

Growing trees to sequester carbon in the UK: answers to some common questions

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Summary

There has been renewed interest in the issue of growing trees to sequester carbon following the Kyoto Protocol in 1997. It is a complex issue, raising many questions. In this paper, the author offers answers to some of the questions commonly asked in the UK. These questions concern: (1) the basic rationale for growing trees to sequester carbon (does it make sense?); (2) the size of the reservoirs, sinks and sources of carbon in the UK (how important are the forests?); (3) effects of species, site and management (which is most effective at storing carbon?); (4) areas and numbers of trees needed to offset fossil fuel emissions (how many trees need to be planted per person or per car?); and (5) the monetary value of the carbon stored (what is it worth?). The answers given are taken mostly from published literature.

Introduction

There is increasingly convincing evidence that the earth is getting warmer (Mann *et al.*, 1998) and that future warming could have effects on the climate system which will seriously affect human affairs (Mitchell and Johns, 1997). Climatic change is now firmly on the environmental agenda of the UK Government, with commitments under the UN Framework Convention on Climate Change (FCCC, along with 173 other countries) to stabilize greenhouse gases in the atmosphere at a level which will not 'dangerously' affect the earth's climate system.

The first step towards achieving a reduction in greenhouse gas emissions was taken in Kyoto in December 1997, when 36 nations (the Annex I

countries) agreed an overall 5.2 per cent reduction in emissions from 1990 levels by 2008–2012. The Kyoto Protocol is, however, very limited: (1) if implemented, it will reduce warming in 2100 by only about 8 per cent below business-as-usual (Wigley, 1998), (2) it places no restrictions on emissions from non-Annex I (mostly developing) countries, (3) implementation will be difficult without ratification by the USA, and (4) there is skepticism whether the 5.2 per cent target will be met, given that emissions in the USA and Japan rose by 5 per cent between 1990 and 1996. Nevertheless, it is a serious attempt to address the issue and has opened the way for further discussion.

In order to get agreement at Kyoto, four factors were included in the Protocol, which are

being taken forward in current discussions: (1) six greenhouse gases were included, not just CO₂, (2) carbon reduction credits can be traded between Annex I countries ('Joint Implementation'), (3) non-Annex I countries can assist Annex I countries to meet their targets through joint projects which reduce emissions and achieve sustainable development ('Clean Development Mechanism'), and (4) Annex I countries can reduce their emissions not only by cutting fossil fuel emissions, but also by increasing net carbon sequestration in terrestrial sinks – restricted to afforestation, reforestation and deforestation since 1990. The latter restriction means that the 'Kyoto forests' represent a small proportion of the sinks and sources due to land use change (IGBP Terrestrial Carbon Working Group, 1998) but overall, the proposals for Joint Implementation, Clean Development and the inclusion of terrestrial sinks has intensified interest in the role of forestry.

Meanwhile, outside the inter-Governmental process, many individual companies and some Governments have been supporting CO₂ emission reduction projects, including sequestration by afforestation, reforestation and forest management schemes. Notably, the Dutch Electricity Generating Board set up the FACE Foundation (Forests Absorbing Carbon dioxide Emissions) in 1990, supporting projects around the world which will sequester an estimated 31 MtC¹ over the next 100 years (Verweij, 1998) and the USA has launched an Initiative on Joint Implementation (USIJI, 1996) which has approved 13 forestry projects (Trexler and Kosloff, 1998).

This activity, coupled with public concern and the threat of carbon taxes (already imposed in the Netherlands, Finland, Norway and Sweden) has prompted many UK companies to develop greenhouse friendly policies and to explore opportunities to offset their emissions by planting trees. Some basic questions are being asked by these companies and by foresters who wish to respond. This paper is written in response to that demand for basic information, summarized from a range of sources.

The rationale for growing forests to sequester carbon

Can enough carbon be stored in forests to materially affect the rate of global warming?

Several estimates have been made of the realistic scale of forest planting worldwide that could be realized over the next few decades. The most authoritative is that estimated by the Intergovernmental Panel on Climate Change (Watson *et al.*, 1996) which took into account the availability of land for forestry, motivations for forest and agro-forest planting, national forest and land use plans (e.g. Tropical Forestry Action plans), costs and the likely timetable. They also counted tropical forest areas that could be conserved rather than deforested, as assumed in the IPCC business-as-usual projections of global carbon emissions.

