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Woodland for Water: Woodland measures for meeting Water Framework Directive objectives

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Forest Research Monograph: 4

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Executive Summary

The report considers the key issues relating to woodland and the Water Framework Directive (WFD) in England and Wales, but has application to Scotland and Northern Ireland.

Protecting and enhancing the water environment is a key aim of Forestry Commission England's Corporate Plan and also features strongly in The Welsh Assembly Government's (WAG) Woodlands for Wales Strategy and the Scottish Forestry Strategy. In order to guide Forestry Commission England's Actions for the natural environment, the Woodlands for Wales Action Plan for environmental quality, and the Scottish Forestry Strategy Implementation Plan, there is a need to review the latest evidence base concerning the positive and negative impacts of woodland on surface and groundwaters. The review focuses on native woodland creation but also considers the impact of new conifer woodlands and bioenergy plantations in light of climate change and renewable energy policies. Emphasis is given to the literature from UK and Northern European studies.

The aims of this review were three-fold:
- To collate existing scientific research and policy options to increase our understanding of how woodland can be used to improve water quality and water management to help meet WFD objectives of achieving 'good ecological and chemical status' in all water bodies, where possible;
- To provide a robust evidence-base for developing woodland and environmental policies; and,
- To review relevant studies that could inform the development of a cost-benefit analysis of proposed measures, summarising available valuations of those 'ecosystem services'.

An additional element was to undertake a mapping-based case study to assess how woodland creation could be better targeted to locations within catchments where it would contribute most to maximising water and other benefits, and minimising risks. The review was framed around a set of pre-defined questions covering the main issues of diffuse pollution, water resources, flood alleviation, riparian management, climate change, contaminated land and waste, and land use and spatial planning.

The review provides strong evidence to support new proposals to expand woodland in appropriate locations for soil and water benefits. Main drivers for woodland expansion include sustainable flood management, water bodies remaining at risk of failing good water status despite improvements in agricultural land practices, and the need to mitigate the effects of climate change.

The benefits are potentially greatest for the planting of riparian and floodplain woodland, which can help to reduce diffuse pollution, protect river morphology, moderate stream temperature and aid flood risk management, as well as meet Biodiversity Action Plan targets for the restoration and expansion of wet woodland.

The contribution to tackling diffuse pollution includes both a barrier and interception function, whereby the presence of trees reduces the risk of direct contamination by agricultural activities on the adjacent land, and helps to trap and retain nutrients and sediment in polluted run-off. Riparian and floodplain woodland benefits for protecting river morphology and moderating stream temperatures are well proven, while a good case can also be made for mitigating downstream flooding. Planting Short Rotation Coppice or Short Rotation Woodland in these locations could help to maximise some benefits but also presents some risks.

Targeted woodland buffers along mid-slope or downslope field edges, or on infiltration basins also appear effective for slowing down run-off and intercepting sediment and nutrients but the evidence base is limited. Wider woodland planting in the landscape is known to reduce potential pollutant inputs compared to agriculture in the form of fertiliser and pesticide loadings, as well as protect the soil from regular disturbance and so reduce sediment delivery to watercourses.

Despite strong policy support for woodland expansion for water benefits, the scope for woodland planting remains limited by insufficient financial incentives and wider land use constraints. There is a need to increase incentives for woodland planting by making these better reflect the full range of water and other benefits. Landowners and farmers are likely to be very resistant to land use change unless it is economically attractive. Planting on better quality land can result in a reduction in land value, a loss of agricultural subsidies and a reduction in income. There will be a need to provide sufficient compensation for these losses or funding provided for land purchase to secure change. This is especially the case where the type of woodland and management practices required to promote water benefits represents an added cost or low return. Experience from the rest of Europe and further afield provides a range of examples of effective payment schemes for water-related forest services, which have succeeded in achieving woodland creation for water protection.

There is a need to raise awareness amongst policy makers and planners of the benefits of woodland for water. In particular, the potential of woodland to aid water management merits a much greater profile within River Basin Management Plans (RBMP) and Catchment Flood Management Plans (CFMP). Currently, woodland solutions are largely absent from these plans. In the future, woodland creation may have an important role to play in mitigating more intractable water pollution problems within Water Protection Zones.

