cut with a spade. A winch was attached to the base of the stem and used to pull out the tree with as much of the peat sod intact as possible to ease complete root system excavation. Further excavation of all roots to a diameter of 2 mm from the sampling area was completed manually to the maximum depth at which they occurred. The sample trees were then separated into their component parts (namely roots, stem and foliage). Fresh component weights (FW) were recorded in the field, sub-sampled and returned to the laboratory for drying as described further in Green et al. (2005).

Table 2: Characteristics of sites where understorey vegetation samples were collected. Values in parenthesis are one standard deviation.

Stand	Co-ordinates	Age (yr)	Stocking (stems ha^{-1})	Average Tree Height (m)	Tree Species[a]	Significant understorey species[b]
U1	54° 01´N, 09° 05´W	2	2333	0.50 (0.12)	SS, L	1, 2, 3
U2	54° 02´N, 09° 12´W	2	2600	0.97 (0.24)	SS, L	5, 6, 14
U3	53° 58´N, 09° 19´W	3	2600	0.85 (0.20)	SS, LP, L	1, 3, 4
U4	54° 11´N, 09° 21´W	4	2466	1.86 (0.62)	SS	6, 1, 5
U5	54° 03´N, 09° 11´W	4	2533	0.84 (0.13)	SS, LP	1, 2, 15
U6	54° 11´N, 09° 23´W	4	2933	1.00 (0.50)	SS, LP, L	2, 15, 4
U7	54° 02´N, 09° 04´W	6	4066	1.90 (0.3)	NS, O	1, 6, 2
U8	53° 57´N, 09° 24´W	7	2000	1.36 (0.57)	SS, LP	2,4,3
U9	54° 09´N, 09° 12´W	7	2333	2.71 (0.72)	SS	14, 8, 9
U10	54° 15´N, 09° 18´W	7	2333	1.38 (0.35)	SS	2, 4, 1
U11	54° 01´N, 09° 19´W	8	2800	3.20 (1.06)	LP	2, 1, 3
U12	53° 58´N, 09° 20´W	8	2466	4.06 (0.75)	SS	1, 4, 2
U13	53° 55´N, 09° 05´W	9	2333	2.44 (1.17)	NS	5, 1, 6
U14	54° 10´N, 09° 22´W	9	2200	3.22 (0.66)	SS, LP	2, 7, 1
U15	54° 12´N, 09° 29´W	9	1733	2.34 (0.71)	LP	6, 4, 2
U16	53° 54´N, 08° 46´W	11	2333	2.09 (0.65)	NS	6, 1, 2
U17	54° 18´N, 09° 29´W	11	2600	1.90 (0.48)	SS, LP	6, 4, 2

Stand	Co-ordinates	Age (yr)	Stocking (stems ha^{-1})	Average Tree Height (m)	Tree Species[a]	Significant understorey species[b]
U18	54° 04´N, 09° 18´W	13	4466	5.05 (1.42)	O	9, 12, 10
U19	54° 06´N, 09° 08´W	13	2333	7.40 (1.00)	A, B	1, 9, 6
U20	54° 07´N, 09° 37´W	13	2333	1.35 (0.81)	SS, LP	2, 11, 6
U21	54° 12´N, 09° 21´W	14	2266	7.87 (1.21)	SS	4, 11, 6
U22	54° 07´N, 09° 00´W	15	1866	9.61 (2.43)	SS	14, 12, 11
U23	54° 09´N, 09° 12´W	15	2333	8.96 (1.26)	SS	13, 5, 11
U24	53° 59´N, 08° 29´W	15	2733	9.74 (1.49)	SS	4, 13, 14
U25	54° 09´N, 09° 23´W	15	2600	1.66 (0.56)	SS	1, 4, 2
U26	53° 57´N, 09° 04´W	15	2333	12.55 (0.96)	SS	2, 11, 13

a. Tree species present

(SS) *Picea sitchensis*, (LP) *Pinus contorta*, (L*) Larix* spp. (NS) Picea abies, (B) Betula pubescens, (O) Quercus robur, (A) Fraxinus excelsior