The IPCC concluded that 'the cumulative amount of carbon that could potentially be conserved and sequestered over the period 1995–2050 by slowing deforestation (138 million ha) and promoting natural forest regeneration in the tropics (217 million ha), combined with the implementation of a global forestation programme (345 million ha of plantations and agro-forests) would be about 60–87 GtC (Gt = thousand million tonnes), equivalent to 12–15 per cent of the projected cumulative fossil fuel and deforestation emissions over the same period' (Brown *et al.*, 1996).

Thus, globally, it may be possible to plant and conserve enough forests to remove from the atmosphere an amount of carbon equivalent to a cut in business-as-usual fossil fuel emissions of 12–15 per cent between now and 2050. But this would not stabilize atmospheric CO₂ levels nor hold them at below 600 p.p.m. next century, which some regard as necessary to avoid 'dangerous' climatic change. Forestry is, therefore, a contributor to the solution, not the sole answer; there is no avoiding having to cut fossil fuel emissions.

Globally, the UK is obviously a small player. Annual UK fossil fuel carbon emissions are only about 2.5 per cent of the global total and even a sustained programme of new afforestation in the UK of 30 000 ha a⁻¹ (combined with complete restocking of harvested areas) will sequester less

¹ The unit MtC = million tonnes of carbon. To convert this to CO₂ multiply by 3.67.

than 2 per cent of the UK fossil fuel carbon emissions (Cannell and Dewar, 1995). The justifications for cutting emissions and storing carbon in forests in the UK would be to fulfil our obligations and take a lead within the global FCCC.

Is locking up carbon in trees a sensible way of mitigating the greenhouse effect?

The basic arguments in favour of planting trees to sequester carbon are that (1) if done globally, it 'buys time' during which longer term solutions can be sought to meet world energy supplies without endangering the climate system, and (2) it may be a cheaper option of slowing the increase in CO₂ concentrations than reducing fossil fuel energy use (Trexler and Kosloff, 1998). Also, of course, in many regions of the world, increased afforestation, forest conservation and agro-forestry are desirable anyway.

The main arguments against using forestry as a means of mitigating the greenhouse effect are that (1) it is a limited, short-term measure, (2) it may be used as an excuse not to cut fossil fuels, and (3) if no technical solution is found, it may be storing up trouble for the future. Carbon sequestration in forests places a burden on forest owners to maintain that carbon reservoir once it has been created – and that cannot be guaranteed across generations, given the threat of fire and other hazards including climate change itself. The more carbon that is stored in forests now – the more time that is 'bought' – the greater the hazard if it were released later. In the long term, carbon is more securely stored in oil, gas and coal deposits than in forests.

Current reservoirs, sources and sinks of carbon in the UK

How much carbon is emitted by burning fossil fuels in the UK (in total and per person) and what cuts have the UK agreed?

Currently, about 154 MtC (565 Mt CO₂) are emitted into the atmosphere in the UK per year by burning fossil fuels, about 30 per cent from power stations, 23 per cent from industry and 24 per cent from all forms of transport (70 per cent of which is from road vehicles) (Table 1).

Emissions from transport sources increased by 60 per cent between 1970 and 1996 owing largely to an increase in the car population. Emissions from industry decreased by 44 per cent between 1970 and 1990 owing to the rundown of heavy industries. Emissions from power stations decreased by 19 per cent between 1990 and 1995 because of the switch from coal- to gas-fired burners and growth in nuclear power generation. Total electricity consumption in the UK has actually increased (from about 200 TWh in 1970 to 270 TWh in 1990) but the energy released per tonne of carbon emitted is very much larger for gas than for coal (about 45 compared with 28 Terajoules/tC).

The UK population was 55.5 million in 1970 and 56.4 million in 1990. Thus, the average fossil fuel emission per person was 3.3 tC a⁻¹ in 1970 and 2.8 tC a⁻¹ (10.3 t CO₂ a⁻¹) in 1990. Currently, about 0.6 tC a⁻¹ is emitted per person to sustain all forms of transport.