The case for woodland solutions also needs to filter down to sub-basin/catchment plans and local farm plans. To achieve this, woodland measures would have to be given greater prominence within relevant land management advice and guidance, WFD Programmes of Measures and agricultural best management practice handbooks, as well as greater acknowledgement in assessment procedures for evaluating applications for woodland planting and management grants.

Training of agricultural advisers is also required, as is the provision of better guidance on woodland creation and management to farmers and other landowners. Local demonstration sites could help to communicate how woodland can contribute to tackling issues such as diffuse pollution and flood risk.

The report calls for closer integration of forestry and water policy to enable better decisions to be made and available incentives and regulatory controls used more effectively to secure woodland opportunities for water. It also highlights the need for more research to quantify water benefits and evaluate how woodland can be best integrated with agriculture and urban activities for water and wider environmental benefits, while minimising any water trade-offs.

Spatial mapping offers significant potential for promoting integrated catchment management and delivering new woodlands where they can best benefit society. 'Opportunity mapping' has been developed to help direct woodland onto preferred sites for protecting sediment sources, intercepting the pathways of diffuse pollutants, reducing rapid run-off, enhancing flood storage and to attenuate flood flows.

Acknowledgements

1. Introduction

The report considers the key issues relating to woodland measures for meeting Water Framework Directive (WFD) objectives in England and Wales, but has application to Scotland and Northern Ireland. Woodland cover in the UK at 13% of land area remains one of the lowest in Europe. The UK National Ecosystem Assessment (UKNEA, 2011) highlights the 'ecosystem services' provided by woodland and national governments acknowledge the need for more woodland for the multiple benefits provided, which is helping to push woodland higher up the hierarchy of land use. Country forestry strategies reflect the potential of woodland to deliver WFD objectives, including highlighting opportunities for woodland to reduce the impact of diffuse pollution from agriculture and urban activities, as well as assist flood risk management. Protecting and enhancing the water environment is a key aim of Forestry Commission England's Corporate Plan and also features strongly in The Welsh Assembly Government's (WAG) Woodlands for Wales Strategy and the Scottish Forestry Strategy. In order to guide Forestry Commission England's Actions for the natural environment, the Woodlands for Wales Action Plan for environmental quality, and the Scottish Forestry Strategy Implementation Plan, there is a need to review the latest evidence base concerning the positive and negative impacts of woodland on surface and groundwaters. The review focuses on native woodland creation but also considers the impact of new conifer woodlands and bioenergy plantations in light of climate change and renewable energy policies. Emphasis is given to the literature from UK and Northern European studies.

Well planned and managed woodland can be of significant benefit to the local and global environment and may play an active role in rehabilitating degraded and contaminated land, act as a sink for or protect against potential sources of diffuse pollutants and, arguably, reduce flood risk. However, environmental problems can arise if woodland is poorly managed or planted in unsuitable locations. In considering any expansion of woodland cover, the environmental impact of the displaced land use is as important as the impact of the woodland itself, and it is the net effect of new woodland that is most relevant.

In an ideal world woodlands should be targeted to provide the optimum combination of environmental, social and economic benefits. Improved modelling of the impacts of new woodland would support decision making and allow more effective targeting of available incentives and regulatory controls. Public funding for the planting of new woodland is mainly through Rural Development Programmes (RDP). In the future, the next review of the Common Agricultural Policy (CAP) may provide further opportunities for woodland either through financial incentives or from increasing the value of uncropped land.

There is a need to know the relative attributes and interdependencies between woodland and water to better target new woodland schemes to help achieve WFD objectives.

Climate change brings a number of new drivers to the potential expansion of woodland, from biomass for energy to sequestering carbon in the growing timber, the potential after use and in the organic matter that is created in the soils. Delivery of some of these benefits, however, may involve trade-offs for water.

