Carbon Capture and Storage in Forests

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1 Introduction: The Role of Forestry in Climate Change Mitigation

The Kyoto Protocol to the United Nations Framework Convention on Climate Change[1] was adopted in 1997 and became legally binding (on its 128 Parties) in 2005. The Parties have committed themselves to actions directed towards stabilising atmospheric Greenhouse Gas (GHG) concentrations, including those of carbon dioxide (CO_2). This is to be achieved by reducing emissions (reduction of sources) and removing GHG from the atmosphere (enhancement of sinks), including by carbon capture and storage (CCS) in forests. (Note: the term 'carbon sequestration' used elsewhere in this chapter may be considered as equivalent to both capture and storage of carbon, but, for simplicity, 'sequestration' usually is used as a substitute for 'storage'). Article 3.3 of the Kyoto Protocol (KP) states that biological carbon sinks enhanced through afforestation, reforestation and the decreasing of deforestation rates since 1990, should be utilised for meeting the commitments of the countries during the stipulated period. *Afforestation* is an expansion of forest on land which more than 50 years ago contained forests but has since been converted to other use. *Reforestation* is a restoration of degraded or recently (20–50 years ago) deforested land.[8] In this chapter, we do not make any distinction between these terms. Since the Conference of the Parties,[2] afforestation, reforestation, forest management and soil carbon have become eligible climate policy measures.

In Europe, aid for woodland development is provided by the programmes of Member States and by the EU initiative that focuses mainly on marginal agricultural land, 1 Mha of which was afforested in 1994–1999 (ref. 3). The total area of EU forests (113 Mha) has expanded by 3%, with 1 Mha having been afforested between 1994 and 1999 (ref. 4). If this trend continues, the

Issues in Environmental Science and Technology, 29
Carbon Capture: Sequestration and Storage
Edited by R.E. Hester and R.M. Harrison

Published by the Royal Society of Chemistry, www.rsc.org

carbon sequestration potential of 3.84 Mt C yr^{-1} will be achievable during the first commitment period. Taking into account 25 Member States, a technical sequestration potential of 34 Mt C yr^{-1} could be reached in the long-run.[5] However, only a fraction of this amount could be accounted for, under the current rules, because most of this carbon uptake is not "additional" with reference to the 1990 baseline. Carbon sequestration forestry activities are supported by afforestation schemes and rural development regulations. The principal forest policy initiatives that increase CCS are recognised as maintaining and enlarging carbon pools by improving existing forests through their protection and sustainable management; expanding the forest area through afforestation (largely with species adapted to local conditions); replacing fossil fuels with fuel wood from sustainable managed forests; and replacing high-energy products with industrial wood products.[6]

Along with afforestation schemes, the European Commission (EC) adopted the White Paper that identifies the need to raise energy production from renewable sources from 6% in 1998 to 12% by 2010 (ref. 7), including the increasing use of woody biomass in energy production. Successful implementation of this policy contributes to carbon sinks provided by standing forests, and adds to the reduction of CO_2 concentrations in the atmosphere from using wood instead of fossil fuels, after timber is harvested. In Europe, the potential to sequester carbon from short rotation timber plantations (SRTP) and from substitution of biomass for fossil fuel, is in the range of 4.5–9 Mt C per year.[5] Depending on SRTP development, even higher carbon savings could be achieved in the future, though this would require proper incentives and links between the Common Agricultural Policy (CAP) and climate policy measures, particularly concerning changes on set-aside and marginal lands.[9]

The last few years have seen an upsurge in the number of scientific papers and reports addressing different aspects of carbon sequestration through forestry-based activities, both internationally and in Britain. Various aspects of using forests to mitigate climate change have been discussed in the literature for Canada, Finland, the Netherlands, Russia, the UK, USA, and other countries.[10–18] Terrestrial carbon sink is on the agenda of international conferences, including the Conferences of Parties.

Carbon sequestration through afforestation is commonly considered as: cheap (cost efficient); clean (it may concurrently provide other ecosystem services); proven (many countries have the legacy of tree-growing); effective in the short-term, providing almost immediate effect after the tree-planting; and as a less resource and energy consuming climate policy measure. It can be incorporated in multi-functional forest use to simultaneously enlarge timber production and bring a variety of other benefits, and can provide economic incentives for sustainable forest management.[19]

The Stern Review[20] examined the socio-economic impacts of climate change. The Carbon Trust[21] published recommendations on how best to deliver carbon emission reductions and different bio-energy options for Britain. A report by AEA Technology[22] analysed the potential of biomass for renewable heat. More specific documents have assessed the relevance of biomass options in regional contexts,[23,24] the importance of climate policies in setting business strategies, and manifold implications of policy decisions and their effects on the way that businesses operate.[25] The most recent publications highlight that social and spatial issues are important in determining the range of land types which are likely to become available for new woodland development; that the main difficulties associated with the use of wood for energy have been policy-oriented and socio-economic, and technological, rather than fuel-related; and that comparative indicators of the cost-effectiveness of alternative climate change mitigation strategies in forestry are needed.[26]

Surprisingly, despite the size of their forests and large areas of marginal agricultural land, there remains only limited room for forest sector policies to sequester carbon in the major wood-producing countries, such as Canada, Finland, Sweden or Russia.[27] In Canada, for example, there is a limit to the amount of carbon offset credits that can be claimed on existing forestland (largely, publicly owned), and the focus is now shifting to afforestation of agricultural land, where the role of private landowners is important and the potential of afforestation is around 1 Mha.[31]

The analysis of the role and place of forestry to mitigate climate change is more relevant to countries which have a substantial potential for forestry development.[28] Therefore, carbon inventory and monitoring, cost-effectiveness of afforestation and forest management, social acceptability of various carbon sequestration options, existing challenges and opportunities of woodland development on high carbon soils, using wood in renewable energy projects, and in wood products, are highly relevant topics, for instance in Scotland. The reports by the Sustainable Development Commission[29] and the Fraser of Allander Institute[30] have provided information on the potential of the wood fuel market and on competitiveness of different wood fuel scenarios. A review addressing biomass production and consumption in Scotland has been published by SEERAD.[26]

The reports provide a broad picture concerning technological aspects, GHG life-cycle emissions, air pollution impacts of biomass production and consumption. However, an overall assessment of the role of forests in climatic and atmospheric changes is needed to develop a better understanding and, where appropriate, to improve, simplify and extend the manner in which this role is taken into account. Through the analysis of biogeochemical processes involved, and by assessing the opportunities for forestry to sequester and store carbon, it becomes possible to suggest climate policies and measures at various spatial levels and to advise on their proper sequencing in time. Institutional and economic aspects of CCS in forests are areas that merit special attention.

It is anticipated that forestry-based activities could help reduce CO_2 concentrations in the atmosphere by increasing biotic carbon storage, decreasing emissions and producing biomass as a substitute for fossil fuels. Reducing rates of deforestation, increasing forest regeneration, agroforestry, improving forest and land-use management, and growing energy crops are activities that are supposed to assist countries in coping with the changing climate.[32] In practice, however, existing opportunities are only partially used, as this chapter will discuss further.

The chapter presents the results of analysis of opportunities for terrestrial CCS in forests to mitigate climate change. It is supported by official documentation, including that of DEFRA[33–35] and the Forestry Commission,[36,37] and by other literature available on this topic.[18,38–40] The chapter first presents carbon pools and flows in forests. The ecological perspectives of an increased CCS in forests are then discussed, and the carbon sequestration rates and the potential of carbon sequestration in forests are analysed across several European countries. A general overview of the situation in densely wooded regions of the world is given, along with the analysis of the opportunities and challenges of CCS in forests. The focus then shifts towards the social and economic considerations of terrestrial carbon sink. The importance of proper institutions in the development of conditions for creating carbon offsets from forestry is highlighted. The chapter concludes by offering some insights into the feasibility of carbon sequestration in forests and the level of institutional development, as well as by providing some ideas for future research.

2 Carbon Pools and Flows in Forests

Forests cover about 4 Gha of the Earth, or over 30% of the land area, and store around 120 Gt of carbon (in the form of CO_2), more than the total amount in the atmosphere.[37] Forests contain 77% of carbon stored in land vegetation and, of this total, approximately 60% of carbon is stored in tropical forests, 17% in temperate and 23% in boreal forests.[41] Forests account for 90% of the annual exchange of carbon between the atmosphere and the land, and their growth is one of the few ways of taking CO_2 out of the atmosphere.[41] The role of forests in relation to climatic changes is observed in the carbon cycle. Forests are also involved in the cycles of water and GHG, and play a role through their reflectance characteristics (albedo). In return, internal and external drivers, including the changing climate, are affecting forest ecosystems and therefore the carbon cycle.

Trees absorb CO_2 from the atmosphere through photosynthesis and use light energy to run enzyme-catalysed reactions. Much of the carbon eventually goes for production of cellulose, but some is released to the air through respiration. The absorbed carbon goes to form the above-ground biomass (stem wood, branches and leaves), as well as roots. Carbon accumulated in leaves comes back to the atmosphere after a relatively short period of time, when the fallen leaves decompose. Carbon in wood is stored for years. The time depends on tree species, tree-growing conditions and forest management, and on various uncertain occurrences, such as forest fires or diseases. The dry wood is 50% formed from carbon. A widely held assumption is that forests approach carbon saturation at maturity, and when trees reach it they stop sequestering carbon, but with a continuous cover forests could act as long-term storage of carbon. When trees die some of the carbon remains in the forest, being stored in the soil.