b. Three most significant species by % plot abundance

(1) *Molinia caerulea*, (2) *Calluna vulgaris*, (3) *Scirpus* spp., (4) *Sphagnum* spp., (5) *Lolium perenne*, (6) *Juncus effusus*, (7) *Myricaceae* spp., (8) *Thalictrum* spp., (9) *Urtica dioica*, (10) *Taraxacum officinale*, (11) *Cladonia* spp., (12) *Rubus fruiticosus*, (13) *Pteridium aquilinum*, (14) *Potentilla anserina*, (15) *Ulex europaeus*

A relationship between measured tree height and dry biomass was then developed (Equation 1).

$$LN(DB) = \alpha LN(h) + \beta \qquad (1)$$

where;

DB = dry biomass (kg), h = tree height (m) and α and β are parameters

Correction factors (cf) for converting log-transformed predicted values back to arithmetic units were calculated as the antilog of half the sample variance (Niklas 1995).

Aboveground Understorey Biomass

A plot of radius 7 m was randomly located within each location (U1 – U26). The three main understorey species (by % cover) were recorded. All standing aboveground biomass was removed from three randomly located 0.25 m^2 quadrats within the plot. Dead vegetation was considered litter and not sampled. Vegetation from each quadrat was separated in the field into broad species categories, namely; moss, herb, shrub (woody with a height potential $\geq$ 0.5 m) and brush (woody material with a height potential < 0.5 m). Fresh vegetation from each quadrat was placed in sealed plastic sample bags and returned to the laboratory for processing. Fresh weights were recorded and then samples were dried at 70°C till constant dry weight was recorded. Relationships between the average tree height of the stand and total understorey biomass (t ha^{-1}) were developed to model the change in understorey biomass stock with stand development.

Regional C Stock Change Estimates

Stand C stock changes were modelled using site indices (SI) developed from regional NFI data (Figure 8.2) where y is height and x is age. For each NFI plot in the region the average tree height for each species was divided by the stand age to determine an average height increment (I_h). The height of the initial seedling was assumed to be 30 cm and was deducted from I_h. The values were sorted in ascending order and graphed. An SI was allocated to points between a gradient change in the linear progression. A linear relationship was then developed using these points from which I_h could be modelled. SI1 is the most productive areas and SI4 being the least.

