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Forest bioenergy or forest carbon: A review

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Abstract: An article by Jon McKechnie *et al* entitled Forest Biomass or Forest Carbon purports to use an integrated life cycle assessment (LCA) and forest carbon analysis when examining the use of wood for electrical generation. Most publications assume that the CO_2 emitted is carbon neutral because plants will re-absorb the CO_2 through photosynthesis. However, the article challenges this hypothesis and states that incomplete LCAs are undertaken. The article demonstrates that it will take many years to recapture the CO_2 when the wood is used for bioenergy. But when analyzing the capture of CO_2, only regrowth is considered and not the tree growth of the whole forest. If in the example given, a full account is taken of the above-ground yield, it is shown that the annual increment from the management units is nearly double the potential removals for wood products, including bioenergy. Thus, rather than a decrease in forest capital there is an increase. Proper and full LCAs must be undertaken of the whole forest, rather than partial analysis: the latter results in erroneous accounting. It is very misleading and should not be used or cited. This same error has been made by a number of other quoted publications.

Keywords: Carbon Accounting, Carbon Sequestration and Use, Bioenergy, Life Cycle Assessment

1. Introduction

An article entitled Forest Bioenergy or Forest Carbon: Assessing Trade-offs in Greenhouse Gas Mitigation with Wood-based Fuels, by Jon McKechnie *et al*,[1] which was published in the Journal of Environmental Science and Technology # 45, 2011, uses integrated life cycle assessment (LCA) and forest carbon analysis when examining the use of wood for electrical generation or ethanol production compared to leaving the trees in the forest to sequester carbon. It concludes that "Application of the method to case studies of wood pellet and ethanol production from forest biomass reveals a substantial reduction of forest carbon due to bioenergy production. For all cases, harvest-related forest carbon reductions and associated GHG emissions initially exceeded avoided fossil fuel-related emissions, temporarily increasing overall emissions. In the long term, electricity generation from pellets reduces overall emissions relative to coal, although forest carbon losses delay net GHG mitigation by 16-38 years depending on biomass source ---. Forest carbon more significantly affects bioenergy emissions when biomass is sourced from standing trees compared to residues and when less GHG-intensive fuels are displaced. In all cases, forest carbon dynamics are significant. Although study results are not generalizable to all forests, we suggest the integrated LCA/forest carbon approach be undertaken for bioenergy studies".

The article is based on the supply of biomass from standing trees and harvest residues from the Great Lakes-St. Lawrence (GLSL) forest region of Ontario. The supply of hardwood and softwood species comes from 10 forest management units covering 5.25 million hectares in the GLSL forests. Historically, significantly less than the allowable harvest has been harvested. Therefore, the 'excess' wood could be used for bioenergy. In addition, residues from tree tops and large branches etc. are a second source for bioenergy. Biomass availability is derived from actual forest management plan simulations undertaken by the Strategic Forest Management Model (SFMM), predicated on forest inventories formulated through Ontario's forest management process. While the article should be based on the sustainable use of wood for all purposes from the 5.25 million hectares, it concentrates on 'forest regrowth' rather than the annual increment of the trees in the 10 management units.

2. Methods Used in the McKechnie Article

Under methods, the article states "We develop a

[1] Henceforth referred to as the McKechnie article

framework integrating two analysis tools: life cycle inventory (LCI) analysis and forest carbon modeling. ---. The LCI is based on the assumption of immediate biomass carbon neutrality, as is common practice, and is therefore employed to quantify the impact of all emissions on atmospheric GHGs with the exception of biomass-based CO_2". It further states: "Forest carbon modeling quantifies the impact of biomass harvest on forest carbon dynamics, permitting an evaluation of the validity of the immediate carbon neutrality assumption. If biomass-based CO_2 is fully compensated for by forest regrowth, biomass harvest will have no impact on forest carbon stocks. Reduced forest carbon indicates that a portion of biomass-based CO_2 emissions contribute to increased atmospheric GHGs and should be attributed to the bioenergy pathways". And, "The total emissions associated with a bioenergy system are the sum of the two sets of GHG flows (those resulting from the LCI and those from the forest carbon analysis). GHGTot(t) = ΔFC(t) + GHGBio(t) where GHGTot(t) is the total emissions associated with bioenergy, ΔFC(t) is the change in forest carbon due to biomass harvest for bioenergy, and GHGBio(t) is the GHG emissions associated with bioenergy substitution for a fossil fuel alternative [all reported in metric tonne CO_2 equivalent (t CO_2equiv)] at time t." Furthermore, "The change in forest carbon, ΔFC (t) is the difference in forest carbon stocks between harvest scenarios: those 'with' and 'without' bioenergy production. ---. Carbon in biomass harvested for bioenergy is assumed to be immediately released to the atmosphere. However, forest regrowth will capture and store atmospheric CO_2 over time".

The article stresses that many previous papers and assumptions have not employed proper LCAs, yet this article only uses partial analysis by limiting the analysis to forest regrowth, not total tree growth, that will capture and store CO_2 over time. Naturally, in most temperate countries, it will take decades of regrowth in newly felled areas to sequester the carbon given off when used for energy. Therefore, there will be an automatic CO_2 deficit, when emissions are compared to regrowth until equilibrium is reached.

3. Bioenergy for Electricity Generation

The article examines the saving of fossil fuel using a 20% mix of pellets with coal to generate electricity in a conventional power station. First it estimates the quantity of wood that could be used sustainably for bioenergy production from the ten management units in the GLSL forest region. Table 1 gives a breakdown of potential wood supply. It is assumed that 4.46 million ha (85%) out of 5.25 million ha is managed for wood products. At present, the wood comes from clear felling (50%), shelterwood over-storey removal (25%) and selection harvesting (25%), [KBM Forestry Consultants Inc. 2008]. Little, if any thinning is undertaken, but in a fully managed forest, about 50% of the total removals could be from thinning, - a management tool that could be used to increase the sustainable off-take of wood energy etc., while increasing the value of the remaining stock.

The McKechnie article accounts for the use of fossil fuels for felling, extraction, pelletization and transport to the power plant. In addition, 15% of the wood (338,000 odt) is used in the conversion process of roundwood to pellets; therefore, available wood energy will be 1.914 Modt. An input/output factor of wood and coal for electrical generation of 1: 0.33 is assumed with the energy value for standard coal of 33.0 GJ per odt (82% carbon) and that of wood of 18.7 GJ per odt (50% carbon). The bottom line is that 1.914 Modt of pelletized wood could save 1.167 Modt of coal annually, emitting about 3.509 Mt CO_2.[2] If the wood is assumed to be carbon neutral then the 4.129 Mt CO_2 emitted from 2.252 Mt of bioenergy wood, including 338,000 odt for pelletization, would be reabsorbed quickly, resulting in no 'carbon debt'.