Afforestation affects the climate in more ways than through CCS, but the effect is very much case-specific, depending, for instance, on whether the trees are planted on mineral or highly organic soils. Also, some models, for example, predict that older forests could become net emitters of CO_2 as the relative rate of decomposing wood to new growth becomes unfavourable.[44] There is also some evidence to argue that warming as a result of planting trees in the boreal zone might overcome the cooling effect due to carbon sequestration by new forests. Moreover, as forest canopies reflect sunlight differently than open spaces (covered with snow in winter), in the zone of distribution of boreal forests, tree-planting might not be helping to alleviate global warming.[45]

An example of carbon exchange associated with an oak forest in England of general yield class $6\,m^3\,ha^{-1}\,yr^{-1}$ and gross primary productivity of *ca.* 14.0 t $ha^{-1}\,yr^{-1}$ is shown in Figure 1. The figure explains the exchange of carbon between the atmosphere and all carbon pools in the forest, *i.e.* above ground

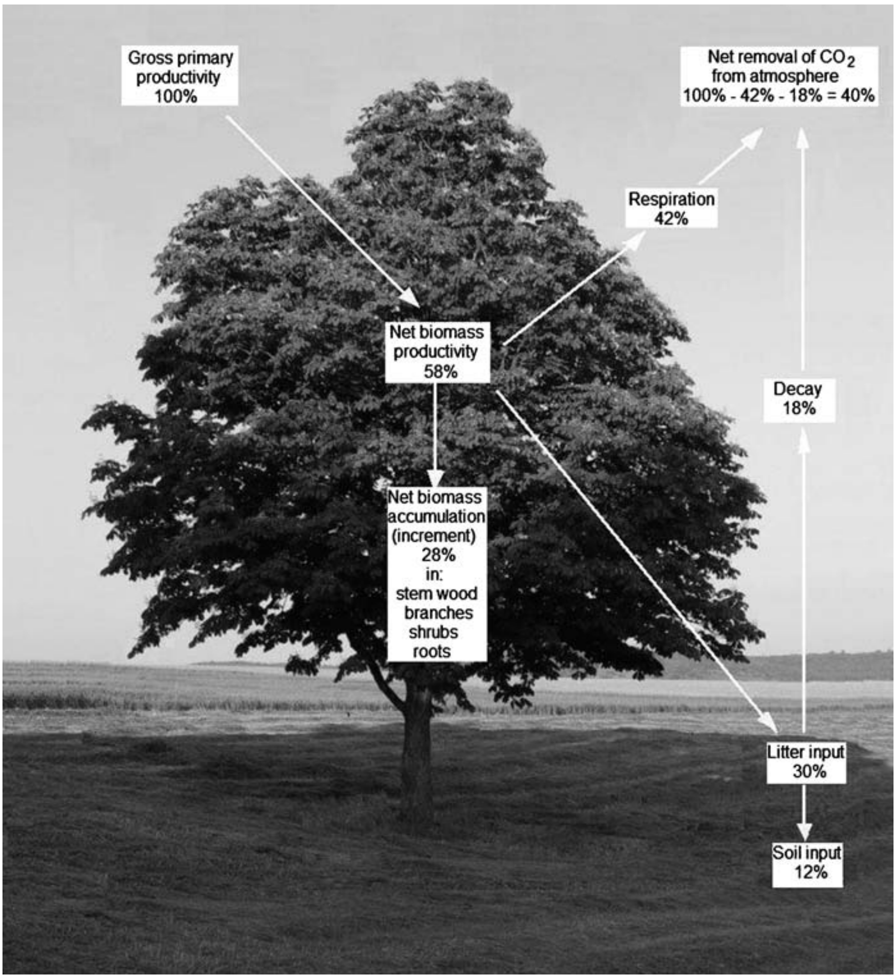

Figure 1 Representation of carbon exchange associated with forest components. (Source: adapted from the summary given in ref. 16).

and roots, and forest soil and litter. Accumulation of carbon proceeds until equilibrium is reached. Afterwards, if the forest is not maintained, carbon is released through wood decay or burning. The rate, dynamics and patterns of carbon sequestration in the forest (*i.e.* when carbon is "locked" into a more stable carbon stock), depends on tree species, their characteristics, and naturally on tree-growing conditions, particularly on temperature, CO_2 concentration and forest management. Over the lifetime of the forest more carbon is captured than is released, and there is a net sink of carbon.

About 48 Gt C is exchanged globally between forest ecosystems and the atmosphere each year.[42] A generally accepted estimate of carbon content in a forest derives from forest biomass. As an example, the biomass content (dry matter) and carbon content of forests in Ukraine is presented in Table 1. The table shows the estimates for coniferous, hard and soft deciduous species and provides total figures. It illustrates that Ukrainian forests possess a total forest biomass of 956 Mt of dry matter, with a carbon content of about 474 Mt. The estimates are lower than for carbon pools in such large countries as Canada (9.3 Gt C) and the USA (11–12.6 Gt C), but higher than the carbon content in the UK forests (150 Mt C), and much higher than the carbon in forest biomass in the Netherlands (20 Mt C; ref. 37,46). With respect to the carbon content per hectare of forest land, the estimates are comparable between countries. In the UK, this estimate ranges from 30 to 60 t C per ha (mature broadleaved forests in Britain may contain up to 250 t C per ha; the long-term average amount of carbon in conifer plantations with rotation length of *ca.* 50 years is 70–90 t C per ha; ref. 42); in Canada, it is 38.3 t C on average; in the USA, it is 56.2 t C; in Ukraine, 55.1 t C; and it is 59.7 t C per ha of forest in the Netherlands.[47]

On the basis of the estimates of carbon content in forest biomass, the net change in carbon pools can be assessed. For example, largely due to the distinct tree-growing conditions and the different areas covered by forests, the average annual net uptake by forests in the UK is about 3 Mt C, and in Ukraine it is about 15 Mt C. The estimates roughly correspond to 1.1 t C ha^{-1} yr^{-1} and 1.6 t C ha^{-1} yr^{-1}, respectively, excluding the carbon sink in the forest soil and litter.[46] Annual carbon uptake in excess of 4 t C ha^{-1} can be expected in fast growing conifer stands, *e.g.* of Sitka spruce.[42] The figures for the UK and Ukraine are comparable with the estimates provided for temperate and boreal forests in Canada,[48] the Netherlands,[11] and Finland.[49] Average net uptake by

Table 1 Forest biomass and carbon content in Ukrainian forests, Mt.[43]

Phytomass Components	*Coniferous*	*Hard wood*	*Soft wood deciduous*	*Total*
Foliage	31.65	7.81	2.66	42.10
Crown wood	45.25	53.44	9.65	108.30
Stemwood	289.35	290.05	58.42	637.80
Stump and roots	55.03	45.78	18.38	119.20
Understory	14.63	24.80	9.78	49.2
Total	435.93	421.88	98.90	956.70
Total Mt carbon	215.65	209.31	48.83	473.80

forests in Canada is 0.64 t C ha^{-1} yr^{-1}; in the USA, it is 1.6 C ha^{-1} yr^{-1}; and in the Netherlands, it is 2.0 t C ha^{-1} yr^{-1} (ref. 47).

The IPCC[32] identified the following measures to be implemented to increase the forestry potential in terms of carbon sequestration:

- The afforestation of abandoned and marginal agricultural land.
- Forest management to increase carbon density at the stand and landscape levels, *e.g.* maintaining forest cover, minimising forest carbon soil losses, increasing rotation lengths, increasing growth and managing drainage.
- Increasing off-site carbon stocks in wood products.
- Enhancing product and fuel substitution.

Afforestation is the most straightforward policy measure to enlarge the carbon sink in forests and it has been widely analysed in the literature. For the reason that carbon sequestration positively correlates with the growth rates of trees, it is advocated to plant the most fast-growing tree species, *e.g.* hybrid poplar or Sitka spruce, where appropriate,[31,50–52] or to establish SRTP for the purpose of carbon uptake. The choice of species depends on the location and tree-growing conditions, on the purpose of tree- growing, and other factors.

The carbon sequestration estimates per hectare of forest expansion in the USA and Ukraine, for example, come close and are higher than annual net uptake per hectare of forest development in Canada,[46] because of the presence of vast Canadian boreal forests with lower rates of growth. However, in the Carpathian Mountains, for instance, spruce stands grow rather slowly, and so carbon sequestration in spruce forests proceeds gradually. But when the trees reach maturity, they accumulate a volume of stem of 500 m^3 and higher, and so it is their carbon storage function, rather than that of carbon uptake, that is important.

Estimated[46] cumulative carbon uptake by fast-growing tree species across the main forestry regions in Ukraine, shown in Figure 2, describes the stem volume. However, carbon taken from the atmosphere is stored also in branches, leaves and roots of the trees and in understory, forest soils and litter.

Forests add to the reduction of CO_2 from the atmosphere as long as there is a net growth. In the figure, a 40-year time horizon is considered, because, in the observed conditions, the growth rates of trees chosen for planting increases until the trees reach 40 years of age.[46] Consequently, the highest rates of carbon uptake are observed within this time horizon.

When trees are cut, the above-ground biomass minus the commercial part of the bole that constitutes a log enters the litter account. Later on, when a new generation of trees comes up, there is a re-growth of the non-bole biomass and a re-growth of the volume of stem wood. The process is assumed to continue indefinitely with new generations of trees coming in place of old ones. This observation allows us to model at once all the above ground biomass of the trees.[28,50] In addition to the above-ground biomass, the root component of forest plays a role in the carbon budget. For example, the carbon sequestered by the root pool of poplar stands in British Colombia, Canada was estimated[48]

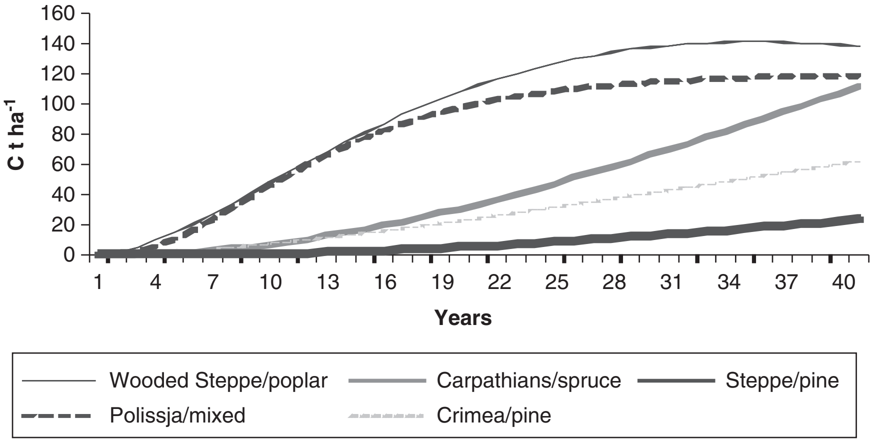

Figure 2 Cumulative carbon uptake by fast-growing tree species across regions in Ukraine, 0% discount rate.[46]

according to the following relationship:

$$R(G) = 1.4319\, G^{0.639}$$

where: R is root biomass (m^3) and G is above ground biomass (m^3).