The UK carbon emissions in 1996 were below those in 1990, consistent with the UK's commitment under the FCCC to stabilize greenhouse gas

Table 1: Amount of carbon emitted to the atmosphere as CO₂ from different sources in the UK (million tonnes of C per year). Taken from DETR (1998) and DTI (1997a)

Source	1970	1980	1990	1993	1994	1995	1996
Power stations	57	58	54	45	44	44	43
Industrial combustion	66	43	36	36	36	36	37
Domestic	26	23	22	24	23	22	25
Transport	21	27	36	36	36	36	36
Other sectors	12	13	11	11	11	11	12
Total	182	164	159	152	151	149	154

The data given here are those calculated according to the Intergovernmental Panel on Climate Change methods (Salway, 1997). Multiply by 3.67 to obtain million tonnes of CO₂.

emissions (measured in CO₂ equivalents) to 1990 levels by 2000 (see Table 1). However, to meet our target under the 1997 Kyoto Protocol, the UK needs to cut emissions by 12.5 per cent by 2008–2012 compared with 1990 levels (as part of an overall 8 per cent cut within the EU). If only fossil fuel emissions are counted, this will mean cutting emissions to 139 MtC a⁻¹, about 20 MtC a⁻¹ less than in 1990 and 15 MtC a⁻¹ less than in 1996 (DETR, 1998; Table 1).

How much carbon is currently stored in UK forests, other vegetation and soils?

The total amount of carbon in British vegetation in 1990 has been estimated to be 114 MtC (Cannell and Milne, 1995; Milne and Brown, 1997). This figure omits urban trees, for which there is no UK estimate. Note that 114 MtC is less than that emitted annually from fossil fuels in the UK (Table 1). In other words, the annual carbon emission from fossil fuel combustion is more than would be emitted if all UK vegetation were burned.

Cannell and Milne (1995, their Table 1) reported the amounts of carbon in different vegetation types and tree species. About 80 per cent of the carbon in British vegetation is in forests and woodlands (92 MtC) although occupying only 11.2 per cent of the rural land area. Broadleaved woodland alone accounts for 47 per cent of the total of 114 MtC because those woodlands are older and contain, on average, 62 tC ha⁻¹ compared with 21 tC ha⁻¹ in conifer forests. Conifers cover 6.1 per cent of the land area, compared with 4.1 per cent by broadleaved woodlands, but contain only 25.3 per cent of the total of 114 MtC.

British soils have been estimated to contain 9839 MtC, 86 times as much as is contained in vegetation (Milne and Browne, 1997). However, 4523 MtC (46 per cent) of this carbon is in 'deep' peats (over 45 cm deep) in Scotland and this figure is known only to within ± 50 per cent owing to uncertainty in peatland areas, depths and bulk densities. There is an estimated 2425 MtC in non-peat soils in Scotland and 2890 MtC in all soils in England and Wales (Milne and Brown, 1997).

How much carbon is being exchanged annually between UK vegetation/soils and the atmosphere?

Globally, about 100 GtC cycles between the land surface and the atmosphere each year as a result of photosynthesis and all forms of plant and soil respiration. This land–atmosphere exchange is very large compared with the 7–8 GtC a⁻¹ that is currently emitted into the atmosphere globally by burning fossil fuels and deforestation. That is, global anthropogenic emissions represent a small perturbation of the natural carbon cycle.

At the UK scale, the annual exchange of carbon between the land and atmosphere is of the order 100–150 MtC a⁻¹. This figure is based on predictions of gross photosynthesis made using the Hurley Pasture and Edinburgh Forest models at sites in lowland England and upland Scotland (Thornley, 1998 and personal communication). Note that this 'natural' carbon exchange is similar to the amount of carbon added into the atmosphere each year by burning fossil fuels (Table 1).

The net exchange of carbon between the land and atmosphere depends on the balance between gross photosynthesis and total plant and soil respiration. For grasslands, averaged over the UK, this exchange varies (approximately sinusoidally over the year) from a net uptake of about 1.5 kgC m⁻² day⁻¹ in May–June (when photosynthesis exceeds respiration) to a net loss of about 1.5 kgC m⁻² day⁻¹ in September–October. These figures imply that about 9 MtC month⁻¹ is removed from the atmosphere in May–June and 9 MtC month⁻¹ is returned to the atmosphere in September–October. Meanwhile, an average of about 12 MtC month⁻¹ (148/12) is emitted by burning fossil fuels – ignoring seasonal fluctuations in fossil fuel consumption of about 5 per cent (DTI, 1997b).