Table 1. *Estimated annual wood available for traditional and bioenergy use in the GLSL forest region.*

	Felling/(thinning)	**Potential residues**	**Total**
	Modt[1]	**Modt**	**Modt**
Existing area	2.836	0.383	3.219
Available for bioenergy	1.869[2]	(0.300)[3]	1,869
Total	**4.705**	**0.683**	**5.088**
Traditional use	2.836	0	2.836
Bioenergy potential	1.869	0.383	2.252
Total	**4.705**	**0.383**	**5.088**
Total m^3	9.175[4]	0.747[4]	9.922[4]

Note. 1. odt = oven dry metric tonne.
2. This has been adjusted from 1.811 Modt to correct an addition error.
3. This is the collection of residues from standing trees available for bioenergy. It was not considered in the original study nor has it been included here. It is assumed to rot on the forest floor. If used, it would save another 0.144 Mt coal each year, which would emit 0.433 Mt CO_2equivalent.
4. A conversion factor of 1.95 m^3 per odt has been used. (KPMG 2008). This conversion factor may be too high. A figure of 1.80 m^3 per odt may be more accurate, although in Table 4 below a factor of 1.67 is used. This would reduce the total estimated volume to 9.158 or 8.497 Mm^3.
Source. McKechnie *et al*, 2011. Table S-1 and text on page S-5. KPMG 2008.

4. Forest Carbon Accounting

Because the 'Forest Bioenergy or Forest Carbon' article assumes that the annual emitted carbon dioxide from bioenergy comes from tree regrowth, – 4.129 Mt CO_2 from 2.252 Modt wood (excluding 300,000 odt of potential residues), it will take many years to recapture this CO_2. It is assumed that if the 1.869 Modt of stemwood are not felled annually for bioenergy, they never will be and so will be left to grow until they reach a point where either the current annual increment is zero and they eventually die, or through competition and age, some of the trees and/or branches will die and decompose slowly. Regarding the 383,000 odt of residues (Table 1), if they are not used they will be left on the forest floor and will gradually rot. Table S-7 of the supporting information on page S-14 gives decomposition

[2] If natural gas is used (energy value 38.1 GJ/t [35.2 MJ per m^3]) then the annual saving, assuming an efficiency of 60% for a gas-fired boiler, would be about 586 Mt of natural gas; this would emit about 1.612 $MtCO_2$ equiv't

rates (k) for hardwoods and softwoods divided into pulpwood and sawntimber harvest, ranging from 0.042 to 0.083. This information is used to calculate the forest carbon stock change for residues and standing trees from continuous harvesting for bioenergy: it is given as Table 2 of the article. One-hundred years is the time frame chosen to track changes of continuous and constant harvesting. After 10 years, the forest carbon stock changes result in emissions, in Mt CO_2equivalent, of 8.2 for residues and 43.6 for standing trees. These negative values gradually rise to 15.2 for residues after 90 years. For standing trees the maximum emissions value of 150.8 is reached after 90 years and then starts to decline, reaching minus 150.7 at year 100. Thus, the combined total at 100 years is nearly -166 Mt CO_2equivalent. This is a stock decrease of 90 Modt wood. However, over the 100-year period, 225.2 Modt of wood will have been used to generate electricity[3] and save 116.7 Modt of 'standard' coal containing 95.7 MtC, which will emit 350.9 MtCO_2 equivalent, thus more than twice as much CO_2 will be saved by using wood in place of coal.

The article does not explain how the numbers in Table 2 have been derived. It appears that the 'residue' calculation is based only on the annual use of 383,000 odt of wood for electrical generation and does not include the 300,000 odt left to decay. My estimate for the former is a maximum cumulative emission of 13.4 Mt CO_2 after 100 years, and including the 300,000 odt (annual total of 683,000 odt), the cumulative sequestered total is 30.1 Mt CO_2, equal to 16.4 Modt of wood. Likewise, no rotation age is given for estimating the 'carbon balance' from using 1.869 Modt of wood annually from felling 19,700 ha equivalent. It seems that a 50-year rotation has been chosen, but a carbon balance is derived for both two fifty year rotations and one 100 year rotation. The bottom line is with the former, the net sequestration after 100 years is over 44 Mt CO_2 and with the latter it is over 59 Mt CO_2. This is entirely different from the emission figure given in Table 2 of 151 MtCO_2. Taking into account the saving of coal emissions, the cumulative sequestration totals range from 315 to 330 Mt CO_2 after 100 years. (See Annex 1).

Although the article states that the actual and potential wood use is (or will be) sustainably harvested, the method chosen to quantify forest carbon stock actually results in an annual reduction of forest stock of up to 90 million odt of wood after 100 years due to bioenergy use. As pointed out, this is because only regrowth of trees are considered. Generally, a forest comprises a range of age classes and species; this is the case for the GLSL forest areas. Therefore, it is pertinent to examine the growing stock and annual yield on the 4.46 Mha of 'managed forests', assuming that the other 790,000 ha (15%) out of a total of 5.25 Mha have been set aside for protection, water catchment and leisure etc[4]. The article states that "The forest carbon dynamics relating to biomass harvest are evaluated using FORCARB-ON, an Ontario-specific adaption of the FORCARB2 model (Chen J *et al* 2008)". However, the Chen article states that while most of the carbon storage for the next 100 years will be in timber products from the forests, there will be a modest increase in carbon storage in the forests themselves over a hundred year period. Even the FORCARB2 model for the USA predicts a C storage increase in their forests, despite a decline in the forest area[5]. There was an estimated 6.1% gain in forest tree carbon between 1990 and 2010 and a loss of 2.1% in forest soils, for an overall carbon gain of 2.6% in the example given (USDA 2009).

Table 2 gives a 2011 estimate of forest carbon in trees, litter and forest soils for the Algoma Forest Management Unit (Chen J *et al* 2010) in terms of total and per-hectare stored carbon and the tree volume equivalent.

The estimated carbon in wood, including the under-storyis 42% of the total of which 84% is above ground. The volume in above-ground trees is estimated at 264 m^3/ha,[6] (244 m^3/ha with a conversion factor of 1.8 m^3 per t of wood), 98% of which is in trees with a top diameter of 78 mm, (3 inches). The McKechnie article and the accompanying notes, give no information on volume or age-class distribution in the 10 management units of the GLSL forest area included in the assessment. Other publications were examined to try and assess the growing stock and yield for the 4.46 Mha under review.