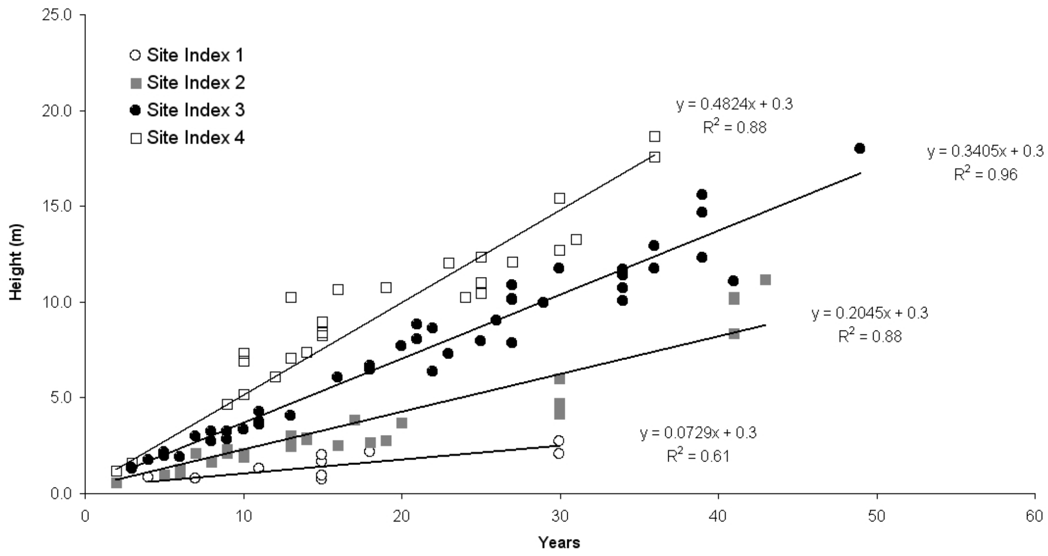

Figure 8.2: Site index models for estimating average annual height increment

Typical tree stocking of 2500 stems per hectare (Anon 2000) was assumed and the default C conversion factor of 0.5 (Penman et al. 2004) applied in the development of tree biomass C stock. The model assumed no removals from thinning which is consistent with current practice on these site types (Byrne and Farrell 2005). The deadwood and litter pools were assumed not to be a source of C and therefore omitted from calculations.

The understorey was modelled based on the developed relationship between Tree height and understorey biomass stock. An emission factor for blanket peatland soils of 1 t C ha^{-1} yr^{-1} was assumed to be constant post drainage for forestry. This emission factor was selected from national research on young lodgepole pine sites on blanket peat (Byrne and Farrell 2005). The emission factor used compared well with that estimated for forest sites on blanket peatland in Scotland (Hargreaves et al. 2003) and was within the IPCC default emission factor range for drained peatland soils (Penman et al. 2004). The approach was repeated for each identified SI to determine at what age stands on blanket peat in this region become a C sink. C.

Results

Above- and Belowground Tree Biomass

Trees between 0.67 m and 4.18 m in height for Sitka spruce and 0.62 m and 3.85 m in height for lodgepole pine were harvested across the five stands (Table 2). A strong relationship was established between tree height and biomass, independent of tree age, for both species investigated (Table 4). No significant difference between the slopes and intercepts of the species-specific functions were detected for total biomass, aboveground biomass and belowground biomass. Therefore the sample tree data sets were combined to develop equations applicable to both species (Table 3).

Table 3: Equations of the form $\ln(y) = \alpha\ln(x) - \beta$ for species investigated, where y = kg dry matter (kg d.m.)

Equation	α	β	**SEE**	**cf**	R^2
Picea Sitchensis					
Total Biomass	2.758	0.325	0.088	1.004	0.89
Aboveground	2.837	0.744	0.091	1.004	0.89
Belowground	2.756	1.376	0.100	1.005	0.84
Pinus contorta					
Total Biomass	2.830	0.390	0.041	1.0008	0.96
Aboveground	2.770	0.690	0.061	1.002	0.94
Belowground	3.253	1.985	0.084	1.004	0.94
Combined species					
Total	2.876	0.442	0.051	1.001	0.92
Aboveground	2.803	0.763	0.049	1.001	0.92
Belowground	3.076	1.794	0.070	1.002	0.89

Aboveground Understorey Biomass

A strong relationship was developed between stand tree height and understorey biomass (Figure 8.3). Variation in stand biomass stock was greatest where trees were less than 4 m in height. A successional change with age was apparent across the sites investigated (Table 8.3).

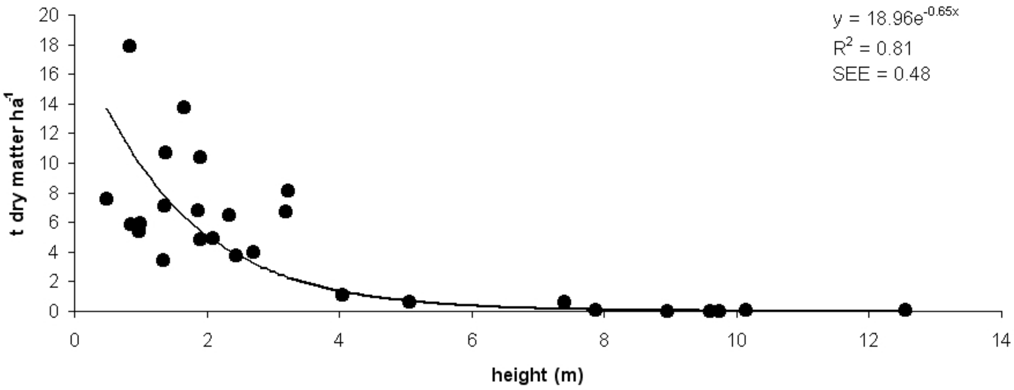

Figure 8.3 Relationship between understorey biomass stock and tree height.