The overall net effect is that only about 3 MtC month⁻¹ may be added to the atmosphere in the UK in May–June, but about 21 MtC month⁻¹ in September–October. This seasonal cycle, occurring in countries over the northern land hemisphere, gives rise to seasonal fluctuations in atmospheric CO₂ concentrations, currently ranging from about 355 p.p.m. in summer to 365 p.p.m. in winter in rural areas of Britain.

How much carbon is currently being sequestered by UK forests (i.e. what is the size of the forest carbon sink)?

Cannell and Dewar (1995) used a dynamic carbon accounting model, based on stem volume yield tables, to estimate the uptake of carbon from the atmosphere and its residence in trees and litter over time for each annual planting of new forest in the UK since 1925. They assumed that (1) all forests were *Picea sitchensis* (Bong.) Carr., clearfelled and replanted every 57 years, with a constant maximum mean annual increment of $14 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$ (General Yield Class), and (2) there was no net change in carbon storage in the soil – that is, inputs of new organic matter were balanced by decomposition losses as a result of disturbing soils which originally had a high organic matter content. It was estimated that the sink represented by British forests (i.e. the net removal of CO_2 from the atmosphere into trees and litter) increased from 1920 onwards, reaching about 2.25 MtC a^{-1} in 1990. A similar value was estimated by Matthews (1991).

The same calculation was carried out for Northern Ireland, which has 73 000 ha of new forest, 83 per cent of which is coniferous. In 1990, these forests were estimated to represent a sink of $0.18\text{--}0.23 \text{ MtC a}^{-1}$ (Cannell *et al.*, 1996).

How do forests compare with other vegetation types as net sinks of carbon in the UK?

A UK national inventory of terrestrial carbon sources and sinks has been summarized by Cannell *et al.* (1999) using databases on soils, land cover and historic land use change. Four appreciable sinks were identified in addition to forests.

First, wood is being harvested from UK forests faster than it is decaying, so there is a growing stock of homegrown timber (in various forms) which therefore represents a carbon sink, estimated to be about 0.5 MtC a^{-1} . Additionally, there is a store of carbon in imported timber in the UK which may be growing at $1\text{--}2 \text{ MtC a}^{-1}$ (Milne personal communication). However, these two sinks do not necessarily represent a net addition to the total carbon store worldwide. So far, there is no internationally agreed method of accounting for the timber in international trade.

Second, there are increasing amounts of organic carbon in agricultural soils owing to the non-cultivation of set-aside land (660 000 ha in 1995) and the incorporation of about 1 MtC of straw per annum in England and Wales since 1992 (Armstrong Brown *et al.*, 1996). Also, the average standing biomass of crops may be increasing along with increasing yields. These carbon sinks on agricultural land could together total around 0.7 MtC a^{-1} .

Third, there is the natural accumulation of carbon in undrained peatlands, which, in the UK is probably in the range of $0.2\text{--}0.5 \text{ tC ha}^{-1} \text{ a}^{-1}$ (Clymo *et al.*, 1998 and personal communication). This is much less than the $2\text{--}7 \text{ tC ha}^{-1} \text{ a}^{-1}$ accumulated in forests, averaged over a rotation (see below). Given that there are about 2 Mha of undrained peatlands in the UK, this sink may be about 0.7 MtC a^{-1} .

Fourth, there is a sink, which probably exists over most vegetated land in the world, due to the promotion of photosynthesis by increasing CO_2 levels, and in many areas by enhanced atmospheric N deposition. In the UK, this CO_2 and N-fertilization sink could be of the order 2 MtC a^{-1} .

All these terrestrial sinks are offset by losses of soil organic carbon in other UK land areas due to increased cultivation, urbanization, drainage of peatlands and fenlands, and also peat extraction. Together, these carbon sources are thought to total about 8.8 MtC a^{-1} . The net national terrestrial carbon flux depends on what is counted, but is most likely to be an emission to the atmosphere – maybe 5.4 MtC a^{-1} as the net result of all land-use practices, or 2.6 if we include the natural accumulation of carbon in peatlands and CO_2 and N-fertilization (Cannell *et al.*, 1998). This emission is additional to the 154 MtC a^{-1} given in Table 1.

Is there any greenhouse benefit in growing forests on drained peatlands, taking into account the effects on both CO_2 and methane fluxes?