Tree growth. To illustrate the growth of trees over time, information from the British Forestry Commission Management Tables for Oak (*Quercus robur, Q. petraea*) Yield Class (YC) 4 is used (HMSO 1971). This is the average stem yield in m^3/ha at the age when the current annual increment (CAI) dissects the mean annual increment (MAI). For YC 4, this age is 90 years. At this age, the main crop volume before thinning is 207m^3/ha and the cumulative volume from thinning/attrition is 153m^3/ha, for a combined total of 360m^3/ha. The yield table represents either a natural succession of a single crop over time, or different age classes in a population. In Ontario, very little thinning is undertaken, thus, it is assumed that through competition, the 'thinning volume' will not be removed, but left to die and rot on the forest floor. The plantation starts with 5,000 trees per hectare and by the time it is 90 years old, only 300 trees remain. If the area is left to grow, there may be only 108 trees

[3] The use of wood for ethanol production, by first breaking it down into simple sugars, is not considered here as the cost is prohibitive. Methanol (wood alcohol) produced from the dry distillation of wood or other biomass is cheaper and may be viable. Methanol can be used directly or as an input to make other fuels/organic chemicals or serve as a hydrogen carrier (CH_3OH)

[4] KBM Forestry Consultants Inc 2008 estimate that 91% of the Algoma forest is managed and the KPMG 2007 study on 'wood pellets' of the Algoma and Martel forest estimate that 93% of the area is managed. Therefore, the assumption that only 85% of Ontario's Crown Forests are managed is conservative.

[5] It was estimated that the overall increase in carbon stored in woody biomass was somewhat offset by a loss of carbon in forest soils due to a switch of forest areas to other uses. The forest carbon loss from forests resulted in a gain by other sectors, although some decrease would occur.

[6] For the forests in Ontario's GLSL forest region, the (latest) 2001 Canadian Forest Inventory (Canadian NFI 2001) gives an average per-ha volume of live trees of 155m^3/ha. This is equivalent to 186m^3/ha with branches, which is 89% of 209m^3/ha

remaining by 180 years with the main crop volume 211m^3/ha, the CAI is zero and the MAI is 2.9m^3/ha. (See Annex 2). Although the volume for YC 4 oak is rather conservative, it is used to estimate the standing volume/mass and yield of the main crop over time.

Table 2. *An estimate of forest carbon in the Algoma Forest Management Unit 2011.*

	Total	**Above ground[1]**	**Below ground[1]**	**Total[1]**	**Above ground[2]**	**Below ground[2]**	**Total[2]**
	MtC		**tC per ha**			**m^3per ha**	
Live trees	30.1	53.7	10.6	64.3	209	41	250
Dead trees	3.5	6.3	1.2	7.5	25	5	30
Downed wood	3.5	6.3	1.2	7.5	25	5	30
Understory	0.8	1.4	0.3	1.7	5	1	6
Sub-total	*37.9*	*67.7*	*13.3*	*81.0*	*264*	*52*	*316*
Forest floor[3]	12.8	27.3	-	27.3			
Soil[4]	37.9	-	81.0	81.0			
Total	**88.6**	**95.0**	**94.3**	**189.3**			
Area (ha)	468,000						
Per ha	189.3	95.0	94.3		264	52	316

Note. 1. The above and below ground totals have been estimated from the FORCARB2 example (Table 1 - USDA 2009).
2. The volume estimates assume 50% carbon in oven dry wood and 1.95 m3 per odt wood.
3. This remains constant over time as new additions are cancelled by decomposition and incorporation into the soil.
4. The forest soil C may be underestimated. In the USDA example it was nearly 60%, increasing the per-ha value to over 200 tC.
Source. Chen J *et al* 2010. USDA 2009. Author's estimates.

5. Age Class Distribution of Trees in the 10 Management Units of the GLSL Ontario Forests

KBM Forestry Consultants Inc. undertook an audit of the Algoma and Martel forests covering 639,310 ha of managed forests. The age-class distribution, in 20-year steps, was given in Table 5 of their Annex on pages A-51 to A-54 for 16 working groups. The totals for the 10 age classes, up to 200 years were then tallied. Figure 5 on page 7 of the main report gives the age-class distribution in 10-year steps. The area of each age-class, depicted in a bar diagram, was estimated and compared to the area as given in Table 5 of the Annex. There is a good agreement between the two sources, except for the years 141-150, which seem to be out by a factor of 10: this was adjusted to agree with Table 5. The areas were then divided into 10-year age groups and the percentage by age-groups calculated as shown in Column 2 of Table 3 below. These percentages were then applied to the total area of 4.46 Mha, assuming that the Algoma and Martel forests have a similar age-class structure to the whole area.

Table 3. *Model for the managed forest area (4.46 Mha).*

Age class	**Area in each class**	**Area by class (rounded)**	**Stem volume, to 7cm t.d. before thin**	**Volume by age-class**		**CAI**	**CAI by age-class to 7cm top diameter (t.d.)**	
				Stem (S)	**S & branch**		**Stem**	**S & branch**
Years	**Percent-age**	**1000 ha.**	**m^3/ha - midpoint**	**Mm^3**		**m^3/ha midpoint**	**Line 3 (area) x CAI 1000 m^3**	
1-10	0.6	27	5	0.14	0.17	0.4	10.8	13.0
11-20	1.7	76	10	0.76	0.91	1.1	83.6	100.3
21-30	1.2	54	30	1.62	1.94	4.4	237.6	285.1
31-40	1.6	71	79	5.61	6.73	5.3	376.3	451.6
41-50	3.0	134	107	14.34	17.21	5.6	750.4	900.5
51-60	7.1	317	135	42.80	51.36	5.6	1775.2	2130.2
61-70	10.6	473	161	76.15	91.38	5.2	2459.6	2951.5
71-80	12.2	544	183	99.55	119.46	4.8	2611.2	3133.4
81-90	20.4	910	200	182.00	218.40	4.3	3913.0	4695.6
91-100	11.8	526	212	111.51	133.81	3.8	1998.8	2398.6
101-110	7.7	343	218	74.77	89.73	3.2	1097.6	1317.1
111-120	6.8	303	221	66.96	80.35	2.7	818.1	981.7
121-130	7.0	312	220	68.64	82.37	2.2	686.4	823.7
131-140	3.5	156	219	34.16	40.99	1.8	280.8	337.0
141-150	2.2	98	218	21.36	25.63	1.4	137.2	164.6
151-160	1.6	71	216	15.34	18.41	1.0	71.0	85.2
161-170	0.4	18	214	3.85	4.62	0.6	10.8	13.0
171-180	0.3	13	212	2.76	3.31	0.2	2.6	3.1
181-190	0.2	9	210	1.89	2.27	0.0	0	0
191-200	0.1	5	208	1.04	1.25	0.0	0	0
Total	100	4,460		825.25	990.30		17,321	20,786
dry wt. 10^6 t.				*423.21*	*507.85*		*8.88*	*10.66*

Note. Stem volume has been taken from the British Forestry Commission Management Tables (FCMT) for Oak, Yield Class 4. It has been extrapolated to year 200. It is assumed that stem and branch volume/increment is 1.2 times stem volume/increment. The thinning volume has been neglected. For the sake of simplicity, it is assumed that little, if any, thinning is undertaken and trees die through competition and are not removed. The Current Annual Increment has been taken from Oak YC4 for years 5, 15, 25, 35 etc. The values for years 5, 15, 155, 165, 175, 185, & 195 are estimated. The FCMT have a built-in reduction of 15% to allow for gaps etc. The increment is 2.1% of the growing stock.
See supporting information concerning Table 2 in McKechnie article.
Source. KBM Forestry Consultants Inc. 2008. HMSO 1971. Author's estimates.