This relationship might not hold for other species and for different conditions of tree-growing. Also, in some regions, *e.g.* in Scotland, soil carbon is also important and should be included in models. When trees reach the culmination of their annual increment, they stop sequestering carbon, because its removal due to the growth of trees comes into a balance with the loss due to the decay of trees, and the forest no longer acts as a carbon sink. Carbon uptake, under a storage policy option (of carbon fixation), has a one-time effect, and eventually, through the decay of wood, all the above-ground carbon is released back into the atmosphere. However, usually, the trees are cut after they reach their mean annual increment (see Figure 3).

The harvested timber enlarges the supply of wood for industry, whereas carbon stored in wood products is an addition to the total carbon sink. Wood received from forest plantations can also be used as a substitute for fossil fuels, or timber used in wood products can later get burned. These policy solutions contribute to carbon sinks provided by forests during their growth, as well as to carbon storage in wood products, and to reduction of CO_2 concentrations in the atmosphere when wood is burned instead of fossil fuels.

If the energy required for the harvesting and processing of wood is not taken into account, the use of timber as a substitute for fossil fuel is a carbon neutral process. The net gain here is the amount of CO_2 that would have been released by burning fossil fuel if not replacing it with wood. The effects for the avoidance of carbon release to the atmosphere through a continual regeneration of

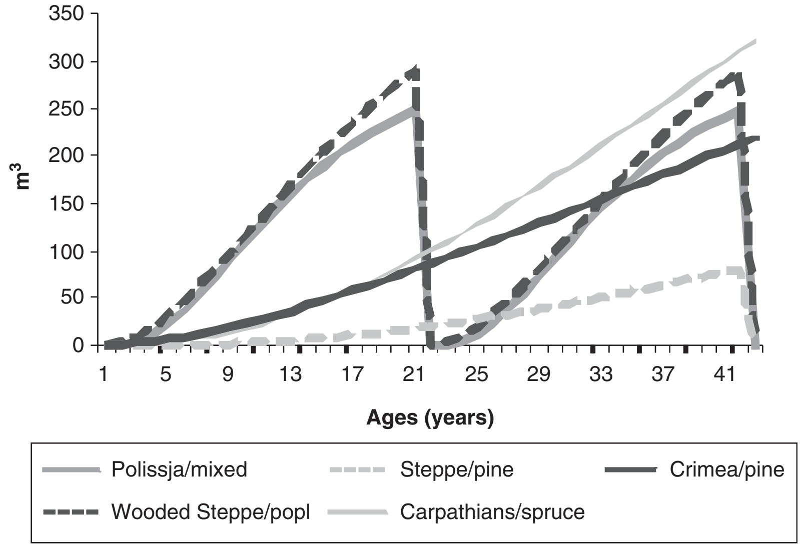

Figure 3 Graphical representation of growth functions of fast growing trees across the regions in Ukraine if the trees are harvested when their groth decelerates.[46]

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the forest after harvesting and by the replacement of non-timber materials with wood (especially of carbon-intensive materials and fossil fuels) are repeatable. Therefore, the social benefits (of CCS and substitution effects) under wood product and bio-energy scenarios in the long-run are expected to be considerably higher than under the strategy of carbon fixation, which presumes one-time tree planting, for example for a period of 40 years, without considering future use of wood and land after timber harvesting (the assumption which can only come along with the assumption that by harvesting the trees, using the revenues to cover future costs of establishing new forests and storing carbon by some means, both the gains and losses in physical and monetary values are relatively balanced).[48] Wood product and bio-energy scenarios, *i.e.* of using wood instead of fossil fuel, are beyond the scope of this chapter. They have been analysed elsewhere,[31] however, for example, for forests in Canada, Ukraine,[50] Slovakia[28] and the UK.[52]

3 Carbon Sink and Storage in Forests: Several Implications from Europe

The potential for CCS in European forests has been analysed, and four examples from countries which differ according to their natural, socio-economic and institutional characteristics, are considered in this section. The UK plays a leading role in global efforts to tackle climate change and shows a sound example of carbon sequestration implications. The selection of Slovakia (EU member state) and Ukraine is based on their high CCS potential and on the similarity between the development paths of these countries, which include the transition to a market economy and the setting up of new institutional frameworks, including those that concern forestry and climate policy. The Netherlands makes a sound comparison with other countries, as in the addressing of Kyoto it can hardly rely on forestry. It invests heavily in energy efficiency and successfully implements the KP Joint Implementation (JI) and Clean Development mechanisms (CDM).

3.1 A Focus on the United Kingdom

The UK has one of the best records in the world in reducing direct GHG emissions within its territorial boundaries. In 2005, UK GHG emissions were reported to be 15.3% below base-year levels, with CO_2 emissions having fallen by 6.4% (ref. 35). The commitment of the UK under the EU burden-sharing target is 12.5% GHG emissions reduction for 2008–2012, relative to the base year. Further, a domestic goal of a 20% reduction of CO_2 emissions by 2010 has been introduced.[9] A series of targets have been set out – including making the UK's targets for a 60% reduction of CO_2 emissions by 2050, and a 26–32% reduction by 2020 (ref. 53). The goal is to achieve the majority of reductions nationally, including through further expansion of forest cover and development of short-rotation forestry, in combination with further using of wood as a construction material and a renewable energy source.[5]

The UK is on track to meet its targets. Its emissions in 2010 are predicted to be 23.6% below base-year levels, and 11.1% lower than required.[53] The Stern Review[20] examined the economics of climate change and explored stabilising GHG in the atmosphere. The UK Climate Change Act[54] – the first of its kind in any country – set out a framework for moving to a low-carbon economy with a target of 80% emissions reduction by 2050. The documents demonstrate the UK's desire to deal effectively with climate change, including by terrestrial carbon capture and storage.[55] The UK Climate Change Programme[34] set out policies and priorities for action. It targets are linked across policy objectives, including those of carbon sequestration forestry projects.

The UK has one of the lowest percentages of forest land in Europe (11.8% compared with the EU average of 38%), but it has significantly expanded its wooded cover in the last hundred years (currently 2.85 Mha; ref. 56). The dynamics in sources and sinks from forestry and land-use changes (LUC) in the UK is summarised in Table 2.

The policy of woodland development is supported by financial instruments which vary across the territory of the UK. In England, the Forestry Commission (FC) administers the English Woodland Grant Scheme (EWGS).[37] Payments differ depending on localities and land categories, tree species (£1800 per ha for broadleaves, £1200 per ha for conifers) and the likelihood of social benefits. Woodland creation grants also encourage farmers to convert agricultural land into forest and receive compensation to offset the foregone annual

Table 2 Dynamics in emissions due to land-use change and forestry.[57]

Mt C year^{-1}	*1990*	*1995*	*2000*	*2005*	*2010*	*2015*	*2020*
Forest sink[a]	2.6	2.8	2.9	3.2–3.3	3.1–3.4	2.7–3.0	2.4–2.8
Planting since 1990[b]	0	0.2	0.3	0.5–0.6	0.6–0.8	0.9–1.2	1.2–1.6
Emission from LUC[c]	8.7	7.3	6.5–8	4.9–7.8	4.1–8.2	2.8–8.4	1.4–8.3

[a]carbon accumulation in biomass, soil, litter and in wood products.
[b]entries from woodlands planted since 1990, excluding in timber products.
[c]net emissions caused by LUCA. (The trends do not consider possible effect of climate change on forest productivity).

income.[37] In Scotland, as part of the Rural Development Programme (RDP), new grants have been introduced which aim to deliver targeted environmental, social and economic benefits from forests. The RDP brings together a range of formerly separate support schemes, including those covering farming, forestry and primary processing sectors, rural enterprise and business development, diversification and rural tourism. Grant support will now be delivered through a number of forestry-specific (*e.g.* SRTP of willow or poplar) and non-specific (*e.g.* support for renewable energy – forestry) options, including those of CCS.[37] The Bioenergy Infrastructure Scheme funded by DEFRA was set up to provide grants to farmers, foresters and businesses to help in developing the supply chain required to harvest, store, process and supply energy crops and wood fuel to end-users.[52]

The maximum rate at which the woodlands expanded during the 20th century was about 40 kha yr^{-1} in the early 1970s, with this taking place primarily in the uplands. However, the establishment of 1.3 Mha of mainly monoculture conifer plantations met with considerable objections, due to their perceived impact on social, ecological and environmental components of sensitive rural landscapes.[18] Partly as a result of this, and also because of low forest profitability and uncertainty over CAP reform, the average rate of forest expansion went down to 10 kha per year in the last decade. Nowadays, forests in the UK sequester nearly 3 Mt C yr^{-1}, with 0.5 Mt C by trees planted since 1990 (ref. 37). The largest carbon pools in the UK are in soils and litter.[58,59] However, carbon stock in vegetation is also high, with total above ground in woodland of around 120 Mt C, and total including roots close to 150 Mt C (ref. 37). In the future, forests will probably expand on average at *ca.* 8 kha yr^{-1} rate. Given these assumptions, the forest sink is expected to rise to about 3.1 Mt C yr^{-1} in 2020, storing by then an extra 50 Mt C (ref. 33).

For the UK to be carbon neutral using only afforestation as the mitigation measure, each year it would need about the same amount of woodland as the current area.[37] However, this is a very static assertion, considering also that the age structure of forests, declining availability of land suitable for afforestation and public preferences for multifunctional LUC suggest that in recent times the net rate of carbon sequestration in forests peaked around 2005. The projections[60] show that potential carbon savings from forestry, timber production and bio-energy could enable avoidance of *ca.* 8 Mt C yr^{-1} over the next fifty

Table 3 Carbon sequestration potential of afforestation in the UK, kt C per yr.[61]

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Year	Carbon sequestration from forest land		Additional carbon sequestration potential
	Baseline	*Abatement*	
2007	3909	3867	–42
2008	3761	3711	–50
2009	3528	3495	–32
2010	2939	2949	–10
2011	2921	2991	70
2012	2715	2853	137
2013	2444	2648	204
2014	2331	2598	268
2015	2137	2464	327
2016	2107	2489	382
2017	2113	2548	435
2018	2114	2599	486
2019	1851	2386	535
2020	1376	1960	584

years. Woodland expansion alone (6.2 Mha, 50% broadleaved and 50% conifer) could save 4 Mt C yr^{-1} for the second half of this century.[42] Some authors[18] provide even higher estimates of the potential carbon sequestration by forests in the UK. These projections are largely based on assumptions that concern the expansion of forest cover. Although they show the role of forests in climate change mitigation, they do not account for a broad range of uncertainties associated with forest CCS and soil carbon estimates.