The implementation of the EU RDP regulations is set out in Defra's UK National Strategy Plan (2006), which recognises that sustainable and competitive agriculture and forestry sectors are a prerequisite for improving the environmental quality of the countryside. The plan identifies common elements that run through the RDP strategies of each country (Scotland, England, Wales, and Northern Ireland), which include the protection and enhancement of natural landscapes in rural areas. Key needs are:

*   improving coverage and/or penetration of agri-environment and woodland schemes to increase habitat networks, combat diffuse pollution, and address climate change;
*   encouraging energy crops and wood fuel as part of an increasing use of renewable energy.

Realisation of woodland benefits for water, however, will depend on persuading farmers and other landowners to change land use and plant the right tree in the right place. However, there are many barriers to woodland expansion on farmland that will need to be addressed if this approach is to succeed. These include:

*   The comparatively low economic returns from woodland as opposed to agriculture
*   Length of the required investment period.
*   Potential higher reward and increased flexibility for alternative uses of marginal land.
*   Grazing pressures from deer affecting the success and costs of establishment and regeneration in certain areas.
*   Cultural factors, including the protection of cultivated lands.
*   Land ownership.
*   Perceived reduction in land capital values.
*   Desire to preserve 'traditional' landscape views.
*   Lack of experience and knowledge about farm woodland management.

Despite strong policy support for woodland expansion for water benefits, the scope for woodland planting remains limited by insufficient financial incentives, the long time-frame of returns on investment from eventual harvesting of timber and wider land use constraints, including debates over 'food security'. Nature conservation is a key constraint, with large areas of the country designated for preserving extensive open grassland, heathland and wetland habitats. The recently published Natural Environment White Paper (HM Government, 2011) calls for a review of how we use advice and

incentives for farmers and land managers, to create a more integrated, streamlined and efficient approach that yields better environmental results.

The climate change agenda may act as a catalyst for a renewed focus on woodland creation. The UK Low Carbon Transition Plan outlined Government support for a new drive to encourage private funding for woodland creation, which is being taken forward through the work of the Forestry Commission-led Woodland Carbon Task Force. The Scottish Government also plan to use woodland creation to help meet carbon budgets, and increasing annual woodland planting to 10-15,000 ha by 2015 is set as a key milestone in the Scottish Government's Climate Change Delivery Plan. As part of the Climate Change Strategy for Wales, the Welsh Assembly Government has set a target of 100,000 ha of new woodland to be created over the next 20 years to be delivered through the Glastir Scheme.

2. Aims

The aims of this review are three-fold:
- To collate existing scientific research and policy options to increase our understanding of how woodland can be used to improve water quality and water management to help meet WFD objectives of achieving 'good ecological and chemical status' in all water bodies, where possible;
- To provide a robust evidence-base for developing woodland and environmental policies; and,
- To review relevant studies that could inform the development of a cost-benefit analysis of proposed measures, summarising available valuations of those 'ecosystem services'.

3. Literature review

The literature review considers the scientific understanding of the interactions between woodland and water and the policy options to control risks and promote benefits. It is framed around a set of pre-defined questions covering the full range of issues; closely related questions are considered together. Questions are grouped by issue and the findings summarised at the end of each question (in italics).

3.1 Background

The speciation and distribution of woodland and forests within the UK has changed considerably over time. At the start of the 20th century, UK forest coverage was the lowest in Europe (approx. 5%). Major losses of ancient woodland were made to industry and defence, as well as clearance for agriculture (Farmer and Nisbet, 2004). Policy from the 1920s and reaffirmed in the 1940s (following further deforestation to meet the needs

of the Second World War), encouraged rapid 'blanket' afforestation of non-native coniferous species (mainly North American) to build a timber reserve. Economic factors such as land value led to a preference for upland areas, previously used as sheep farming (Farmer and Nisbet, 2004). The preponderance of poorly drained and infertile soils necessitated extensive cultivation, drainage and fertilisation to secure tree establishment and promote growth and forest stability.

Afforestation peaked in the 1970s, but by the 1980s had met increasing criticism regarding adverse effects on biodiversity, landscape and the water environment (SEPA, 2007a). This led to a marked shift in forest policy in the 1990s away from solely timber production to delivery of multiple benefits. Sustainable forest management became the central goal underpinned by the UK Forest Standard and a set of supporting Guidelines (FC, 2004). As a result of the successful implementation of best practice, there is now a broad consensus that well designed and managed forests and woodland can protect and enhance the water environment (e.g. SEPA, 2007a; Defra, 2007a; FC, 2001). Consequently, targets have been set for woodland expansion to deliver a range of public benefits (e.g. increasing woodland cover from 17% to 25% of Scotland's land area by second half of the 21st century), including helping to meet WFD objectives and mitigate climate change. The climate change agenda is likely to act as a catalyst for a renewed focus on woodland creation.