6. Forest Volume and Annual Yield: GLSL Ontario Forests

The division of the area by age-classes is given in Column 3 of Table 3. Column 4 shows the estimated mid-point volume for the 20 age classes. This was taken from Oak YC 4 (HMSO 1971). The stem volume in each age class was then calculated by multiplying the area by the mid-point volume and then totaled, giving a standing stem volume of 825 Mm^3 (equal to 185 m^3 per ha). The volume of stem plus branches was then estimated by adding 20% to the stem volume. This gave a figure of 990 Mm^3 (222 m^3 per ha). Excluded from these estimates are dead and downed trees and the understory, which in Table 2 are 26% of the stem volume. If included, this would bring the total above-ground volume with branches to 280 m^3/ha and the stem volume to 233 m^3/ha. If the age-class structure is a good approximation for the managed forest in GLSL forest area, then it is very unbalanced. Only 8% of the area is less than 51years old, with 62% being from 51 to 100 years old and 30% of the forest area is greater than 100 years old. Because the 'optimum' rotation age is generally less than 100 years, it will take many decades to adjust the age-class structure - 65% of the volume is below 101 years with 35% of it greater than 100 years. The annual increment by age class was then calculated by multiplying the area by the mid-year CIA for each age class. The stem volume increment is given in Column 8 of Table 3. The total for the 4.46 million hectares come to 17.3 Mm^3 (nearly 9 Modt). The largest share of increment is in the age classes 51 to 100 years. They occupy 62% of the area, but produce 73% of the annual increment. The older age classes from 150 years onwards, while occupying 3% of the area only provide 0.5% of the annual increment, indicating that they add very little new sequestered carbon in biomass: a case could be made for felling these old trees in order to increase the annual increment and wood raw material. If branches are included, then the estimated annual increment is nearly 21 Mm^3 – 10.7 Modt.

7. Faulty Accounting Leads to False Figures

Because accounting was done by only considering regrowth of felled trees, the McKechnie article estimates that in CO_2equivalent terms, 15 Mt will be emitted from forest residues and 150 Mt from stemwood used for bioenergy over a 100 year period (Table 2 in the article). *But this is a partial analysis.* A full analysis should examine the annual increment of the whole management area and then compare it to removals for all uses not just for energy. If the annual increment is less than annual consumption of wood products from the GLSL forest management areas, then the forest capital is being reduced and there will be a net emission of CO_2. On the other hand, if the annual increment is more than the annual removals, then there will be no 'carbon debt': in fact there should be an increase in the store of forest carbon, as stated in the article 'Carbon budget of Ontario's managed forests and harvested wood products' (Chen J *et al* 2010).

Table 1 above estimated that the managed forests in the GLSL area of Ontario supplied 2.836 Modt to existing industries in the region (5.5 Mm^3) in 2010 and could supply a further 2.552 Modt for bioenergy (5.0 Mm^3) for a total of 5.388 Modt (10.5 Mm^3). The estimated annual increment of stemwood from the 4.46 Mha in the GLSL forest areas is 8.88 Modt (17.3 Mm^3) and 10.66 Modt of stemwood and branches (20.8 Mm^3) disregarding dead and fallen trees (Table 3). Therefore, there is a surplus of 5.27 Modt of wood from the annual increment of the forest: this total is nearly double the estimated demand requirements. Thus, considerably more wood could be extracted for all purposes without reducing the forest capital. Contrary to what the McKechnie article claims, there is no carbon deficit and all the CO_2 emitted for bioenergy uses is more than reabsorbed by the annual growth of trees in the GLSL forests. Naturally, there will be an emission of CO_2 from bioenergy if only regrowth is considered: *this is partial analysis and creative accounting.*

The McKechnie article quotes other articles to back up the emissions thesis, namely 'Biomass sustainability and carbon policy study' (Manomet Center 2010) and Searchinger T *et al,* (2009). Both of these articles confine the accounting methodology to regrowth of trees and not to the total forest area growth. A detailed assessment of the Manomet project was undertaken and the flaw was pointed out, but as yet no reply has been received. Recent articles and papers have been published by Searchinger T (2012), 'Sound principles and important inconsistency in the 2012 UK bioenergy strategy', the Institute for European Environmental Policy (IEEP) (2012) 'Does biomass have a role to play in reducing Europe's GHG emissions' and the sensation-seeking article by the (UK) Royal Society for the Protection of Bird/Friends of the Earth/Greenpeace (2012) 'Dirtier than coal? Why [UK] government plans to subsidise burning trees are bad news for the planet'. All these writings use the partial analysis of only considering tree regrowth. *If a falsehood is repeated often enough it may be believed!*

8. Benefits of Sequestration and Use

Rather than calling the McKechnie article 'Forest bioenergy or forest carbon?' a more accurate title should be 'Forest bioenergy and forest carbon'. Both the articles by Chen J *et al* (2008; 2010) demonstrate that rather than just leaving the forests to sequestering carbon in trees there will be more carbon sequestered if the forests are used both for storage and use. In addition, if wood used for energy purposes substitutes for fossil fuels, then CO_2 emissions are saved, provided that on average the harvested wood is equal to or less than the annual increment of the whole forest area. This is illustrated with an example given in the IEEP (2012) report.