Undrained peatlands emit small amounts of the powerful greenhouse gas, methane ($0.03\text{--}0.30 \text{ tC ha}^{-1} \text{ a}^{-1}$) and absorb large amounts of the weaker greenhouse gas, CO_2 ($0.2\text{--}0.5 \text{ tC ha}^{-1} \text{ a}^{-1}$). Both processes depend upon anaerobic conditions. At present, it is not known whether the net greenhouse effect is zero, but if it is, then stopping both

processes by draining will obviously not alter the greenhouse balance of these processes (Cannell *et al.*, 1993).

After forest planting, there is accelerated aerobic decomposition of the peat and an accumulation of carbon in the trees. In the UK, conifer plantations, their litter and the soil derived from the litter, may add a total of about 160 tC ha⁻¹ to peatlands, averaged over several rotations. This is equivalent to the carbon contained in less than 20 cm of shallow peat or 40 cm of deep peat. Thus, the whole system will be a carbon sink only until 20–40 cm is lost by decomposition. Current estimates suggest that it will take over 100 years for this to occur, meaning that the forest will be of greenhouse benefit for 1–2 rotations (Cannell *et al.*, 1993). However, over centuries, draining deep peats will release more carbon than can ever be sequestered by forests planted on them.

Is respiration by the increasing human population contributing to the greenhouse effect?

This curious question is included simply because it is often asked. The answer is no. The CO₂ produced by humans (and other animals) is not a net addition to the atmosphere; it is part of the natural cycle of photosynthesis and respiration referred to above. If food were not consumed and oxidized to produce CO₂ in the body it would be oxidized by decay organisms anyway. The increase in human population has simply routed an increasing proportion of the carbon fixed by photosynthesis through humans to the atmosphere rather than through microbes and other organisms.

Tree species, sites and forest management

Which are the best tree species to grow to sequester carbon?

If the aim is to sequester carbon rapidly then it is best to grow fast-growing species. Poplars at Yield Class 12 m³ ha⁻¹a⁻¹ accumulate about 7.3 tC ha⁻¹ a⁻¹ in tree biomass, litter and soil organic matter over a rotation of 26 years, Sitka spruce at YC 16 about 3.6 tC ha⁻¹ a⁻¹ over 55 years and beech at YC 6 about 2.4 tC ha⁻¹ a⁻¹ over 92 years. Estimates for a range of other species were given

by Dewar and Cannell (1992) and Cannell and Milne (1995).

If the aim is to make a long-term contribution to carbon sequestration, over the next 100–200 years, then it becomes less critical which species is grown. The time-averaged amount of carbon stored in trees, litter and soil is similar for successive rotations of poplar (YC 12), Sitka spruce (YC 16) and beech (YC 6), at about 200 tC ha⁻¹ (Dewar and Cannell, 1992).

What are the best soil types on which to plant trees to sequester carbon?

The best soils are those which are fertile enough to support rapid tree growth but which contain relatively little carbon when the forest is established. On these sites, the carbon added to the soil in forest litter is not offset by a loss of carbon from the original organic matter as a result of drainage and cultivation.

The overall carbon sequestration at the site is appreciably greater when the forest creates a carbon-rich soil as well as sequestering carbon in the trees. Scots pine planted on sandy soils in the Brecklands was estimated to produce, after 35 years, a surface organic layer containing 17.5 tC ha⁻¹ (Ovington, 1959) in addition to about 59 tC ha⁻¹ in aboveground biomass (Ovington, 1957). Averaged over two to three rotations, the 'equilibrium' addition of carbon to litter and soils by forests in the UK may be similar to that stored in the trees and their wood products (Dewar and Cannell, 1992).

Unfortunately, most conifer plantations in the UK are established on peaty gley and other organically rich soils which contain around 4–8 tC ha⁻¹ per centimetre depth in the surface peaty layers (Cannell *et al.*, 1993). The decomposition of 10–20 cm of this organic matter may approximately cancel out the carbon added to the soil in forest litter. Consequently, the UK forest carbon sink was calculated assuming no additional soil carbon in conifer forests (see above).

Are plantations that are managed for timber production more effective at sequestering carbon than woodlands grown to maturity for amenity purposes?

Averaged over the period from planting to clear-felling (at the optimum time) a plantation

contains only one-third to one-half as much biomass and hence carbon as it would if it were fully mature for that period (without fire or windthrow) (Cooper, 1983; Cannell and Milne, 1995). Old growth forests contain considerably more carbon than even mature plantations (Harmon *et al.*, 1990). Thus, more carbon is sequestered in *forest biomass* by growing amenity woodlands, which are left to reach full maturity and remain so, than in plantations grown for timber.