Carbon uptake in trees is temporary overall. Nevertheless, our research supports the suggestion that forestry development is a relatively effective and low-cost option for the UK to mitigate climate change, especially if fast-growing AQ7 species are planted on marginal land. Following,[33] we considered a planting rate of 30 kha yr^{-1} for conifers under the abatement scenario. The baseline scenario extrapolated the 2005 planting rate of 8 kha yr^{-1} until 2020. The carbon sequestration potential of afforestation in the UK is shown in Table 3 (ref. 52). The results imply that under the abatement scenario, on average in the UK, new forest plantations could annually offset about 4.9 Mt CO_2.

The results suggest that the woodlands expansion policy measure will likely be competitive with other means of removing carbon from the atmosphere, and that choosing appropriate species and management regimes is important for saving economic costs.

3.2 A Focus on Transitional Countries of Ukraine and Slovakia

In transition countries, primarily as the result of economic recession in the early 1990s, CO_2 emissions have fallen much below these countries' KP commitments (the fall of 30.7% on average was observed in 2000; erf. 62). These countries, therefore, have reached their KP targets and stand to profit from the sale of "hot air". Although "hot air" trading may appear advantageous to these particular countries, they will not necessarily be able to rely on it, because "hot air" is a hot topic pertaining to the environmental effectiveness and economic efficiency of implementation of the KP.[31] The countries in transition to a market economy are therefore wide open to a range of opportunities for cleaner industrial and energy production. Due to substantial carbon emissions per unit of GDP, these countries have a high potential for cheap Joint Implementation.[63] However, they have an insufficient institutional capacity[28] for foreign investors to enter their business environment effectively. Hence, over and above the emissions reduction, an enhancement of CCS in forests is important.

Ukraine is among the largest by area of all the countries in Europe (58 Mha), but it is sparsely forested (16.5% of its land).[56] Its forests have mostly been turned to agricultural land.[64] Nevertheless, because of the vast territory, Ukraine's forests possess a total biomass of about 1.7 Gt, containing 600 Mt C only above ground,[56] with average actual net carbon uptake of 17 Mt C per annum. Approximately 2.29 Mha of land is suitable for tree-planting, and afforestation would allow a 23% increase in Ukraine's forest cover.[46] Thus through afforestation in Ukraine, total cumulative carbon sequestration in forests can be increased by 180 Mt (0% discount rate for carbon savings) over a 40-year time horizon. The maximum additional amount of carbon sequestered annually could reach 4.6 Mt (C savings not discounted), or about 1.0 Mt if C savings were discounted at 4%. This roughly corresponds to 4.6% of the Ukraine's annual CO_2 emissions. Primarily due to the diversity of conditions, the potential benefits vary considerably through the territory of the country (see Table 4; ref. 28,46).

The estimates differ substantially also across the territory in Slovakia. Over 1.9 Mha is classified as forest land in this country, with the wooded cover being 40.1% (ref. 56). Forests in Slovakia possess a total above-ground biomass of 334 Mt, containing 167 Mt C (ref. 56), with a forest sink of 1.9–4.7 Mt C per year.[65] More than 50% of forests are owned privately in Slovakia but are managed by state-owned companies, leasing forests from their owners.[66]

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Table 4 Carbon sequestration for the above-ground biomass and its value per ha in €, at 4% discount.[28]

	Slovakia			*Ukraine*				
	Western	*Central*	*Eastern*	*Polissja*	*Wooded Steppe*	*Steppe*	*Carpa-thians*	*Crimea*
Total tonnes per year of C	432.2	492.6	315.1	1846.2	2372.5	143.0	676.7	584.3
Permanent tonnes	8.4	9.6	6.2	36.9	47.5	2.9	13.5	11.7
Value of C uptake	124.7	149.0	90.2	553.9	711.8	40.1	203.0	175.3

Approximately 0.41 Mha of largely marginal and abandoned land withdrawn from agricultural production in the last decade is suitable for tree-planting. Its afforestation would result in 0.9 Mt C sequestered annually (4% discount rate), and this counts for *ca.* 1.4% of Slovakia's CO_2 emissions.[28]

In Ukraine, where nearly 66% of the forest land (7.1 Mha) is publicly owned, tree-planting activities are under the execution and control of the State Committee of Forests. The weaknesses of a "command-and-control" mechanism of afforestation include the lack of flexibility and economic incentives for encouraging tree-planting. Control mechanisms, however, could be justified on efficiency grounds, if the savings in transaction costs exceeded the gains from using other co-ordination mechanisms.

Afforestation enlarges social benefits, primarily to agriculture, because of soil protection and improved hydrological forest functions, and to society in terms of climate change mitigation. Due to market failures, however, the social gains from afforestation (external benefits) could hardly be achieved, and welfare maximisation conditions could hardly be met without government regulation. The main reason is the discrepancy in the distribution of benefits and costs from forestry development. The establishment of forest plantations, including those for CCS, is executed in the forest sector, while climate-change mitigation benefits accrue to society. The problem "who pays and who receives the benefits" cannot be solved through the market. Hence, despite afforestation costs being relatively low in the transition countries, a large-scale tree-planting for CCS will not take place, without government subsidies or foreign investment.

This argument has been proven in Slovakia, where with the cancellation of the state law and state forestry framework, according to which by the year 2000 the area of afforested land would have been 50 kha, the area actually afforested appeared to be just 877 ha. During the transition process, when 42% of previously state-owned forests were given back to their former owners and more than 90% of claims were processed, the incentives in support of afforestation were ineffective. The afforestation process was negatively influenced by uncertain land ownership and by problems with the allocation of subsidies to land owners. An average size of a private plot of land in Slovakia is 0.45 ha, and such fragmentation of the land also hampers afforestation.[28] As long as forest land remains fragmented into small ownership parcels and there is a lack of long-term investment and appropriate incentives for tree-planting, the land owners are unlikely to undertake afforestation activities.

A very important task pertaining to reconciliation of sustainable forest management and climate change mitigation is to settle upon a proper structure of land (forest) ownership. The countries' legal documents have to redefine (where necessary) and enforce property rights on forest resources and wooded land, for instance through the introduction of community-managed forests and de-fragmentation of private plots of land. There is also a need for simplified forest management guidelines for various owners within their land. Privatisation of forests is not the only solution for transition economies to enhance sustainable forest management.[67] The forest inventories may comprise public (state) forests; forests of municipalities, farmers, enterprises, organisations and institutions; as well as privately owned wooded land and land that undergoes afforestation. An afforestation fund may include state, communal and private land to be sold or leased for forest development.[28]

To date, climate change mitigation opportunities that involve forestry are not viewed as priorities for the national climate policies, forestry policies and rural development strategies in transition countries.[66] However, as the above analysis demonstrates, carbon sequestration through afforestation represents an opportunity, given the decline in agricultural production and increase in abandoned land. Therefore, afforestation of non–forested areas, increasing the level and efficiency of wood utilisation, using biomass as a substitute for fossil fuels and the protection of existing carbon storage, could provide relevant policy measures in transition countries trying to cope with the changing climate.

3.3 A Focus on The Netherlands

The Netherlands has a more energy-intensive economy than the EU average. Therefore, after the burden-sharing process within the EU, its emission reduction commitment was fixed at 6%. This country considers GHG emissions reduction (see Table 5) as the priority measure of its climate policy, and it does much to achieve its emission-reduction targets. Concerning the role of forestry, a payment discount has been introduced into regulatory energy tax to accelerate afforestation. The objective of Dutch forestry is to expand wooded area by 75 kha until the year of 2020. Over 63.5 kha is to be planted with trees through governmental agencies, mainly in rural areas (54 kha, of which 30 kha are on agricultural and 15 kha on natural land), but also in urban areas.

The present rate of afforestation, however, is lagging behind (around 70%) the planned expansion rate due to an increased demand for space and, consequently, due to high land prices. Recently, therefore, the Netherlands has revised its forest policy into more general objectives of an expansion of its wooded area.[69] Being the country which is the smallest by area (3.4 Mha) among the countries analysed, and the most homogeneously and densely populated, the Netherlands has little room for coping with changing climate through forestry. Although a 20.5% increase in wooded cover is projected (see

Table 5 Projections for Netherlands' sector emission reduction.[68]

Sector	*Emission in 2010 in Mt CO_2 eq.*	*% Reduction in 2010*
Industry (incl. refineries)	89	11.2
Energy/Waste companies	61	13.1
Agriculture	28	7.0
Forestry	0	0
Traffic	40	7.4
Households	23	10.0
Trade, service, government	12	8.3
Other	6	–

Table 6 Carbon storage in forests across several countries in Europe and their potential for afforestation.[56]

Country	*Wooded cover, % area*	*Forest area, Mha*	*Stock of forest above-ground biomass, Mt*	*C in forest, above-ground, Mt*	*C in forest soil, Mt*	*Projected increase of wooded cover, %*
Netherlands	10.8	0.365	43	21	40	20.5
Slovakia	40.1	1.929	334	167	270	21.5
UK	11.8	2.845	190	95	719	25.0
Ukraine	16.5	9.575	1199	600	n.a.	23.9

Table 6), this country is to rely on markets as a governance structure and on common values and norms, rather than on domestic CCS forestry initiatives.[31]

The Dutch implementation plan calls for 50% of the KP commitments to be met internally. Thus, 50% of the required emissions reduction is to be achieved externally, using the flexibility mechanisms of Joint Implementation and Clean Development. Promising CCS initiatives are already in place. They concern voluntary carbon markets, including those available in Europe, such as pilot afforestation projects for a total of 5 kha in Ukraine where a project was designed to regenerate forests on the land affected by radioactive contamination after the Chernobyl nuclear accident.