Based on the three most abundant species present, the vegetation changed from typical peatland species such as *Sphagnum, Calluna vulgaris, Molina caerulea* (Otte 2003) to species found more readily in drier conditions such as *Urtica dioica (L.), Rubus fructicosus* and *Pteris aquiline*. Understorey biomass stocks were quite high in plantations with trees less than 4 m in height, ranging from approximately 3 to 18 t C ha^{-1}.

Regional C Stock Change Estimates

The estimated net C stock change suggested that sites afforested on blanket peat are sources of C in the initial stages of stand development. Depending on the tree growing conditions, the time for the site to become a net C sink ranged from 3 to 34 years (Figure 8.4). At sites experiencing poor growth (SI1) tree biomass increment failed to have a significant impact on the net C budget and subsequently these sites remained a C source during the commitment period. A total of 9% of the NFI plots in the region fell into this SI, being equivalent to an area of 2800 ha. The most predominant SI in the region is SI3, which accounted for 43 % (~13,200 ha) of conifer plantations on peat soils. These sites are estimated to become a C sink five years following afforestation.

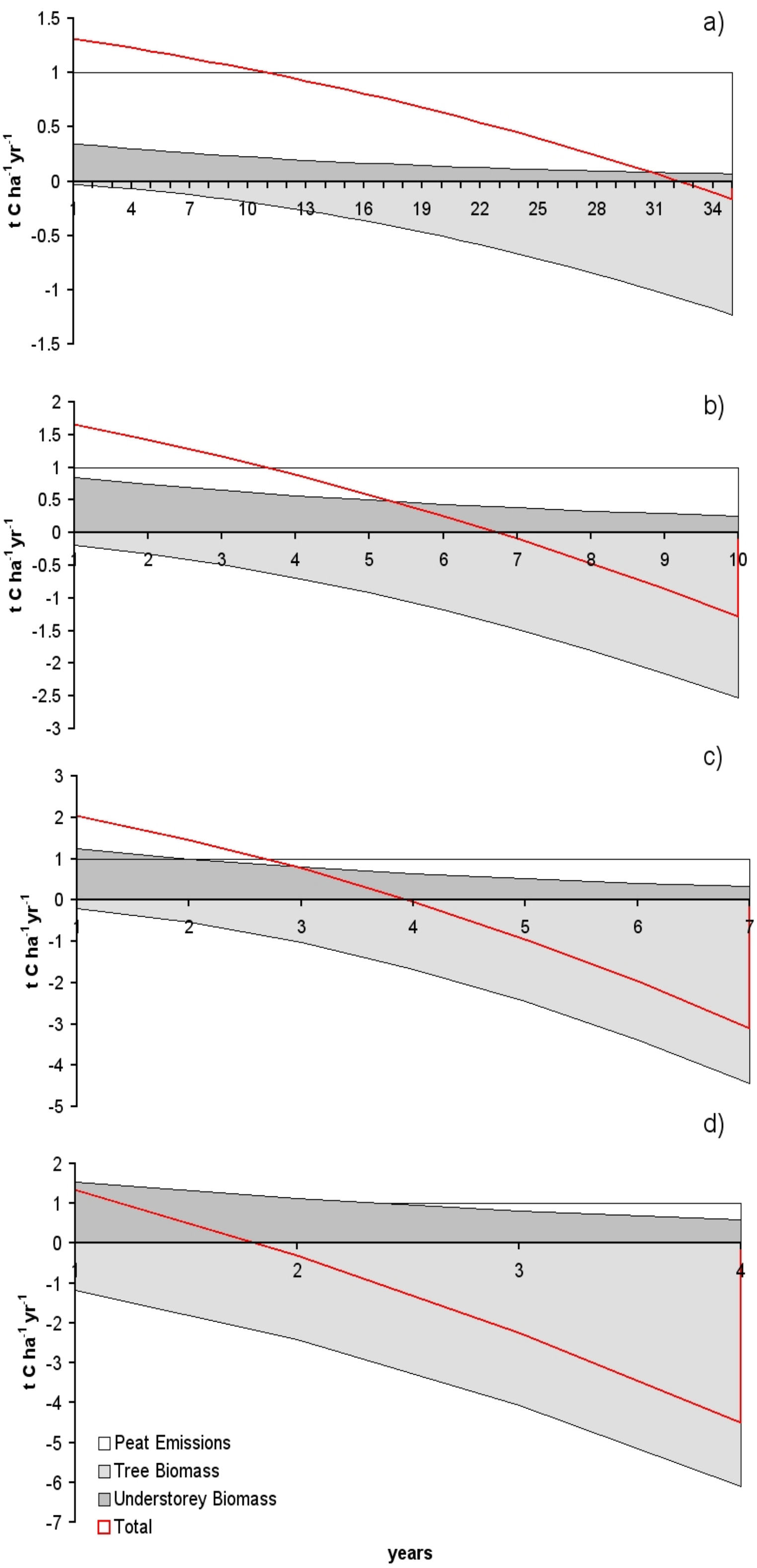

Figure 8.4. Carbon stock change in the tree biomass, understorey biomass and soil following afforestation of blanket peatlands in the West of Ireland. Negative numbers represent C uptake, positive C release. The red line represents total net C change, depicting the years taken post establishment for sites to become a sink, (i.e. where it crosses the x-axis) in growing conditions that are a) poor (SI1), b) below average (SI2), c) average (SI3) and d) above average (SI4).

Discussion

It is widely agreed that biomass functions can vary depending on species, site type, age, and management regime (Somogyi et al 2005) making most biomass functions arguably case specific (Wirth et al. 2004). In this study we found that in the early stages of tree development no significant difference was detected between biomass functions for Sitka spruce and lodgepole pine. This is likely to be a result of the growth stage of the plantations investigated.