However, this ignores the carbon stored in harvested timber. If that is counted, plantations look better relative to old woodlands, but plantations plus their products will equal the carbon storage in amenity woodlands only if the harvested timber decays slowly (i.e. is not converted to paper) and/or if the amenity woodlands are subject to periodic loss of biomass by windthrow (followed by timber decay), fire and pest damage (Cannell and Milne, 1995).

What plantation management methods maximize carbon sequestration?

All practices which increase forest growth rates will increase the rate of carbon sequestration. According to Dewar and Cannell (1992; also Cannell and Milne, 1995), as the Yield Class of Sitka spruce increases from 8 to 24 m³ ha⁻¹ a⁻¹ the average rate of carbon storage during a rotation increases from 2.4 to 4.4 tC ha⁻¹ a⁻¹ and the long-term average carbon storage over several rotations increases from 61 to 98 tC ha⁻¹ a⁻¹.

The optimum harvest date to maximize carbon storage depends on whether the harvested wood is included in the calculation and the lifetime of the wood products. If harvested wood is excluded, then most carbon is stored in the forest by delaying harvesting for as long as possible. If harvested wood is included, then most carbon is stored in the forest-plus-products by harvesting at the time of maximum mean annual increment, provided that the average lifetime of the wood products is equal to, or exceeds, the length of a rotation. If the forest is grown mainly for pulp and short-lived products, then it becomes advantageous to delay harvesting for as long as possible (Cannell and Milne, 1995).

Areas of forest and numbers of trees needed to offset fossil fuel emissions

What forest area must be planted to sequester the carbon emitted by an average car, lorry or motorcycle per year?

According to the guidelines of the Intergovernmental Panel on Climate Change, the average fuel efficiency of a European petrol passenger car is about 12 km litre⁻¹ (34 miles gal⁻¹) (Houghton *et al.*, 1996). Each litre emits about 0.6 kgC (3 kgC gal⁻¹), giving 55 gC km⁻¹ (89 gC mile⁻¹). In 1996, there were 23 million cars in the UK, which travelled a total of 450 000 million km, each car averaging 19 500 km a⁻¹ (12,000 miles a⁻¹) (Whitaker's Almanack, 1998). Thus, the average

Table 2: Approximate areas of forest that need to be planted (once) to absorb the annual carbon emissions (tC a⁻¹) of different types of road vehicles over periods of about 26 years (poplar), 55 years (conifers) or 90 years (hardwoods)

	Annual carbon emission (tC a ⁻¹)	Hectares of forest that need to be planted to absorb emissions from one vehicle		
		Poplar YC = 12 (26 years)	Conifers YC = 16 (55 years)	Hardwoods, e.g. beech YC = 6 (90 years)
Road vehicle travelling 12 000 miles a ⁻¹				
Motorcycle	0.5	0.07	0.17	0.25
Car	1.1	0.16	0.37	0.55
Bus/lorry	2.0	0.29	0.67	1.00
Large truck	3.0	0.43	1.00	1.50

YC = Yield Class in m³ ha⁻¹ a⁻¹. It is assumed that the average rate of carbon storage during a rotation is 7, 3 and 2 tC ha⁻¹ a⁻¹ for poplar, conifers and hardwoods, respectively (Dewar and Cannell, 1992). The stands are periodically thinned.

car emitted 1.1 tC a⁻¹. Equivalent figures for a motorcycle, bus/lorry and large truck are about 0.5, 2.0 and 3.0 tC a⁻¹.

Assuming, in round figures, that poplars (YC 12) sequester an average of 7 tC ha⁻¹ a⁻¹ over 26 years, conifers (YC 16) about 3 tC ha⁻¹ a⁻¹ over 55 years and hardwoods such as beech and oak (YC 6) 2 tC ha⁻¹ a⁻¹ over 90 years, Table 2 gives the area of each type of forest that needs to be planted to sequester the emissions of each type of vehicle. For example, to absorb the emissions of an average passenger car (1.1 tC a⁻¹) about 0.37 ha of conifers needs to be planted. This area will sequester 1.1 tC each year for about 55 years, averaged over the 55 years (less in the early years of growth, but more in the peak growth period). At clear-felling, at age 55, this 0.37 ha needs to be restocked and an *additional* 0.37 ha planted in order to maintain 1.1 tC a⁻¹ sequestration for another 55 years.