Table 4. *Stock and yield on a 50 ha forest under three management regimes over 200 years[1;] units tC.*

Carbon storage and yield	Sequestration only (SO)		Semi-management		Commercial forest (CF)	
	per-ha	50 ha	per-ha	50 ha	per-ha	50 ha
Average above-ground stock	220[2]	11,000	166	8,300	70	3,500
Average below- ground stock[3]	55	2,750	41.5	2,075	17.5	875
Sub-total	275	13,750	207.5	10,375	87.5	4,375
Soil carbon[4]	250	12,500	188.6	9,430	79.5	3975
Total carbon stock	**525**	**26,250**	**396.1**	**19,805**	**167**	**8,350**
Additional C stock compared to CF		17,900		11.455		0
Annual above-ground yield for bio-energy per 50 ha	zero	zero	100 for 100 years	10,000	180 for 150 years	27,000[5]
Additional yield compared to SO		0		10,000		27,000
Total stock &yield		**26,250**		**29,805**		**35,350**
Additional Stock &Yield compared to SO		0		3,555		9,100

Note. 1. Based on YC 12 for Sitka spruce (*Picea sitchensis*) from the British Forestry Commission Management Tables.
2. Reaches full stocking at age 142 years assuming area planted over a 50 year period.
3. Below-ground stock assumed to be 25% of above-ground stock, or about 20% of total stock.
4. Additional soil carbon assumed to be in proportion to woody biomass stock. For the semi-managed and commercial forests, this may be an underestimate compared to the non-commercial managed forest.
5. This 27,000 tC in wood, if used for electrical generation, would save approximately 29,000 t of standard coal that would emit 86,000 t CO_2, assuming the same end-use efficiency and 15% of the wood energy used to prepare wood pellets.
Source. Figure 2, IEEP 2012. (UK) Forestry Commission 2003. HMSO 1971, Author's estimates.

Figure 2 on page 32 of the report is a comparison of (above-ground) carbon stock between a forest under a) non-commercial management and b) a high-yielding commercial forest. It is based on Sitka spruce YC 12 from the British Forestry Commission Management Tables (HMSO 1971). This was taken from a UK Forestry Report on 'Forests, carbon and climate change': the UK contribution to climate change, (Forestry Commission 2003) submitted to the Intergovernmental Panel on Climate Change (IPCC). For illustrative purposes, it is assumed that both forests have an area of 50 ha, with one ha in each age class from 1 to 50. The two forest types are compared over a period of 200 years. Diagram 2a in the IEEP (2012) report illustrates what would happen if the newly created forest is left to grow to maturity under non-commercial management. It will reach maturity at year 92 and is then left to stand. The above-ground carbon stock on this 50 ha area will be 11,000 tC. (Table 4 above). The same diagram shows a stock fluctuation ranging from a maximum of 220 tC/ha to a minimum of 120 tC. This is because of the introduction of some management into the 'mature forest' with the off-take being used for bio-energy: it is an alternative for this forest. The estimated above-ground carbon stock on this 50 ha option is 8,300 tC and the annual off-take will be 100 tC. For the high-yielding commercial forest (diagram 2b in the IEEP report), the stock on the 50 ha will be 3,500 tC and the annual yield will be 180 tC. This can be removed yearly without reducing the forest capital. This is what Matthews R *et al* (2012) demonstrates in their paper 'Carbon impacts of using biomass in bio-energy and other sectors: forests', a report published in support of the UK bio-energy strategy. Figure 2 in the IEEP report only shows the above-ground biomass, but there will be carbon sequestration in the below-ground biomass and in the forest soil. Table 4 above examines these three alternatives.

While the un-managed forest has about three-times the amount of carbon in the wood and forest soil as does the commercial forest - the counterfactual assessment - when the total stock and yield are taken into account over the 200 year period, the total carbon store and production is 35% more in the commercial forest compared to the unmanaged forest: this gap increases with time. *This is a full LCA!*

In most, if not all cases, the management of forests, for stock and yield will generate more carbon production than just leaving forests unmanaged. Carbon will still be stored in the trees and in non-energy wood products and if used for bioenergy it will substitute for fossil fuels. Generally, this latter does not result in a reduction of forest carbon, unless the annual harvest is more than the annual growth of the trees. By only considering the growth of the present and future fellings, it will lead to underestimating carbon capture and to false and misleading accounting as in the McKechnie and other quoted articles. It is important to correct this error and set the record straight. A full knowledge of perennial crops and their growth is important when analyzing carbon sequestration and use, otherwise bogus conclusions will be drawn.

Annex 1: McKechnie *et al* Article: Analysis of Table 2.

Table 2 of the article is given below for stock chances for residues and standing trees together with the recalculated figures.

Table 2. *Forest carbon stock change (Mt CO_2 equivalent)*

Age (yr)	10	20	30	40	50	60	70	80	90	100
Residues	-8.2	-11.8	-13.0	-13.5	-13.9	-14.3	-14.7	-15.0	-15.2	-15.2
Standing trees (ST)	-43.6	-80.9	-106.3	-112.5	-113.4	-112.7	-132.8	-143.6	-150.8	-150.7
Recalculated cumulative estimates										
Residues	-6.6	-12.1	-13.8	-12.4	-8.4	-2.2	5.2	13.4	21.8	30.1
ST 100 yr rotation	-43.6	-82.1	-100.7	-102.8	-90.3	-67.4	-39.0	-6.5	27.0	59.5
ST 50 yr rotation	-43.6	-67.7	-69.5	-35.4	22.2	-21.4	-45.5	-47.3	-13.2	44.4
Recalculated cumulative estimates with 'coal savings'										
Residues	-0.8	-0.6	3.5	10.7	20.5	32.5	45.6	59.6	73.8	87.9
ST 100 yr rotation	-16.5	-28.0	-19.5	5.44	45.0	95.0	150.4	209.9	270.4	330.0
ST 50 yr rotation	-16.5	-13.5	11.7	72.8	157.5	141.0	144.0	169.2	230.3	315.0

Note. Negative values indicate a GHG emission source indicating that forest carbon stocks are reduced due to biomass harvest. For the 100 year rotation oak yield class 4 is used and for the 50 year rotation, oak yield class 8 is used based on the UK's F.C. Management Tables (HMSO 1971). For residues, the formula given in the notes is used. These carbon stock changes are just for the present and future fellings, (19,700 ha /yr) and not for the whole area.
Source. McKechnie J. *et al* 2011. HMSO 1971. Author's calculations.

No explanation is given as to how the standing tree stock changes are calculated. For residues a formula is given to calculate the carbon stored in uncollected residues, based on the decay rates for hardwood and softwoods and pulpwood and sawlog harvest. An average decay factor (k) of 0.05 has been used, which I consider to be on the low side. However, using this figure, the residue total becomes positive in years 61-70. This is much different from the figures given in Table 2.