The net C balance of afforested peatland areas was modelled as the result of the net gain in C associated with tree growth combined with the net loss of C related to ground vegetation (i.e. moss, heather, grasses) as well as peat decomposition following plantation establishment. Unlike studies undertaken in peatland forest sites in Scotland (Hargreaves et al. 2003) our peatland forestry C balance was largely based on measuring biomass stocks and applying a constant peat soil emission factor rather than measuring site C fluxes. Our approach captured an exponential decrease in understorey vegetation with stand development (i.e. height increment) and when combined with the peat soil emission factor, all sites were a C source in the early stages of establishment. Depending on the SI this period could range from 3 to 34 years.

Our estimates are based on models and assumptions that contribute to the uncertainty in the estimates. The site indices developed to simulate height increment are based on the first round of NFI measurements. Without a measured increment such site indices approximate growth and may not be typical of long term forest development. However when combined with the biomass functions developed specially to model young trees this approach is believed to be more reliable than the use of UK yield models (Edwards and Christie 1981) which are based on trees of greater than merchantable timber volume. Forest plantations on peat soils in Ireland are reported to be more productive than their UK counterparts (Farrell and Boyle 1990; Green et al. 2005) and thus the tree growth increment is expected to be somewhat higher than that reported in the Hargreaves study. Maintaining this productivity in these regions however, is reliant on forest management practices such as repeated fertilisation.

As shown by these results, understorey vegetation on peatland sites accounted for a large proportion of the C stock where canopy closure has not yet occurred. Understorey variations in the early establishment phase of the plantation will be influenced by disturbance during the installation of drainage, combined with the resultant lowering of the water table and application of fertiliser leading to altered growing conditions (Laine and Vanha-Majamaa 1992; Laine et al. 1995). The response in growth or suppression to these variables is likely to have contributed to the large variation in C stocks in the early stages of forest development reported here. Although these factors were not explored here, the model developed allows an estimation of the contribution of understorey biomass to site C stock based on stand characteristics measured in the NFI.