However, woodlands development for multiple purposes, where an increase in amenity and other landscape values comes along with CCS, is viable for the Netherlands not only beyond its boundaries but also internally. Various agreements with stakeholders to maintain multi-functional rural-land use in a sustainable manner and plant new forests, including for the purpose of climate-change mitigation, have been made. The National Green Fund, for instance, issues certificates for the number of hectares for which CO_2 sequestration rights have been acquired. Any company or organisation wanting to acquire the right for CCS can deduct €4.5k from its energy tax bill, providing this amount to the Fund.[68]

To complete the analysis of CCS across several countries in Europe we present in Figure 4 carbon sequestration rates per hectare of the selected forests in the UK, the Netherlands, Ukraine and Slovakia,[28] showing that these rates are comparable. The results of the analysis[28,50,52] across the selected countries in Europe allow us to argue that marginal lands would be available for tree-planting until 2020 and that, over and above other climate policy measures, an enhancement of CCS in forestry, including by use of bio-energy, is likely to be applicable in all these countries except the Netherlands.

The most optimistic projections are for Ukraine.[46,50] They suggest that with afforestation for CCS in this country, 80 t C per ha on average can be sequestered in the subsequent 40 years. This might be important for Ukraine and other Annex B countries (the 39 emissions-capped industrialised countries, including countries in transition listed in Annex B of the KP)[41] and especially for those where GHG emissions reductions are costly. In view of the KP commitments (and prospective international carbon-trade agreements), the

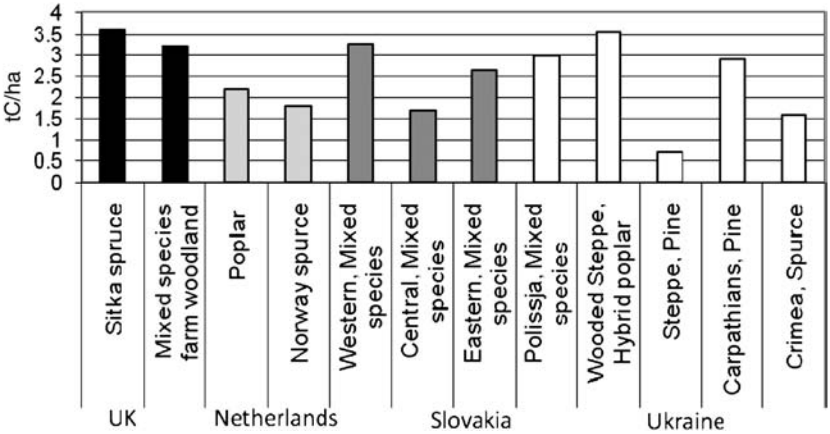

Figure 4 Comparison of averaged carbon sequestration rates across several European countries, $t\,C\,ha^{-1}\,yr^{-1}$ (ref. 11,33,38).

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prospects of selling carbon-offset credits by Ukraine to these other countries is an issue that merits attention.

4 A Focus on Tropical Forests

In most major industrial wood-producing countries, such as Finland, Sweden and Canada, forest legislation stipulates reforestation of sites after forest harvesting. For these and other reasons, forests in temperate and boreal areas have expanded. During the last five years, the majority of countries in the Caribbean, North America, Oceania, and Western and Central Asia had no significant changes in forested area. In 2000–2005, there was a net gain in forest land in Asia (*ca.* 1 Mha per year), primarily as a result of large-scale (4.1 Mha per year) reforestation in China.[37] Policy and environmental drivers have resulted in a continuous growth of forest cover in Europe. Between 1990 and 2005, it increased by 13 Mha. However, approximately the same area of forestland got lost in tropics.[37]

In 2000–2005 the highest annual losses of *ca.* 4.3 Mha were observed in South America, followed by Africa which was losing about 4 Mha of forest land each year. Indonesia was losing *ca.*1.9 Mha and Brazil over 3 Mha of forest each year.[56] Although the rates have decreased more recently, deforestation and forest fires are now responsible for nearly 75% of Brazil's GHG emissions. Land has been cleared for cattle and soya bean production, which is increasing, and due to illegal logging that continues.[70] Globally, therefore, the forest area is decreasing. To compare with forests in other regions, tropical forests have substantial carbon content of biomass (see Table 7). Therefore, when tropical forests are burned a huge amount of CO_2 is instantly released to the atmosphere. Given the rates of deforestation and the losses it brings, it is imperative to alleviate its occurrence and to save existing forests first of all, allowing for

Table 7 Carbon content of biomass across tropical forests and regions.[56]

Region	*Wet Tropical Forest*	*Dry Tropical Forest*
Africa	187 t C ha^{-1}	63 t C ha^{-1}
Asia	160 t C ha^{-1}	27 t C ha^{-1}
Latin America	155 t C ha^{-1}	27 t C ha^{-1}

their enhanced resilience to disturbances and their continual natural regeneration.

Deforestation accounts for 18% of global CO_2 emissions, which is the second largest contributor to net emissions (after power stations, 24%) and a larger net emitter of CO_2 than agriculture (14%) and transport (14%). By slowing down deforestation and by increasing the rate of afforestation, the potential for increasing carbon storage in forests may reach 60–90 Gt C over 50 years, compared with current emissions from fossil fuels of 6.5 Gt C per year.[42] Reducing deforestation can be achieved by conserving and managing existing forests, *e.g.* by implementation of long rotations for carbon sequestration, which is cheaper than afforestation. However, whereas afforestation is likely to generate benefits from the double perspective of CCS in the forest and substitution benefits, the implementation of long rotations needs further investigation.[52] Apparently, this strategy is more pertinent for natural forests in the tropics or for primeval beech stands in the Carpathian Mountains, *i.e.* those which are valuable by their biodiversity and other ecosystem functions, including carbon storage. Lengthening rotations (and so slowing down the harvest rate) elsewhere may miss important opportunities of using wood for wood products and as a substitute for fossil fuels. Thus this issue needs to be analysed in detail and in connection with study areas under observation. Reducing deforestation can also be achieved through tackling its causes, reducing rates and decreasing the amounts of losses it brings, for example, by means of protection and enhancement of forest ecosystems services, including those of CCS, or by means of natural forest regeneration.

Forests in the tropics provide a range of ecosystem services, including biodiversity conservation, watershed protection and soil conservation, protection and enhancement of rural livelihoods, *etc*. The ecosystem services that forests in developing countries provide already necessitate their sustainable use and conservation. The countries, therefore, should have policies, capabilities and flexible mechanisms in place to combat deforestation. However, there is often a lack of resources, policies and institutions to pursue forest sustainability in developing countries. Tropical deforestation is not included in the Clean Development Mechanism and there is now serious consideration that it should be included. Emissions reduction from deforestation is to be linked to efforts to tackle other types of emissions and the markets are to be created and developed to enhance efficiency in reaching climate policy targets. The problems to be solved include: (i) how developing countries might receive tradable carbon credits at the national level, and (ii) in which ways the benefits arising from meeting agreed national targets, should be shared by people so as to result in real changes in managing tropical forests at a local level.

Carbon markets are already starting to provide finance to support low-carbon development, including through the CDM. Although deforestation (*i.e.* forest conservation projects) has not been included in the scheme, the CDM allows eligible activities, which primarily comprise: tree-planting projects to enhance carbon sinks (generate certified emission reductions, CERs) and promote sustainable development in a developing country. However, under the regulatory scheme of the CDM, the percentage share of forestry projects in total expected CERs until 2012 comprises less than 0.5%. Only one project (in AQ8 China) was registered, with seven projects (under validation, 30) with detailed information and others under various levels of development.[72]

Implementation of regulatory trading schemes of the KP requires: accurate measurement of CCS and of the costs; reliable monitoring of the carbon sinks; addressing the problems of durability (permanence) of forestry projects; and alleviation of possible carbon leakages. The issues that make forestry-project implementation difficult under the CDM, and make them both time- and resource-consuming also include: assurance of project eligibility; demonstration that activities will contribute to sustainable development in a host country; arranging finance, property rights and legal matters; proper monitoring, verification and reporting; valuation of the baseline emissions; CER establishment and certification; registry, creation and acceptability of carbon trading; administration and adaptation assistance; establishment of an executive board; distribution and enforcement of responsibilities and designation of operational entities; provision of various kinds of support; and the introduction and imposition of penalties for non-compliance, *etc*.

Thus, the key obstacles for forestry projects to develop successfully under the CDM concern asymmetric information and too-high transaction costs. Consequently, to compare with the total of *ca*. 3000 projects eligible under the KP scheme, forestry activities are lagging behind. At the same time, voluntary carbon offsetting in forestry is performing successfully. It is popular in both developing and industrialised countries and comprises 37% of total voluntary transactions by sector.[73]

5 Economic Considerations of Carbon Sink and Storage in Forests

Afforestation is often considered to be among the low-cost methods for controlling the increase of CO_2 in the atmosphere.[74] However, a meta-analysis of various studies[75] estimated carbon-sequestration costs and identified their huge variability across countries worldwide. Under baseline conditions of forest conservation for CSS, the costs were in the range of €35– €199 per tonne of carbon and, when opportunity costs are taken into account, the cost range increases to €89–€1069 per tonne C. In the Netherlands, the costs of €199–€286 per tonne C are the highest of all the countries examined. The costs in the

Netherlands will not fall below €65–€202 per tonne C (ref. 11,48) even when the benefits are not discounted. These results can be explained by the high opportunity costs of land. Again, among the options for the Netherlands to contribute to joint efforts of coping with the changing climate is to establish forests outside its territory, *i.e*. in countries where land values are lower than in the Netherlands but the rates of carbon uptake may be even higher, for instance in Ukraine, as shown previously. Despite high cost-estimates of carbon uptake in some regions,[76] there is enough evidence to argue that, particularly in developing and transition countries with good tree-growing conditions, large amounts of carbon may be sequestered by forestry at costs of $30 per tonne C and lower.[28,42,50]

Several methodologies are in use[77] for estimating the cost of carbon sequestration in forests. They include econometric studies, optimisation models, and a bottom-up approach which is probably the most straightforward way to estimate costs. The estimates of marginal costs of carbon uptake provide benchmarks for cross-comparison of different measures and scenarios. To assess whether forestry offers an economic opportunity for CCS and in relation to which types of forests (their species composition, age structure and management), the marginal costs per tonne of sequestered carbon and the present value (PV) of costs per tonne of carbon have been computed for the UK, Ukraine and Slovakia.[28,50,52,78]

Since different methodologies and assumptions were applied in these countries, the cross-country comparison of the estimates cannot be precise. The stock-change approach (which consists of summing up carbon stocks over the length of the rotation) was used to estimate CCS in the UK. Under the assumptions and specific requirements of DEFRA,[78] the carbon sequestration costs range from £30.5 per tonne of carbon (afforestation of sheep grazing areas) to £174.9 per tonne of carbon (afforestation of wheat fields) for a discount rate of 3.5%. The estimates provide empirical evidence in support of prospective afforestation in the UK of marginal land currently used for sheep grazing. These findings[52] are comparable with average costs of carbon sequestration of €72 to €116 per tonne C estimated by other authors.[80]

The costs that were taken into account in Slovakia and Ukraine included tree-planting costs (including soil preparation), care and protection costs, opportunity costs of land, replanting costs and the costs of timber harvesting. In Slovakia, the costs of carbon uptake (discounted at 4%) were estimated to be in the range of €8.5 to €14.2 per tonne (if carbon uptake benefits were not discounted). It is noticeable that the costs of CCS in forests are lower in Slovakia than in the UK (average country estimates). They are the highest in the Western region of Slovakia because of its more fertile soil. In the central region, the low value of the carbon sequestered results in a negative net PV of carbon uptake for the CCS policy scenario (strategy of carbon fixation).