Table A. *Production of stem wood from year 1 to year 100 in 10 year intervals.*

Age group	CAI/ha mid-point	Re-growth on 19,700 ha to 7 cm top diameter		Multiplier for 10 years	Total for 10 year intervals	
years	m^3	m^3	odt		million odt	mill t CO_2 equiv
1-10	0.4	7,880	4,041	55	0.22	0.41
11-20	1.1	21,670	11,113	155	1.72	3.16
21-30	4.4	86,680	44,451	255	11.34	20.80
31-40	5.3	104,410	53,544	355	19.01	34.88
41-50	5.6	110,320	56,574	455	25.74	47.24
51-60	5.6	110,320	56,574	555	31.40	57.62
61-70	5.2	102,440	52,533	655	34.41	63.14
71-80	4.8	94,560	48,492	755	36.61	67.18
81-90	4.3	84,710	43,441	855	37.14	68.16
91-100	3.8	74,860	38,390	955	36.66	67.28

Note. The 10 year multiplier is the number of individual 19,700 ha in each 10 year age group. For example in the first 10 years it is 1+2+3+4+5+6+7+8+9+10 = 55. The current annual increment (CAI) for years 5 and 15 has been estimated from FC Yield Class 4 Table for Oak.
Source. HMSO 1971. Author's calculations.

For standing trees the nominal rotation age is not stated. It may be 50 years or it may be 100 years. I have calculated the changes in forest carbon based on 100 year and 50 year rotations. My results for standing trees are shown on lines 6 and 7 in the above table and for residue on line 5. Detailed work sheets are given below. As can be seen for the 100 year calculation for standing trees, the cumulative stock change is positive by year 90 and for the 50 year rotation it is positive by year 50. Again for residues, it is positive by year 70. The following tables show how my figures are derived.

Based on the Model for the managed forest area (4.46 million ha), the average stemwood standing stock is 185 m^3/ha. Felling the equivalent of 19,700 ha per year would give 3,644,500m^3 or 1.869Modt. Table A gives the estimated production of wood in 10-year intervals based on YC 4 CAI.

It is proposed to use 1.869 Modt of stemwood for bio-energy each year. This will give off 3.430 MtCO_2 equivalent or 34.3 MtCO_2 equiv. for a 10-year period. Table 2 has the equivalent of 43.6 MtCO_2equiv. for the first 10-year period. This is 9.3 Mt CO_2equiv. more than from the bio-energy wood (34.3 Mt CO_2). It is assumed that this additional total is given off by carbon in roots and soil. In the first 10 years, 0.41 Mt CO_2 equiv. are captured by tree re-growth. So in year zero, the stock of CO_2 will be 44.01 Mt CO_2 equiv. It is also assumed that with the re-growth, the emissions of CO_2 from old root and soil will be countered by root re-growth and soil carbon accumulation, so by year 50 there will be no net-emissions from roots and soil. Table B gives the estimate of the carbon dioxide balance for the 100 year period in 10 year intervals, by comparing emissions to stem re-growth.

Table B. *Estimate of the carbon balance from using 1.869 Modt stemwood for bioenergy and tree re-growth on 19,700 ha.*

Units: Mt CO_2 equivalent

Period: yrs	1-10	11-20	21-30	41-40	41-50	51-60	61-70	71-80	81-90	91-100
Emissions	-44.01	-41.68	-39.36	-37.03	-34.71	-34.71	-34.71	-34.71	-34.71	-34.71
Capture	0.41	3.16	20.80	34.88	47.24	57.62	63.14	67.18	68.16	67.28
Net em.	-43.60	-38.52	-18.56	-2.15	12.53	22.91	28.43	32.47	33.45	32.57
Culm em.	-43.60	-82.12	-100.68	-102.83	-90.30	-67.39	-38.96	-6.49	26.96	59.53

Note. Culm em = cumulative emissions (em.). Negative values indicate a GHG emission source specifying that forest carbon stocks are reduced due to biomass harvest. Positive values indicate that carbon is being accumulated.
Source. McKechnie J. *et al* 2011. Author's calculations.

Compared to Table 2, assuming a 100-year rotation for the felled area for bio-energy, by year 50, there is a net accumulation of carbon stock and from then onwards it increases and these increases negate the cumulative emissions by year 81. By the end of the 100 years, the net accumulation of wood is over 32 million t.

Alternatively, Table 2 may be based on a 50-year rotation. If that is the case, I assume that the annual growth of trees in the felled area must be better than yield-class 4. I have assumed that it will be yield class 8 for oak from the F.C's management tables. This will give an annual yield by year 50 slightly in excess of 1.869 million t of wood from 19,700 ha. Thus, in theory, no new areas of forests need to be cleared or if they are, the output of wood for bio-energy could be doubled. Table C gives the estimated production of wood in 10-year intervals based on YC 8 CAI for oak assuming a 50 year rotation.

Table C. *Production of stem wood from year 1 to year 50 in 10 year intervals.*

Age group	**CAI/ha mid-point**	**Re-growth on 19,700 ha. To 7 cm top diameter**		**Multiplier for 10 years**	**Total for 10 year intervals**	
years	**m^3**	**m^3**	**odt**		**Modt**	**Mt CO_2 equiv**
1-10	1.9	37,430	19,195	55	1.06	1.94
11-20	6.8	133,960	68,697	155	10.65	19.54
21-30	8.2	161,540	82,841	255	21.12	38.76
31-40	11.0	216,700	111,128	355	39.45	72.39
41-50	11.1	218,670	112,138	455	51.02	93.63

Note. The 10 year multiplier is the number of individual 19,700 ha in each 10 year age group. For example in the first 10 years it is 1+2+3+4+5+6+7+8+9+10 = 55. The current annual increment (CAI) for years 5 and 15 has been estimated from FC Yield Class 8 Table for Oak.
Source. HMSO 1971. Author's calculations.

Table D. *Estimate of the carbon balance from using 1.869 Modt stemwood for bio-energy and tree re-growth on 19,700 ha for two 50 year rotations.*

Units: Mt CO_2 equivalent

Period	**1-10**	**11-20**	**21-30**	**31-40**	**41-50**	**1-10**	**11-20**	**21-30**	**31-40**	**41-50**
Emissions	-45.54	-43.61	-40.61	-38.29	-36.01	-45.54	-43.61	-40.61	-38.29	-36.01
Capture	1.94	19.54	38.76	72.39	93.63	1.94	19.54	38.76	72.39	93.63
Net em.	-43.60	-24.07	-1.85	34.10	57.62	-43.60	-24.07	-1.85	34.10	57.62
Culm em.	-43.60	-67.67	-69.52	-35.42	22.20	-21.40	-45.47	-47.32	-13.22	44.40

Note. Culm em = cumulative emissions (em.). Negative values indicate a GHG emission source specifying that forest carbon stocks are reduced due to biomass harvest. Positive values indicate that carbon is being accumulated.
Source. Author's calculations.

Table D give the estimated CO_2 balance for two 50 year periods in 10 year intervals, by comparing emissions to stem re-growth.