What forest area must be planted to sequester the carbon emissions of all cars, all fossil fuel emissions and the amount of carbon emitted per person in the UK?

The forest area required to sequester emissions from all 23 million cars in the UK is about 3.7 million ha of poplars or 8.5 million ha of conifers or 12.6 million ha of hardwoods. These areas may be compared with the current total woodland/forest area in the UK of about 2.5 million ha and the total rural land area of about 23 million ha.

In order to sequester the 154 MtC a⁻¹ emitted from all sources in the UK in 1996 a conifer area of about 154/3 = 51 million ha would need to be planted, which is twice the land area of the UK. About one hectare of conifer plantation of YC 16 is required to absorb the average emission of about 3 tC a⁻¹ per person.

Table 3: Approximate carbon accumulation by widely-spaced trees with typical Yield Classes in the UK (it is assumed that the trees are spaced to allow 'free growth' with only about 60 per cent canopy cover)

Species (Yield Class, m ³ ha ⁻¹ a ⁻¹)	Wild cherry [8]	Oak [6]	Poplar [10–12]
Lifespan (years)	45	100	25
Spacing (m)	10.4¶	12.6¶	8
Trees/ha	92	63	156
Final breast height diam. (cm)	50	60	ca30
Final dominant tree height (m)	20	25	30
Stemwood vol. (m ³ tree ⁻¹)	2.53¶	3.53**	1.6††
Aboveground wood vol. (m ³ tree ⁻¹)*	3.6	5.0††	2.3
Wood specific gravity (g cm ⁻³)†	0.6	0.8	0.4
Carbon in aboveground wood (tC tree ⁻¹)‡	1.08	2.0	0.46
Carbon in whole tree (tC tree ⁻¹)§	1.54	2.86	0.66
C Sequestration rate (kgC tree ⁻¹ a ⁻¹)	34	29	26
Nos trees to sequester 1.1 tC a ⁻¹	32	38	42
Land area to sequester 1.1 tC a ⁻¹ (ha)	0.35	0.60	0.27

* Assuming branches comprise 30 per cent of above-ground woody biomass and volume (Cannell, 1984).

† Oven dry weight/green volume.

‡ Above-ground woody volume × specific gravity × 0.5.

§ Assuming roots and foliage comprise 30 per cent of total tree biomass (Dewar and Cannell, 1992).

¶ Spacings giving 60 per cent canopy cover, assuming the crown diameter/stem diameter relationship given by Pryor (1988) for wild cherry, which is similar to that of many tree species (Dawkins, 1963).

¶ Taken from Pryor (1988, Table 2) and Savill and Spilsbury (1991).

** Height (25 m) × basal area (0.785 × 60²) × stem form factor (0.5, from Cannell, 1984).

†† Savill and Spilsbury (1991) estimated 4.06 m³/tree of stemwood and branchwood, excluding twigs and stump.

‡‡ Assuming 250 m³ ha⁻¹ of stemwood (Evans, 1984, p. 198).

How much carbon do individual widely-spaced trees sequester, and how many must be planted to sequester the carbon emissions of an average car per year?

Information on the dimensions of widely-spaced trees, with 'free growth', in the UK is available for wild cherry (Savill and Spilsbury, 1991), oak (Pryor, 1988) and poplar (Evans, 1984). Table 3 presents a calculation of the amount of carbon sequestered by such trees over their lifetime, assuming average Yield Classes, specific gravities of wood and best-guess factors to derive total tree biomass from stemwood biomass.

A wild cherry tree, at YC 8, may be expected to accumulate about 1.5 tC over a period of 45 years, averaging 34 kgC a⁻¹ and requiring 32 trees to sequester the 1.1 tC that is emitted by an average passenger car each year. That is, 32 trees, widely spaced over about one-third hectare, will absorb the emissions of an average car for 45 years. Equivalent figures for oak trees, at YC 6, are about 2.9 tC per tree after 100 years, averaging 29 kgC a⁻¹ and requiring 38 trees to absorb the emissions of an average car over the 100-year period. Interestingly, the number of poplar trees needed to absorb the emissions of a car is similar to the number of oak trees (42 compared with 38, given the assumptions in Table 3) although the poplars will be effective for only 25 years.