The principal regulatory instrument driving good forest practice for the protection of freshwaters is the Forests & Water Guidelines (FC, 2003). Although, these have no formal legal status, compliance is required for approval of forest operations on public lands and grant support on private lands. The Guidelines were first published in 1988, with subsequent revisions in 1991, 1993 and 2003 to ensure that they kept up to date with developments in science, policy and practice; a fourth review is now complete and a new version is due to be published soon. In 2008, some elements of the guidelines were incorporated into a generic set of rural best land management practice measures and made statutory in Scotland as General Binding Rules under the Controlled Activities Regulations (2005).

3.2 Diffuse pollution

What mechanisms are already deployed in Europe and the UK to encourage the use of woodland to reduce diffuse pollution?
The potential benefits of unmanaged and well managed woodlands to water quality have been formally recognised in the devolved forestry strategies and corporate plans. Woodland creation and restoration targets have been set to expand the total area of woodland and energy crops, including Short Rotation Coppice (SRC), and to increase biodiversity and priority species in existing and new woodland. Government policy promotes targeted woodland planting in areas where trees can contribute environmental benefits, including reducing diffuse pollution: "The Right Tree in the Right Place". Local

targeting of woodland to act as nutrient soaks on farmland and Riparian Woodland Buffer Strips (RWBS) could be regarded as options which satisfy this principle. Buffer strips are recognised within the Environmental Stewardship (ES) scheme options, but only for grass strips, with no reward for the establishment of woodland buffers. Points are awarded irrespective of location within the landscape.

The incorporation of measures targeted at woodland creation in agricultural landscapes into River Basin Management Plans (a prerequisite of the WFD), was suggested by Farmer and Nisbet (2004) as a means of proactively targeting reductions in sedimentation and diffuse pollution. While the emphasis remains on improving agricultural practices to reduce diffuse pollution at source, there appear to be limits on this approach and an increasing recognition that some problems may only be solved through a degree of land use change (e.g. nitrates issue). However, the role of woodland is under-represented in the River Basin Management Plans (RBMP). In the future, woodland creation could have an important role to play in helping to solve more intractable water pollution problems within Water Protection Zones.

FC England's Woodland Creation Grant offers support for woodland planting for multiple benefits but has only recently started to target water benefits. Broadleaved woodland, which provides the greatest benefits to water quality, receives the highest payments. The regional scoring system that is used to assess individual planting applications now offers points for water services in some regions (e.g. the East of England region gives 5 points (the highest score is 6) for the establishment of wet woodland and 2 points for planting within priority catchments under the England Catchment Sensitive Farming Delivery Initiative), but this does not include any additional financial incentive to secure planting schemes. However, an additional contribution of £2,000/ha was introduced in 2010 in the Yorkshire and The Humber Region to encourage new planting in areas contributing to flood risk management (see below). In Scotland, some of the Rural Priority options under the SRDP address soil and water quality issues and the benefits of woodland creation, but there is a need to strengthen the linkage to WFD objectives and support the targeting of measures to failing water bodies. The intention is to deliver more focused regional priorities and one option would be to extend the use of Challenge funds to better target woodland planting for mitigating diffuse pollution.

Stronger incentives are available in other parts of Europe and have led to co-operative agreements between stakeholders to promote afforestation/reforestation for the protection of water quality. A survey by the United Nations Economic Commission for Europe and the Ministerial Conference on the Protection of Forests in Europe found over 500 designations of protection forests in Europe (MCPFE and UNECE/FAO (2003). The principle of using forests to act as protectors of the environment has been adopted across the world (Dudley and Stolten, 2003; Innes, 2004). A key example is the Three Norths Protection Forest system in Northern China, where improved agricultural planning

and a major expansion of forest cover on steep slopes susceptible to erosion has led to a reduction of up to 95% in annual soil loss (Innes, 2004). Other notable case studies are described below and considered further in the section on cost-benefit analysis.