In Ukraine, as shown in Figure 5, carbon uptake costs are €4.6–€78.5 per tonne (when carbon savings are not discounted). The estimates vary across the territory and depend on tree species, tree-growing conditions and forest-management practices. When the benefits of carbon uptake were discounted at 4%,

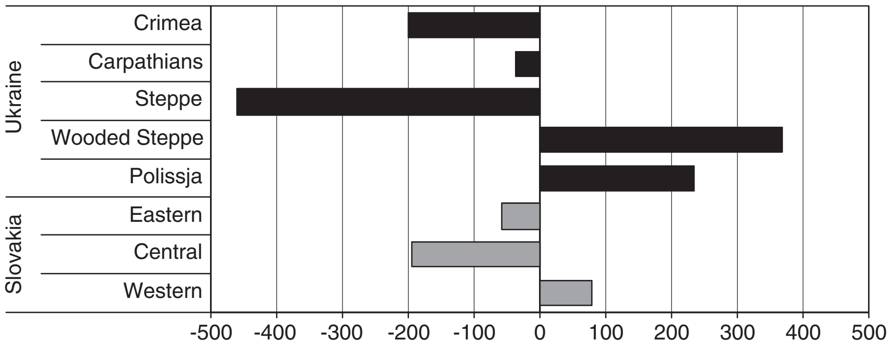

Figure 5 NPV of benefits of carbon storage through afforestation in Slovakia and Ukraine (€ per ha, 4% discount rate, carbon in permanent tonnes).[28]

at the same discount rate as for the costs, the PV of carbon uptake costs appeared to be €7.2–€173.3 per tonne.

For transition countries, the economics of wood products and renewable-energy scenarios were also considered and various discount rates were used to examine their influence on the results. The pilot analysis of renewable energy scenarios has shown that in Ukraine, the costs per tonne of carbon sequestered are more than €36.4 in the Polissja (wooded) region, €32.2 in the Wooded Steppe zone and €124.6 in the Steppe (at 4% discount rate). In Slovakia, the costs are €37– €48 per tonne, but become much higher when the costs for energy production from the planted trees are included.[28,50]

Commonly, in industrialised countries, even when all of the CCS is taken into account (but product sinks are not accounted under the KP), it is unlikely that 'additional' forest management will be a cost-effective and competitive means for sequestering carbon.[79] This is because on less-productive land, which is usually considered for afforestation, the growth rates of trees are usually low. At the same time, in the EU countries and, for example, in the USA and Canada, the land is anyway quite expensive. Afforestation, therefore, does not pay even when multiple benefits are taken into account. Tree planting is often costly in these countries and returns that accrue to forestry in the distant future make the investment unprofitable. However, if SRTP are established, carbon-offset credits competitive with emission reductions might be created. In Canada, for example, hybrid poplar plantations on marginal land will likely be a cost-effective and competitive option.[31]

The costs of carbon sequestration in forests in transitional countries are commonly lower than elsewhere in Europe. For instance, in Ukraine and Slovakia they are lower than in the UK,[52] and even more so than in the Netherlands.[11] However, in some regions of Ukraine and Slovakia the relatively low PV costs of CCS are nevertheless higher than the value of the land. Furthermore, in areas that are strongly affected by the decline in agricultural production and land abandonment, the market prices of land can be significantly lower than the prices set by the government (which are based on the

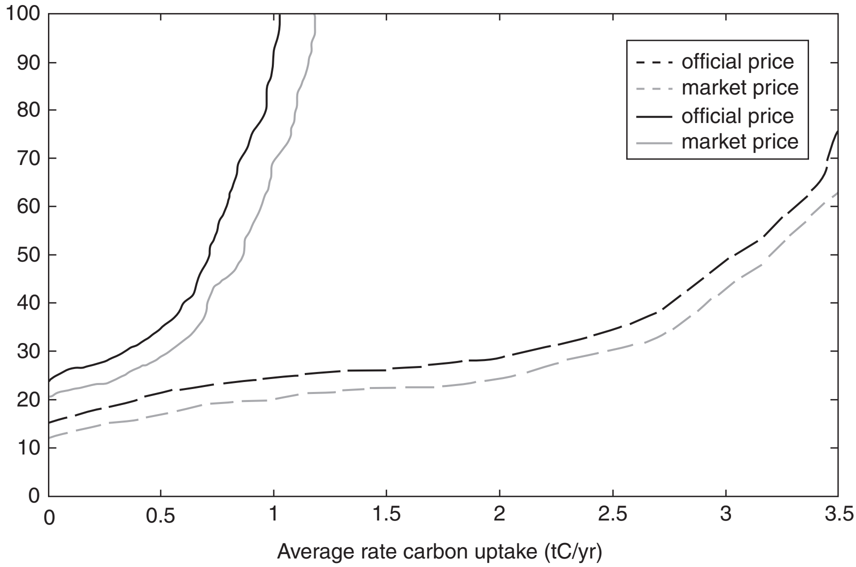

Figure 6 Estimated costs per tonne of carbon uptake for afforestation (dashed line) and short rotation bio-energy plantations (costs of energy production are included, continuous line) in Slovakia, by using land prices set by government (official price) and market price (€ per tonne, 4% discount).[28]

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physical characteristics of the land). This phenomenon is reflected in the estimates of the costs presented in Figure 6 (ref. 81).

The flexible mechanisms of the KP were designed to help Annex B countries to meet their emissions reduction targets at least cost.[1] It provides opportunities for (non-EU) transition countries to sell carbon offsets to industrialised countries. The opportunities arise not only due to the decline of CO_2 emissions during the economic transition compared to their levels in 1990, *i.e.* "hot air", but also due to selling carbon offsets from newly established woodlands. Therefore, carbon sequestration in Ukraine's forests might be beneficial for Annex B countries in view of stabilising their collective emissions in the cheapest possible way *via* the trading of carbon-offset services.

The KP provides opportunities for countries to cope with the changing climate from an economic perspective. The Joint Implementation mechanism presumes attaining GHG emission reductions in another Annex B country, including by CCS (ERU: emission reduction units). The Clean Development Mechanism presumes adding to emission reductions in developing countries, including through tree-planting (the use is limited each year to 1% of 1990 Annex B country's emissions).[41] However, the analysis indicates that under the CDM and JI flexible mechanisms it appears unlikely that credit and permit (allowance) trading, and particularly regulatory carbon offset trading, will occur on a large scale internationally or even nationally. The trading schemes fail not because of a lack of interest from the involved parties, but primarily from a breakdown in the necessary economic and market conditions, such as imperfect information and high transaction costs.

Among the reasons for difficulties (market and governance) of the countries to meet their KP targets are their proclivity to rely primarily on administrative measures and voluntary actions. Further, some countries have low capacity of social capital and inadequate institutions to develop regulatory markets for CO_2 trading. Consequently, the costs of appear to be higher than they need to be, and these high costs lower the efficiency of climate policy implementation. Moreover, the KP addresses only a small proportion of potential global emissions, and it has no effective penalty for non-compliance.

In order to use terrestrial carbon sinks as a flexible mechanism for addressing the KP (and future international agreements), it is important to measure carbon uptake and release, as well as to develop economic and market conditions for creating and trading terrestrial carbon credits. Proper carbon measurement and accounting, reliable monitoring and economic incentives are also required for making bio-energy and wood-products policy scenarios feasible. Various CCS projects that adapted voluntary carbon offsetting schemes have been developed successfully in many countries. The funders are governments and NGOs, businesses and individuals. The projects include reforestation of land and conservation of forests and, in the majority of cases, they offer cheap carbon savings. For expanding internationally and beyond voluntary forest-based carbon markets, it is important to examine the economic efficiency of CCS, determine which scenarios are economically sound and suggest which of them should be implemented, where and how.

The KP "cap-and-trade" system that includes carbon offsets from forestry faces serious challenges in the creation of carbon markets and acceptability of carbon-trading exchanges. The costs per tonne of carbon locked-up and removed by terrestrial ecosystems must be compared with the costs of decreasing the stocks of carbon in ways other than through forestry. When only CO_2 emissions are considered, the emissions cap is set equal to the KP target. When, in addition, carbon offsets are the matter of concern, a cap is required also on permissible offsets.[31] In the light of carbon-trade negotiations, a conversion factor or exchange rate needs to be set. The fact that the sequestered carbon remains in the forest for many years into the future is to be ensured. Evaluation and inclusion of carbon offset credits in a trading system is difficult because of the high transaction costs associated with assessing and monitoring of terrestrial CCS, and due to its temporary and ephemeral nature.[31]

Problems also arise due to the so-called carbon "leakages" which happen when the CO_2 emissions which a project is meant to sequester are displaced beyond its boundaries, so that the full benefit of the project is, in broader terms, reduced. There are ways to cope with "leakages", for example by expanding the scope of the system to "internalise" the "leakages" or to design the project so as to be "leakages" neutralising. Overall, major concern about the cost-efficiency of CSS in forests and numerous problems with the inclusion of carbon offsets from forestry in regulatory emission trading schemes are caused by the following challenges:[31,52]

- Setting up the level of baseline emissions.
- Assurance of "additionality" of the projects.
- Assurance of durability (permanence) of the projects.
- Accuracy in measurement of carbon sequestration and of costs.
- Reliable monitoring of carbon sinks.
- Avoidance of "leakages" and of double counting (which means that no credits ought to be sold twice to a final customer).[82]
- Creation and acceptability of carbon trading.
- Establishment of proper carbon-offsets certification and of their "conversion" into emission permits.
- Assurance that actual carbon sequestration has taken place.
- Development of property rights and institutions for exchanging carbon offsets.
- Various legal aspects.
- Verification of sustainable development requirements, *etc*.