Value of the carbon sequestered

What is the monetary value of carbon stored in forests?

The carbon already stored in forests has a value as a result of the damage that would be caused by global warming should that carbon be released to the atmosphere as CO₂. Similarly, carbon sequestered by growing forests has a value. There are basically two ways of estimating these values, either from the likely cost of warming impacts or from the amount that it may cost (or countries are willing to pay) to reduce the rate of increase in greenhouse gases – the current value of the insurance premium. Estimates in the literature vary from £1 to £240 per tC, but are most commonly in the £2–10 per tC range (Anderson, 1991; National Academy of Sciences, 1991; Nordhaus, 1991). Price and Willis (1993) estimated that carbon fixed by Sitka spruce plantations might be

worth £1–20 per tonne, depending on assumptions and discount rate. An alternative way of assessing the value of a tonne of carbon stored in trees is to assume that it is the same as enacted carbon taxes, which are about £28 per tC in the Netherlands and Sweden and £4 per tC in Finland (Shah and Larson, 1992).

However, at present, carbon retention in forests is not included as a benefit in most UK forestry cost–benefit analyses and does not appear to influence decision making on public investment in forestry (Crabtree, 1997).

Discussion

Some of the salient points that emerge from this overview are as follows.

- Storing carbon in forests may be a cost-effective way of 'buying time' during the next century – delaying global warming by slowing the rate of increase of atmospheric CO₂ by up to 12–15 per cent globally according to the IPCC. However, it is a temporary measure and creates a carbon reservoir which could be released back to the atmosphere in future.
- The UK currently emits 154 MtC a⁻¹ by burning fossil fuels, about 3 tC a⁻¹ per person. This is more than the carbon contained in all vegetation in Britain (114 MtC). UK peatlands contain about 4000 MtC.
- The UK land surface probably exchanges 100–150 MtC with the atmosphere each year by photosynthesis and respiration. The net sources and sinks due to land-use change are small by comparison.
- Forests in the UK are currently accumulating carbon (i.e. are sinks) at a rate of 2–3 MtC a⁻¹ owing to past afforestation. This is less than 2 per cent of UK fossil fuel emissions, but is larger than other terrestrial sinks due to set-aside and incorporation of straw into soils (rather than burning) after 1992 in England and Wales (together amounting to about 0.7 MtC a⁻¹) and the natural accumulation of organic matter in peatlands (about 0.7 MtC a⁻¹). Nevertheless, all these sinks together are probably less than the losses of carbon from agricultural soils and peats in the UK due to past cultivation, urbanization and drainage.
- The amount of carbon removed from the

atmosphere and stored in trees, litter and soil by a range of species in the UK, averaged over several rotations, is about 200 tC ha⁻¹. Fast-growing species achieve this storage in a shorter time than slow-growing species. Most carbon is stored when trees are planted on mineral soils (so that there is an increase in organic matter), when the sites are fertile (so that there is a high Yield Class), when harvesting timber with a long lifetime and/or when allowing the forests to grow to maturity without wind-throw, fire or insect damage.

- The average car emits about 1.1 tC a⁻¹. This amount is sequestered, on average, every year for about 55 years by 0.37 ha of conifer forest growing at Yield Class 16 or for 100 years by about 42 widely-spaced oak trees (Tables 2 and 3). About 1 ha of conifer forest is required to absorb the average fossil fuel emission per person in the UK. Theoretically, about 8.5 million ha of new conifer forest would be needed to absorb current carbon emissions from all UK cars and it would require a forest covering twice the land area of the UK to absorb the total fossil fuel emissions of the UK.
- Carbon stored in forests is commonly being valued at £2–10 per tC, but at present little confidence can be given to these values and they are not used in most UK forestry cost-benefit analyses.

Overall, these are sombre realities for anyone imagining that forestry can solve the greenhouse gas problem globally, much less in the UK. However, it is clear that forestry has a role to play and that the Kyoto Protocol has put forestry on the agenda for future discussions. How far forestry is endorsed as an option to meet reduction targets depends ultimately on the ways governments perceive the costs (and benefits) of climate change relative to the costs of cutting emissions of greenhouse gases. It is beyond the scope of this paper to speculate on this matter, but we may note that 1997 was, globally, the warmest year since instrumental records began and that the recent El Niño Southern Oscillation was the most prolonged.

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