There is a strong need for the development of an evidence base of the potential for 'protection woodlands' in UK conditions. A literature search indicates that this concept has so far been restricted to coastal forest planting associated with the stabilisation of sand dunes (Innes, 2004). Experience from overseas strongly suggests there is further scope for spatially targeted protection forestry to improve water status in the UK, as recommended by the Scottish Forest Strategy (Scottish Executive, 2006).

Case study: Denmark

Despite rapid afforestation over the past century, forest coverage in the UK is only a third of that of the EU-27 average (12% and 37% respectively; FC, 2008). Only Denmark has comparable woodland coverage, although a government pledge has been made to double the woodland area in the country (from 12 to 25%) within a tree generation (Anon, 2005). Afforestation is actively encouraged through both co-operative agreements (e.g. Aalborg, where such concepts have been in practice since 1984) and through Regional (e.g. County of North Jutland) and Municipal (e.g. City of Aalborg) Plans (Anon, 2005). The conversion of farmland to woodland (majority broadleaf) has become the most commonly adopted measure of land use change used in the protection of groundwater aquifers (Anon, 2005). In addition, there are preservation duties in place on all public financed afforestation, preventing conversion back to agricultural land.

Farm woodlands have been a point of focus and research conducted in Denmark in relation to grant uptake and spatial distribution. It would appear that whilst there is a relationship between afforestation and priority areas for groundwater protection, there is considerable fragmentation (Moller-Madsen, 2001). Observed edge effects promoting evapotranspiration and pollutant deposition, suggest that fewer, larger woodland areas may be more beneficial than numerous smaller woodlands from a water quality perspective (although the opposite is the case where woodland is being used to protect/screen vulnerable conservation sites from air pollution; see later sections).

As a consequence of a series of Action Plans (AP) imposed since the mid-1980s, Denmark has been one of the most successful countries within the EU to reduce nitrogen (N) surpluses and losses, whilst still benefiting from increasing animal production and economic gains (OECD, 2001; Kronvang *et al.,* 2008). As such, the Danish model may be a benchmark for other countries experiencing N pollution. Measures to encourage the effective use of woodland to reduce N losses were first introduced in 1998 with 'The Second Action Plan for the Aquatic Environment (AP-II)'. Subsidies to encourage afforestation on up to 20,000 ha of farmland and to establish 16,000 ha of wetlands were provided, specifically designed to reduce demand for N fertiliser and decrease nitrate leaching through denitrification. Further economic incentives for woodland and

wetland establishment were provided in the midterm evaluation of the Second Action Plan for the Aquatic Environment in 2000, alongside recognition of the importance of wetlands in reducing phosphate (P) export to water bodies (Danish government Action Plan target to halve P-balance of 32.7×10^6 kg y^{-1} by 2015). This resulted in a policy to establish 4,000 ha of wetlands and 20,000 – 25,000 ha of new woodland.

A study looking at the effectiveness of land management measures based on monitoring and modelling data revealed that nationally, the average reduction in modelled nitrate leaching within 86 catchments across Denmark between 1990 and 2003 was 33%, directly comparable with the measured decline in stream total N concentration and load. This reduction resulted from a number of different measures, including woodland expansion (Anon, 2005).

Case studies: other EU countries

In France, the bottled drinks manufacturer, Perrier-Vittel, demonstrated that reforestation in sensitive infiltration zones under the guise of protection forestry, alongside co-operative agreements with farmers, proved a cost-effective measure in the protection of French aquifers from agricultural nutrient and pesticide run-off and leaching (Johnson *et al.,* 2001). Farm woodlands are also extensive in Finland, with 95% of working farms having some woodland cover or more extensive areas of forest (Åkerman *et al.,* 2005). This is thought to be a result of government policy which actively promotes wood fuel production, with payments for the production of energy crops made at €45/ha (Agrifood Research Finland, 2006), as well as reductions in electricity prices to farmers growing energy crops. In an agro-economic analysis of willow cultivation in Poland, Ericsson *et al.* (2006) advocates this approach as a viable option for promoting integrated catchment management.