The C emission from the peat soil is a significant contribution to the overall C budget in the early stages of stand development. Although some studies have found a correlation between time following drainage for forestry and C emission factors (Hargreaves et al. 2003), others have shown that the value is highly dependant on peat type and climatic conditions (Minkinnen and Laine 1998; Minkinnen et al. 1999; Byrne and Farrell 2005). In a comparative study Byrne and Farrell (2005) found no apparent pattern in relation to site type (i.e. pre afforestation, different age classes and a clearfell) on blanket peatland in Ireland, suggesting that forestry development did not always lead to increased C emissions. Preliminary information on the effectiveness of drainage recorded in NFI plots on blanket peatland areas indicated that in the short to medium term (i.e. 5 – 20 yrs), drainage may not always be successful in maintaining an aerobic layer (Green et al. 2005). This would subsequently have an impact on the organic soil C dynamics as well as on stand productivity. The existence of such confounding factors makes the changes in C dynamics difficult to model against stand age. In the absence of a dynamic mode, we took the IPCC default approach to estimating losses from organic soil with a constant emission factor (Penman et al. 2004). However to meet good practice reporting to the KP, Ireland will be required to develop a full C budget model for peatland forest areas.

The introduction of the EU habitats directive (92/43/EEC), which in the context of Irish forestry, is supported nationally through county based indicative forest strategies (Anon 2003) and the forest grant and premium application process, has resulted in a decrease in the annual area of blanket peatlands being afforested. The contribution of blanket peatland forests to the annual afforestation program will as a result decline. Subsequently so too will their significance to the overall area reported to Article 3.3 of the KP. Nonetheless significant areas still remain accountable under national greenhouse gas inventory reports to the United Nations Framework Convention on Climate Change (UNFCCC). Modelling the C dynamics of these forests as they reach maturity, are harvested and subsequently reforested still requires in depth study to develop a nationally specific model to provide C stock and stock change estimates in these areas.

Conclusion

The relationships developed here for the estimation of C stocks in the above and belowground biomass pools are based on NFI data inputs. They are particular to plantations where trees have yet to reach merchantable timber volume and are therefore useful in the development of C stocks with low uncertainty for KP purposes. However the emissions associated with the draining of organic soils are significant to the overall C budget in the early stages of stand development and will require further investigation to meet good practice reporting under the terms of the IPCC.

Acknowledgements

This work was made possible through funding provided by the Irish National Council for Forest Research and Development (COFORD), the European Commission: Programme Environment and Sustainable Development (CarboInvent Project: contract No. EVK2-2002-00157) and the FORSEE project co-funded by the EU and ERDF – Interreg Altlantic Area. Many thanks to those farmers who willingly allowed access to their property and the removal of trees. Also to Paul Gardiner, Luke McGurdy and West Coast Forestry for assisting in the field and the laboratory. Final thanks go to Dr Kenneth Byrne for suggesting improvements to this paper.

References

Anon (2000). Code of Best Forest Practice - Forest Service, Department of Marine and Natural Resource, Dublin, Ireland.

Anon (2003). Indicative Forest Strategy for County Mayo. Forest Service, Department of Communications, Marine and Natural Resources, Johnstown Castle Estate, County Wexford.

Brown S (2002). Measuring Carbon in Forests: Current Status and Future Challenges. Environmental Pollution 116: 363-372.

Byrne KA and EP Farrell (2005). The Effect of Afforestation on Soil Carbon Dioxide Emissions in Blanket Peatland in Ireland. Forestry 78 DOI 10.1093/forestry/cpi020.

Byrne KA and M Perks (2000). Possibilities for Carbon Sequestration in Irish Forest. Biotechnology, Agronomy, Society and Environment 4: 300-302.

Cienciala E (2005). Preparation of GHG Reports in the LULULCF Sector Under UNFCCC/KP - Progress in European Countries. Land-use related choices under the Kyoto Protocol. In Obligations, Options and Methodologies for Defining 'Forest' and for selecting activities under Kyoto Protocol Article 3.4, CarboInvent Workshop, Graz, Austria.