Therefore, more attention is to be paid to analysing the role of carbon-uptake credits from forestry in climate-change negotiations, and how to bring terrestrial carbon offsets into regulatory emission-trading schemes. It is important to identify carbon-sequestration projects which will be coherent, effective, cost-efficient, widely acceptable by the public, and consistent with other aspects of sustainable development.

6 Uncertainties Pertaining to Carbon Sink and Storage in Forests

The role for forestry to mitigate climate change comes with a great deal of uncertainty. Firstly, marginal damages from atmospheric carbon over time are uncertain. There is also uncertainty when trying to correctly ascertain the benefits to future generations of carbon-control strategies. Even if the vote of up-coming generations over climate-change mitigation strategies can be taken into account, future preferences are unknown.[83] Difficulties in estimating the future benefits of CCS will also arise due to uncertainties about the dynamics of carbon in forests. It is necessary not only to determine how much carbon is actually sequestered and stored and for how long, but how much carbon will be sequestered in the future, in conditions of changing climate.

The uncertainties also concern causes, magnitudes and permanence of forest carbon. Scientific evidence suggests that the terrestrial carbon sink is increasing. However, complex relationships between climate and the terrestrial carbon cycle result in uncertainties about CCS future projections, in conditions of increasing temperatures and their effects on photosynthesis. Forest ecosystems are vulnerable to the effects of changing climate. For example, there are predictions that large areas of tropical forest in the Amazon may die back from 2040, releasing carbon to the atmosphere[42] and multiplying the effect of global warming.

Although it is now possible to quantify the amount of carbon being sequestered and stored in forests, measuring carbon uptake remains a difficult task, especially if the carbon sink is short-lived.[76] It is now possible to monitor carbon sequestration and to project possible CCS scenarios. However, the results are case-specific and there are considerable variations between sites and forest types.[42] Furthermore, existing methods are labour- and time-intensive and, as they are usually based on measurements in sample plots, the scaling-up of results often leads to significant errors. Recent advances in remote-sensing techniques look promising.

The rates of possible carbon uptake, or loss, depend upon forest management and land-use changes (*e.g.* forest clearance, species substitution for peat bog, heathland, ancient-woodland restoration, increased uptake of silvicultural systems) and on climate change, itself as a causal influence on carbon sequestration, due tochanges in precipitation, temperature or the frequency of extreme events. The concern over non-permanence is tangible, as removed carbon could be released before the accounting period ends. The losses that result in non-permanence of CSS are associated with: increasing forest fires and diseases due to climate change; the losses of dissolved organic carbon in rainwater drainage and runoff caused by climate change and anthropogenic pressures; and reduced soil inputs through stump harvesting, plus increased losses involved in de-stumping soil disturbance.[52]

Discussions of the uncertainties pertaining to terrestrial carbon sink and storage, and of the mechanisms for assuring that the associated emissions reductions in forestry are long-lived and are not double-counted, are available in the literature.[31,82,84]. The temporary nature of terrestrial CCS can be addressed through: partial credits which account for the perceived risk of carbon release; by insurance coverage against the destruction or degradation of forest sinks; by assurance that the temporary activity will be followed by one that results in a permanent emissions reduction; and by using a conversion factor to translate years of temporary carbon storage in a forest into a permanent equivalent, *etc*. Although CCS in trees is carbon neutral in the long-run (at 0% discount rate for carbon-uptake benefits), because the sequestered carbon is eventually released back to the atmosphere through wood decay, some temporary forest carbon may become permanent.[85] The prevailing vision is that CCS in forests is important as it may be a relatively low-cost option and it postpones and reduces climate change, allowing time for adaptation, learning and technological innovation.[86]

However, in addition to the already discussed "pros and cons" of climate-change mitigation through forestry projects, there are various scientific, technological and socio-economic uncertainties pertaining to terrestrial CCS. For example, the assumption that forestry-based carbon sequestration may be considered as a universal remedy discourages our efforts to address emissions reduction. The CCS policy measure does not always complement economic growth. Large-scale afforestation, particularly the establishment of vast areas of fast-growing monoculture plantations, may result in negative environmental and social consequences. These challenges are often multiplied by a great deal of institutional uncertainty associated, for instance, with land (forest) tenure in some developing and transitional countries, and with property rights on carbon offsets, as well as with some managerial aspects in forestry, particularly with those that concern afforestation. Changes in government policies, markets fluctuations, and changes in social norms and behavioural patterns contribute to uncertainties. Analysis of planting trees for CCS, therefore, runs into uncertainties, and the extent to which the strategies can be justified on efficiency grounds also depends on the rate of discounting employed in the analysis.

The discounting of carbon uptake benefits at 0% suggests that the value of marginal carbon damages in the future will increase at the real rate of discount. This implies that all of the carbon sequestered is valued equally, no matter when it is captured.[31] Given this assumption, consider fast-growing poplar stands with initially high rates of carbon uptake, but which shortly decelerate. Consider also spruce stands that grow much more slowly but for longer, and in 100 years from now they can accumulate up to 300 t C per ha. If the costs of carbon sequestration (largely afforestation costs) are equal for these two types of forest, at a 0% discount rate for carbon savings spruce stands are to be chosen for planting. However, this might not be the solution when terrestrial carbon sequestration is considered. Therefore, approaches to CCS project-evaluation are case-specific. The economic way of reasoning, for instance, suggests that in long-term projections in forestry, the setting of a 0% discount rate for carbon savings is a very specific assumption. Cumulative carbon uptake and other benefits in forests would be available in the future. However, in economics, it is important to compare costs and benefits according to their present value. Therefore, to justify the cost-efficiency of carbon-sequestration forestry projects, positive discount settings for carbon uptake benefits could also be advocated.[50]

Among the challenges of CCS in forests is the meeting of the "additionality" condition.[82] In principle, credit should be given only for carbon sequestration above and beyond what occurs in the absence of CCS incentives. For example, if it can be demonstrated that the forest would not otherwise has been established (*e.g.* to provide higher returns to forest owner), the "additionality" condition is met. Similarly, afforestation projects are additional if they provide ecosystem services not captured by the landowner, and would not be undertaken in the absence of economic incentives, such as subsidy payments or an ability to sell carbon credits.[82] Moreover, carbon sink in forests has to take into account the carbon debit from LUC and timber harvesting; carbon stored in wood product sinks (currently, not considered under the KP); various carbon "leakages"; and additional carbon sequestered as a result of forest management activities, including fire control.[31]

To conclude, our major concerns with relation to using terrestrial CCS as a climate policy measure are, as follows:

- Wider use and promotion of CCS in forests, under the KP and upcoming international agreements, may distract attention of policy makers and practitioners from emissions reduction and from novel means of climate change alleviation.
- CCS in forestry tends to be ephemeral and thus not equivalent to emissions reduction. Often, terrestrial carbon sinks are short-lived, and this makes it particularly difficult to compare them with emissions reduction (but the techniques exist).[31]
- The ‘value’ of sinks to a country is tied to the land use existing in 1990 as the base year. Identification of both, a baseline scenario and additional CCS activities, is usually difficult.
- Measurement of carbon flux, its monitoring, and enforcement of durability of projects are costly in the case of carbon uptake in terrestrial ecosystems.
- Accounting for CCS in wood products needs to be resolved.
- Incentives and mechanisms to combat deforestation in some regions of the world, particularly in the tropics, are to be addressed.

7 Social Considerations of Carbon Sink and Storage in Forests

Forestry has been viewed as the basis for timber production, outdoor recreation and support of wildlife habitat, a means of watershed protection, a sink for pollution and an opportunity for carbon sequestration. However, forestry practices that sequester the most carbon may compromise projects that reduce net emissions of CO_2 to the atmosphere. Carbon sequestration activities could lead to changes in fossil-fuel use and could cause LUC that further impact the atmospheric CO_2 pool. Climate policy measures need, therefore, to be effective and feasible, and well embedded in land use and environmental policy strategies. If this is achieved, and economic instruments and flexible policy mechanisms are implemented, there is a scope for multi-functional countryside where CCS, production of sustainable energy, sustainable forestry and agriculture are combined, and where climate policies are connected to the strategies that promote integrated sustainable land use.

Integration of various sectors of the economy should be accompanied by reconciliation of carbon sequestration policies with the strategies dealing with remote rural areas affected by regional disparities. Support for afforestation on marginal land is important, and more attention is being given to agricultural and environmental linkages to climate-change related measures, and to the inclusion of carbon-sequestration forestry activities into rural and regional development schemes. It is anticipated that CCS forestry projects will be more successful if they are consistent with wider programmes of sustainable rural development, and if they focus on multiple (*i.e.* social, economic and environmental) components of sustainability, including on climate-change dimensions and various aspects of land-use policy. This particularly concerns remote rural areas in Europe, where CCS through forestry could target "win-win" situations by bringing together sustainable development and climate-change mitigation, and by combining the socio-economic objectives, *e.g.* those of increasing welfare of communities with the enhancement of nature and rural landscape.

In such a land-rich country as Canada, for instance, which now focuses on afforestation of agricultural land to meet a significant component of its KP commitment, the problem of woodland development is related to the willingness of landowners to create carbon credits rather than to the biophysical possibilities for carbon uptake.[31] This necessitates the development of opportunities and incentives by which the capabilities of landowners to create carbon credits and to market carbon offsets would be enhanced. Landowner preferences for carbon sequestration methods are imperative with this respect, and they probably are influenced by the available information, institutions and uncertainties concerning landowners' potential profits and their eligibility for subsidies.