By year 41, there is an accumulation of forest carbon and by the end of the first rotation there is a positive accumulation, equivalent to 12 million t of wood and by the end of the second rotation it is the equivalent of 24 million t of wood.

Turning to residues, an average decomposition factor of 0.05 has been used in the calculations. This has to be done in two parts. The first part is to compare the negative emissions from burning 383,000 t of wood each year with the positive emissions if the wood is left to decompose. The second part is to compare the emissions from the annual decomposition of 300,000 t of wood with the growth of branch wood in the replanted areas.

Table E looks at the use of 383,000 t of residues for bio-energy (0.702 Mt CO_2/year) or letting 383,000 t decompose on the forest floor. Table F compares the growth of branch wood against the emissions from branch wood on the forest floor.

***Table E.** Estimate of the carbon balance from using 0.383 Modt branch wood for energy or letting the same amount decompose on the forest over 100 years.*

Units: Mt CO_2 equivalent

Period: years	**1-10**	**11-20**	**21-30**	**31-40**	**41-50**	**51-60**	**61-70**	**71-80**	**81-90**	**91-100**
Emissions	-7.02	-7.02	-7.02	-7.02	-7.02	-7.02	-7.02	-7.02	-7.02	-7.02
Decomposition	1.67	3.82	5.10	5.87	6.33	6.61	6.78	6.87	6.93	6.97
Net em.	-5.35	-3.20	-1.92	-1.15	-0.69	-0.41	-0.24	-0.15	-0.09	-0.05
Culm em. minus coal	-5.35	-8.55	-10.47	-11.62	-12.31	-12.72	-12.96	-13.11	-13.20	-13.25
Coal savings	5.77	5.77	5.77	5.77	5.77	5.77	5.77	5.77	5.77	5.77
Net em.	0.42	2.57	3.85	4.62	5.08	5.36	5.53	5.62	5.68	5.72
Culm savings with coal	0.42	2.99	6.84	11.46	16.54	21.90	27.43	33.05	38.73	44.45

Note. Culm em = cumulative emissions. Negative values indicate a GHG emission source specifying that forest carbon stocks are reduced due to biomass harvest. The decomposition is treated as a positive value.
An estimated 185,000 t of coal containing 0.577 Mt CO_2 will be saved annually from using 383,000 of residues, or 5.77 Mt CO_2 every 10 years.
Source. McKechnie J. *et al* 2011. Author's calculations.

It seems that only emissions from the use of residues for fuel had been considered in Table 2, because there is a net accumulation of carbon from year 61 onwards (Table G)! Also, if the saving of emissions from coal is considered then there is a saving of emissions from year 1. After 100 years the cumulative saving is over 12 million t C.

Table F compares the decomposition of 300,000 t of wood residue on the forest floor from the felling of 19,700 ha per year to the annual growth of the branch wood on the 19,700 ha annual planting/regeneration. Because the annual growth of branch wood is on average more than 300,000 t, a reduction factor of 0.80 has been applied to the gross growth figure. YC 4 has been assumed. Again a decomposition factor of 0.05 has been used in the formula given on page S-14 in the articles' accompanying notes. Table G combines Tables E and F to examine total emissions.

***Table F.** Estimate of the carbon balance from letting 300,000 odt branch wood decompose on the forest floor compared to the growth of branch wood on newly planted/regenerated area over 100 year period.*

Units: Mt CO_2 equivalent

Period: years	1-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
Decomposition	-1.31	-2.99	-4.00	-4.60	-4.96	-5.18	-5.31	-5.38	-5.43	-5.46
Capture	0.08	0.65	4.26	7.14	9.68	11.80	12.93	13.76	13.96	13.78
Net em.	-1.23	-2.34	0.26	2.54	4.72	6.62	7.62	8.38	8.53	8.32
Culm em.	-1.23	-3.57	-3.31	-0.77	3.95	10.58	18.20	26.58	35.11	43.43

Note. Culm em = cumulative emissions (em.). Negative values indicate a GHG emission source specifying that forest carbon stocks are reduced due to biomass harvest.
Source. McKechnie J. *et al* 2011. Author's calculations.

***Table G.** Estimated total emissions from residues over a 100-year period.*

Units: Mt CO_2 equivalent

Period: years	1-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
Culm em. without coal savings	-6.58	-12.12	-13.78	-12.39	-8.36	-2.14	5.24	13.47	21.91	30.18
Culm em. With coal savings	-0.81	-0.58	3.53	10.69	20.49	32.48	45.63	59.63	73.84	87.88
Table 2 figures	-8.2	-11.8	-13.0	-13.5	-13.9	-14.3	-14.7	-15.0	-15.2	-15.2

Note. Culm em = cumulative emissions. Negative values indicate a GHG emission source specifying that forest carbon stocks are reduced due to biomass harvest. Table 2 figures are from the McKechnie article.
Source. McKechnie J. *et al* 2011. Author's calculations.

Comparing the second line in Table G, with the article's Table 2 figures, given on the bottom line of Table G, it will be seen that there is a considerable discrepancy from years 51-60 and onwards without coal savings and from year 1 with coal savings. The cumulative savings of carbon is nearly 24 million t.

On a related issue, I think that the decomposition rate is too low. The lifetime of the decaying wood with a decay factor of 0.05 is over 130 year. In my opinion, for tops and branches, the rate should be about 0.15. This would give the lifetime of about 30 years for decomposing small diameter wood.

Table H1&2 looks at the adjusted emission figures for stem wood taking into consideration the coal saving factor. The two rotations have been considered, namely 50 & 100 years. The estimated annual saving of coal from substituting 1.914 Mt of wood is 1.085 Mt coal which would give off 2.708 Mt CO_2equivalent or 27.08 Mt every 10 years.

It seems there are large discrepancies between Table 2 and the above calculations. It is also certain that the article did not consider the annual growth of all the trees, just the areas to be used for bio-energy. If it had done, then it should have concluded that annual growth of wood exceeds annual removals and there are no net carbon emissions. Rather there is carbon capture.