Collins J and T Cummins, Eds. (1996). Agroclimatic Atlas of Ireland. AGMET. Dublin, Prime Print.

Edwards, P and J Christie (1981). Yield Models for Forest Management. Edinburgh, Forestry Commission.

Farrell, EP and G Boyle (1990). Peatland Forestry in the 1990s. I. Low-Level Blanket Bog. Irish Forestry 47: 69.

Gallagher, G, E Hendrick and KA Byrne (2004). Preliminary Estimates of Biomass Carbon Stocks in Managed Forests in the Republic of Ireland over the Period 1990-2000. Irish Forestry 61(1): 35-46.

Green, C, B Tobin, M O'Shea, EP Farrell and KA Byrne (2005). Above- and Belowground Biomass Measurements in an Unthinned Stand of Sitka Spruce. European Journal of Forest Research. DOI 10.1007/s10342-005-0093-3.

Green C, KA Byrne and EP Farrell (2005). Developing a Kyoto Carbon Budget for Afforestation Activities under Article 3.3. CarboInvent Final Report. Dublin, Forest Ecosystem Research Group.

Hargreaves KJ, R Milne and MGR Cannell (2003). Carbon Balance of Afforested Peatlands in Scotland. Forestry 76(3): 299-317.

Laine J and I Vanha-Majamaa (1992). Vegetation ecology along a rophic gradient on drained pine mires in southern Finland. Ann. Bot. Fennici 29: 213-233.

Laine J, H Vasander, R Laiho (1995). Long-term effects of water level drawdown on the vegetation of drained pine mires in southern Finland. Journal of Applied Ecology 32: 785-802.

MacCarthy R and RM Keogh (1984). Biomass Potential of Conifers on Peatlands. In proceeding of 7th International Peat Congress, Dublin.

Minkinnen K and J Laine (1998). Long-Term Effect of Forest Drainage of the Peat Carbon Stores of Pine Mires in Finland. Canadian Journal of Forest Research 28: 1267-1275.

Minkinnen K, H Vasander, S Jauhiainen, M Karsisto and J Laine (1999). Post-Drainage Changes in Vegetation Composition and Carbon Balance in Lakkasuo Mire, Central Finland. Plant and Soil 207: 107-120.

Mitchell R, B Zutter, D Gjerstad, G Glover and C Wood (1999). Competition among Secondary-Secessional Pine Communities: A Filed Study of Effects and Responses. Ecology 80: 857-872.

Niklas KJ (1995). Size-Dependant Allometry of Tree Height, Diameter and Trunk Taper. Annals of Botany 75: 217-227.

Otte ML, (Ed). (2003). Wetlands of Ireland. Dublin, University College Dublin Press.

Penman J, M Gytarsky, T Hiraishi, T Krug, T Kruger, D Pipatti, L Buendia, K Miwa, T Ngara, T Tanabe and F Wagner, Eds. (2004). IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry. Ipcc National Greenhouse Gases Inventories Programme. Institute for Global Environmental Strategies (IGES), Hayama Kanagawa Japan.

Somogyi Z, E Cienciala, R Mäkipää, P Mukkonen, A Lehtonen and P Wiess (2005). Indirect Methods of Large Scale Biomass Estimation. European Journal of Forest Management, In press.

Thysell D and A Carey (2001). Manipulation of Density of *Pseudotsuga Menziesii* Canopies: Preliminary Effects on Understorey Vegetation. Canadian Journal of Forest Research 31: 1513-1525.

Tobin B, K Black, M Nieuwenhuis and J Gardiner (2005). BEFs and Forest Biomass C Stores. In Farrell EP (Ed.) CARBiFOR Final Report. COFORD, Dublin.

Wirth C, J Schumacher and ED Schulze (2004). Generic Biomass Functions for Norway Spruce in Central Europe - a Meta-Analysis Approach Toward Prediction and Uncertainty Estimation. Tree Physiology 24: 121-139.