In England, for example, tree-planting for multiple purposes rather than solely for CCS commonly enlarges social benefits and helps to prevent potential conflicts relating to trade-offs, *e.g.* between biodiversity and carbon sequestration, or between landscape amenity values and those of climate-change mitigation. The Regional Development Agencies are taking a lead in inter-sectoral integration.[87] Although multi-functional forestry may result in lower rates of carbon sequestration, it is expected to be more attractive to people, because in the majority of cases, it will provide additional benefits and contribute to sustainable development.[28] Existing incentives in forestry need to be scanned to assess their influence on both carbon fluxes and climate-change adaptation, and measures enhancing forest sinks need to be based on principles of sustainable forest management and recognition of the multi-functional role of forests.[5] Afforestation for multiple purposes[37] can be seen as a sustainable way of restoring the productivity of abandoned land, whilst utilisation of woody biomass for energy could create new options for land development.

Carbon sequestration strategy [6] in complement with a replacement of fossil fuels by bio-energy is becoming a priority for forestry when coping with climate change. The rising importance of renewable energy could be explained by the fact that the avoidance of carbon release through the replacement of wood for fossil fuels is repeatable, as long as a continual process of tree growing, harvesting and regeneration, with the use of harvested woody biomass for energy, is maintained. Therefore, the social benefits of renewable energy projects and those arising from the substitution of energy intensive materials with wood are likely to be higher, in the long run, than the benefits of the strategy of carbon fixation alone. Carbon sinks in wood products is an issue that merits further attention. This policy option provides multiple benefits by enlarging the supply of wood and adding to the total carbon sink. Wood substitutes for various raw materials implicated in GHG releases and can be used in construction, engineering and production of household goods. In all these cases, wood acts as a sink of carbon (beyond its storage in trees) and with the duration of the sink equivalent to the life of the goods.

A systematic promotion of wood products and renewable energy strategies offers opportunities for innovation and development of energy markets with locally and regionally oriented value chains, and thereby provides new employment opportunities and enhances rural development.[7] Policies and measures for CCS should, therefore, be integrated not only within spatial planning, and agricultural, forest and rural policies, but also with the policies and measures for sustainable energy systems.[51] This will enhance energy savings and will assist in coping with local environmental problems associated, for example, with health risks pertaining to changing climate.

Enhancement of carbon sequestration on marginal land, especially in combination with an increased use of bio-energy, will more likely represent a sound opportunity for rural areas and communities when there is synergy between different, and sometimes contrasting, policy areas, and when attention is given to the provision of long-term initiatives and infrastructure (*e.g.* markets) in support of forest-sector-based CCS. Integrated land-use systems, however, are often problematic because they require fiscal and other incentives outside forestry; they have high transaction costs and tend to deny self-interested landowners the right to determine their preferences which are often not economically optimal (*i.e.* amenity-related landowning).[52] So the institution of private ownership and the extent of amenity land purchase must be understood too. The optimum carbon-offset projects will likely be those which link long-term CCS with long-term substitution opportunities,[18] and which successfully develop capabilities to bridge gaps between rural policy priorities, and those of climate change and other issues of sustainable development.[34]

The bridging of gaps between climate policy and practice, and between various sectors of the economy will improve governance capacity, whether it is based on markets (as in the UK) or on the authority of government (as in Ukraine). Moreover, social and economic policies pertaining to CCS are to be worked out and implemented in collaboration between stakeholders. Substantial efforts are to be made to develop environmental awareness of farmers, forest managers and decision-makers concerning various aspects of climate change. This work is ongoing in the analysed European countries, including transition economies. For example, the Centre of Climate Change Initiatives in Ukraine[90] focuses on institutional strengthening, on increased involvement of NGOs and practitioners in climate-policy activities, and on knowledge transfer. However, there is a need for more information campaigns, training facilities and schemes to demonstrate CCS forest possibilities and make them attractive for end-users and, most of all, for forest and land owners, and managers.

In the UK, a high level of participatory democracy is already manifested in the development and implementing of CCS land use and LUC initiatives (*e.g.* through planting trees); in the involvement of the public in environmental and forestry decision-making and policy implementation (*e.g.* through consultations on Forestry Strategies across Britain, and on Forestry Commission

Climate Change Action Plan); and in the extension of information and education pertaining to climate change.[37] It is crucial to involve key forestry stakeholders and local communities in CCS policy-making, decision-taking and policy implementation. It is important to consult people on what climate policy alternatives are desirable for them and to get to know why it is so, as well as to develop our understanding of public perspectives on the role and place of forestry in the mitigation of climate change.

8 Conclusions

The activities enhancing carbon sequestration and sink in forestry overall contribute modestly to the removal of CO_2 from the atmosphere. The carbon sink of forests that could be accounted under the KP is relatively low. For instance, in 2000, carbon uptake by forests in the UK reached almost 3 Mt, whereas it was only 0.3 Mt from planting since 1990, which is eligible under the KP.[57] There are many uncertainties pertaining to terrestrial CCS as a climate-policy measure. Nevertheless, forestry projects have considerable relevance for national carbon budgeting in individual countries where wooded cover has a potential to grow. They are also important in view of reduction of collective carbon emissions at least cost, by trading of carbon offsets across countries. Important carbon sequestration activities involving forestry include afforestation, an increase of area of SRTP and forest regeneration. Even more pertinent are these activities when combined with substitution of wood for fossil fuels and non-wood materials (especially for energy-intensive materials in construction), and these policy options are to be considered further. Tropical deforestation requires in-depth consideration, particularly the development and implementation of economic incentives to cope with this problem more effectively.

In terms of climate-change mitigation priorities for forestry, the approach that includes the principles of sustainable forest management is advocated.[37] According to this approach, carbon sequestration forest policy measures must be socially and environmentally acceptable and based on sustainable-development principles.[6] Enhancement of carbon sequestration on marginal land in combination with increasing use of bio-energy represents a promising opportunity. It is important, however, to develop and provide knowledge of how to translate sustainability requirements for forestry and biomass production into policy guidelines; how to overcome market limitations and institutional obstacles for terrestrial CCS; how to implement flexibility mechanisms for more effective and cost-efficient use of forestry opportunities to mitigate climate change; and how to develop incentive mechanisms and good governance to implement CCS projects on the ground.

In transition countries, large-scale agriculture under the socialist regime supported the conversion of forest or grassland to agricultural land. Currently, the decreasing agriculture[56] will likely cause an increase of abandoned land. In the EU, policy changes under CAP reform might promote forestry development. Further expansion of woodlands in Europe and a rising role of forestry in mitigating climate change may be predicted. The analysis suggests that over and above other climate-policy measures, the enhancement of carbon 'sinks' and 'reservoirs' by forests is meaningful, and their inclusion in climate-policy activities is logical and viable. It is important, however, to develop our understanding of policy options which are most acceptable by people, and to identify places where CCS projects, including those for biomass production, will function most effectively and could be most appropriately integrated into the general context of land use, where multi-functional forestry and contemporary rural change are currently being observed.

In Europe, the regulations and national programmes supporting the conversion of agricultural land back to forest focus largely on remote areas. Hence, CCS land-use and forest-policy measures should be incorporated in regional schemes of integrated sustainable rural development, where socio-economic, environmental and climate-change-related components of LUC are to be considered jointly (where possible). The effective measures should aim at "win-win" situations,[4] which would benefit the development, environment, people and the economy all together, both at national levels and internationally.

However, carbon uptake in trees is temporary, and this needs to be addressed. Moreover, at some point in time there will be no more land available for tree-planting, and carbon sequestration through afforestation will no longer be applicable. Therefore, CCS in forestry alone (without a consideration of further use of wood after timber harvesting) can hardly be considered as sustainable and a long-term solution. Emissions reduction is seen as the priority for climate policy. Nevertheless, climate-change mitigation through forestry is deemed to be amongst the effective and relatively low-cost (complementary) climate-policy options for many countries, especially if fast-growing species are planted on marginal land, or when forestry projects deliver multiple benefits.

Carbon-sequestration rates per hectare of forest across the several European countries observed are relatively high, and marginal lands are available for tree-planting at least until 2020. The carbon sequestration potential of afforestation is deemed to be substantial in some of the countries. The results of the economic assessment of opportunities for CCS through forestry suggest that this policy measure is likely to be competitive with other means of removing carbon from the atmosphere, and that choosing the right locations for forestry development, and the most appropriate tree species and management regimes to be applied, are important factors for saving economic costs.

Although the potential to sequester carbon through afforestation is high in some countries, the potential for carbon-offsets selling is smaller and is limited to carbon balances resulting from the eligible climate-change-mitigation forestry projects which are subject to the cap set on emissions, as well as by the costs of GHG inventory preparation[1]. Moreover, a rising number of carbon offsets available to buy will likely lead to problems pertaining to the environmental effectiveness and economic efficiency of implementation of international agreements, such as the KP, and to contradictions associated with possible attitudes of policy makers to not restrict the emission targets for a polluting industry.[31] Nevertheless, the development of forestry capabilities for CCS, along with many other climate-policy activities, will contribute to the offsetting of CO_2 emissions and could allow European countries to improve their climate-policy performance.

There is a difference, however, between benefits provided by forest development and the benefits that accrue to a forest developer. Establishment of forest plantations to offset CO_2 emissions requires an appropriate institutional setting, incentives and sources of investment. In the EU, intra-European credits from the activities enhancing carbon sequestration will not be included in the trading schemes.[89] Sound incentives for afforestation are therefore required in individual Member States, with proper subsidies to be given to landowners for planting trees. In the transition and developing countries, for instance, the question of whether tree-planting for carbon-uptake should be on the national or EU-based agenda remains unresolved. European investors are clearly showing the interest to invest in JI and CDM projects.[88] The potential gains from international projects are not seen, however, as priorities for land use and climate policies in host countries.[63] Therefore, unless the necessary institutional infrastructure is developed and the barriers for investment are identified and addressed, the Annex B countries cannot expect to benefit widely from crediting JI and CDM systems.

In order to utilise most effectively and efficiently the potential of forests to contribute to the mitigation of climate change, it is imperative to clarify international agreements and rules on forest CCS accounting; to increase its technical effectiveness and accuracy; and to develop further CCS policies, tenure rights (*e.g.* forest carbon ownership), incentives and carbon markets. Among motivating research topics for socio-economists to consider are: who is responsible for carbon sinks after the KP commitment period to 2012; what is the value of (temporary) terrestrial carbon; and how will the value of terrestrial carbon change as markets develop and institutions evolve to handle the numerous uncertainty aspects affecting both its capture and storage.

Uncited References

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