Table H1. *Estimate of the carbon balance from using 1.869 Modt stemwood each year for bio-energy and tree re-growth on 19,700 ha for two 50 year rotations.*

Units: Mt CO_2 equivalent

Period: years	1-10	11-20	21-30	31-40	41-50	1-10	11-20	21-30	31-40	41-50
Emissions	-45.54	-43.61	-40.61	-38.29	-36.01	-45.54	-43.61	-40.61	-38.29	-36.01
Capture	1.94	19.54	38.76	72.39	93.63	1.94	19.54	38.76	72.39	93.63
Net em.	-43.60	-24.07	-1.85	34.10	57.62	-43.60	-24.07	-1.85	34.10	57.62
Culm em.	-43.60	-67.67	-69.52	-35.42	22.20	-21.40	-45.47	-47.32	-13.22	44.40
Coal savings	27.08	27.08	27.08	27.08	27.08	27.08	27.08	27.08	27.08	27.08
Net em. with coal	-16.52	3.01	25.23	61.08	84.70	-16.52	3.01	25.23	61.08	84.70
Culm em. with coal	-16.52	-13.51	11.72	72.80	157.50	140.98	143.99	169.22	230.30	315.00
					Table 2 figures. McKechnie article					
Standing trees	-43.6	-80.9	-106.3	-112.5	-113.4	-112.7	-132.8	-143.6	-150.8	-150.7

Note. Culm em. = cumulative emissions (em.). Negative values indicate a GHG emission source specifying that forest carbon stocks are reduced due to biomass harvest. Positive values indicate that carbon is accumulating. Carbon saving including coal by year 100 = 86 Mt and without coal 12 Mt. Table 2 of the McKechnie article shows a carbon debt of 41Mt.

Source. McKechnie J. *et al* 2011. Author's calculations.

Table H2. *Estimate of the carbon balance from using 1.869 Modt stemwood each year for bio-energy and tree re-growth on 19,700 ha assuming a rotation of 100 years.*

Units: Mt CO_2 equivalent

Period: years	1-10	11-20	21-30	41-40	41-50	51-60	61-70	71-80	81-90	91-100
Emissions	-44.01	-41.68	-39.36	-37.03	-34.71	-34.71	-34.71	-34.71	-34.71	-34.71
Capture	0.41	3.16	20.78	34.85	47.20	57.57	63.09	67.13	68.10	67.22
Net em.	-43.60	-38.52	-18.58	-2.18	12.49	22.86	28.38	32.42	33.39	32.51
Culm em.	-43.60	-82.12	-100.68	-102.83	-90.30	-67.39	-38.96	-6.49	26.96	59.53
Coal savings	27.08	27.08	27.08	27.08	27.08	27.08	27.08	27.08	27.08	27.08
Net em. with coal	-16.52	-11.44	8.50	24.90	39.57	49.94	55.46	59.50	60.47	59.59
Culm em. with coal	-16.52	-27.96	-19.46	5.44	45.01	94.95	150.41	209.91	270.38	329.97
					Table 2 figures. McKechnie article					
Standing trees (ST)	-43.6	-80.9	-106.3	-112.5	-113.4	-112.7	-132.8	-143.6	-150.8	-150.7

Note. Culm em. = cumulative emissions (em.). Negative values indicate a GHG emission source specifying that forest carbon stocks are reduced due to biomass harvest. Positive values indicate that carbon is accumulating. Carbon saving including coal by year 100 = 90 Mt. and without coal 16 Mt. Table 2 of the McKechnie article shows a carbon debt of 41 Mt.

Source. McKechnie J. *et al* 2011. J. Author's calculations.

Annex 2.

Table 1. *UK Forestry Commission: Management Table for Oak Yield Class 4*

Age years	Plants left per-ha number	Plants thinned/ died/ha number	Main crop Before Thinning: m^3/ha To 7cm top diam.	Main crop After Thinning: m^3/ha To 7cm top diam.	Thinning/death Per 5 yr m^3/ha To 7cm top diam.	Thinning/death Cumulative m^3/ha To 7cm top diam.	Cumulative total m^3/ha 7cm t.d.	CAI m^3/ha To 7cm top diam.	MAI m^3/ha To 7cm top diam.
0	5000	0	0	0	0	0	0	0	0
25	4200	800	30	30	0	0	30	4.4	1.2
30	3750	450	54	54	0	0	54	4.9	1.8
35	2363	1387	79	66	13	13	79	5.3	2.3
40	1702	661	93	79	14	27	106	5.5	2.7
45	1285	417	107	93	14	41	134	5.6	3.0
50	1006	277	121	107	14	55	162	5.6	3.2
55	822	184	135	121	14	69	190	5.6	3.5
60	681	141	148	134	14	83	217	5.4	3.6
65	573	108	161	147	14	97	244	5.2	3.8
70	492	81	172	158	14	111	269	5.0	3.9
75	428	64	183	169	14	125	294	4.8	3.9
80	376	52	192	178	14	139	317	4.5	4.0
85	335	41	200	186	14	153	339	4.3	4.0
90	*300*	*35*	*207*	*193*	*14*	*167*	*360*	*4.0*	*4.0*
95	270	30	212	198	14	181	379	3.8	4.0
100	244	26	216	202	14	195	397	3.5	4.0
105	221	23	218	204	14	209	413	3.2	3.9

Age years	Plants left per-ha number	Plants thinned/ died/ha number	Main crop Before Thinning: m^3/ha To 7cm top diam.	After	Thinning/death Per 5 yr m^3/ha To 7cm top diam.	Cumulative	Cumulative total m^3/ha 7cm t.d.	CAI m^3/ha To 7cm top diam.	MAI m^3/ha
110	201	20	219	206	13	222	428	2.9	3.9
115	185	16	221	208	13	235	443	2.7	3.9
120	171	14	221	209	12	247	456	2.4	3.8
125	159	12	220	209	11	258	467	2.2	3.7
130	149	10	220	210	10	268	478	2.0	3.7
135	141	8	219	210	9	277	487	1.8	3.6
140	134	7	218	210	8	285	495	1.6	3.5
145	128	6	218	211	7	292	503	1.4	3.5
150	123	5	217	211	6	298	509	1.2	3.4
155	118	5	216	211	5	303	514	1.0	3.3
160	114	4	215	211	4	307	518	0.8	3.2
165	111	3	214	211	3	310	521	0.6	3.2
170	109	2	213	211	2	312	523	0.4	3.1
185	108	1	212	211	1	313	524	0.2	3.0
180	108	0	211	211	0	313	524	0.0	2.9

Note. The yield table has been extrapolated from 150 to 180 years. At this point the current annual increment (CAI) = zero. MAI = mean annual increment. The yield table represents either a natural succession of a single crop over time or different age classes in a population. At an early age, many plants that are thinned or die have a top diameter less than 7cm. The MAI at year 180 is 2.9 m^3/ha; this is only 72.5% of the maximum MAI – 4.0 m^3/ha. The table has been modified to give main crop after thinning and the cumulative thinning totals every five years. Excluded are top height, mean diameter, basal area, volumes to 18cm and 24cm of main crop and thinnings, cumulative basal area and basal area increment.

Source. British Forestry Commission Booklet No. 34. Her Majesty's Stationery Office (HMSO) 1971. London, UK.

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