Various research programmes are supporting the development of tools to assist policy making decisions. These include the AFFOREST project (EU 5th Framework Programme for Research & Technological Development), which is developing a Decision Support Tool that considers spatial aspects of afforestation, deforestation and reforestation within the landscape with respect to reducing nitrate loss. Another is PAMUCEAF (Poplars: a multiple-use crop for surplus arable land), a completed EU project considering the environmental and economic consequences of poplar growth. The findings from both of these projects are discussed in later sections of this review.

Case study: USA

Most research on the effectiveness and design of RWBS has been conducted in the Mid-Atlantic and South-Eastern United States (Geyer *et al.,* 2003). The use of RWBS in the protection of the stream environment from diffuse pollution is well established in American Best Management Practices (BMPs). In the Chesapeake estuary (USA), the states of Maryland, Virginia and Pennsylvania formed an agreement to reduce nutrient loadings by 40% (Lowrance *et al.,* 1997). The effectiveness of RWBS for water quality

improvements was found to be site-specific, dependent on proximity of the pollutant pathway to the root zone of the established vegetation. For example, on the thin soils of the Inner Coastal Plain and Piedmont watersheds, expected reductions in total N loading in groundwater and surface run-off (and sediment loss) was in the region of 50-90%, with a lower retention of P of <25% (Lowrance *et al.,* 1997). This was in marked contrast to woodland buffers on deeper soils, which appeared to have little effect on nitrate movement to streams (Bohlke and Denver, 1995). Preliminary results from Geyer *et al.* (2003) from studies in Kansas support the assertion that RWBS can be effective as nutrient soaks for N and P. The relative effectiveness of RWBS on UK soil types, with associated differences in inputs and hydrological conditions compared to the USA, is at present largely unknown and warrants further research.

Despite no formal designation of protection forests in the UK, the potential benefits of well managed woodland for water quality have been formally recognised in the devolved forestry strategies. A rather fragmented suite of policy instruments provides support for woodland creation and appears to be contributing towards achieving targets both in terms of magnitude and species mix (including an increase in Energy Crop Scheme uptake). However, while water benefits are increasingly acknowledged in the management of financial incentives, specific financial support to secure these remains limited. Thus although the area of farm woodland continues to expand in the UK, it is largely untargeted and represents a missed opportunity to deliver better outcomes for water protection. Woodland creation and management for mitigating diffuse pollution needs to be given greater prominence in River Basin Management Plans and underpinned by stronger and targeted financial incentives in national Rural Development Programmes, including greater support for riparian woodland buffers. Further work is required to evaluate the effectiveness of woodland measures for water protection in UK environments.

Are there any circumstances where woodland can contribute to diffuse pollution? Cite examples in UK; and, What is the risk of poor woodland management compromising WFD objectives with respect to nutrient and sediment loss?

Compared to arable land or managed grassland, woodland provides a semi-permanent land cover that receives only very small (often zero) and infrequent inputs of fertiliser and pesticides, resulting in a relatively minor risk of diffuse pollution. However, it is not a panacea and the benefits for water are dependent on good woodland design and management. There are specific life-cycle stages and circumstances where commercial woodland can pose a risk of diffuse pollution, especially when involving more intensive management practices on sensitive soils. The risks are greatest for conifer forest crops on poorer upland soils, where cultivation, drainage, fertiliser and pesticide applications, road construction and harvesting are potential sources of water pollution. These are addressed by good practice measures under the Forests & Water Guidelines (FC, 2003),

including approvals of new plantations being conditionally dependent on critical load maps.

Implementation of the Guidelines has been shown to be good (Newell-Price *et al.,* 2008), although some issues remain linked to historic (pre-guideline) practice. The latter include old-style drainage practice whereby road and land drains may exceed recommended gradients and discharge sediment directly into watercourses. Another issue is the adverse impact on river morphology caused by the continued presence of first rotation conifer plantations, which were originally planted up to the banks of watercourses, without a buffer zone. These problems will be addressed in the second rotation, following clearfelling.

In Scotland, forestry is identified as a major land use pressure within the Scotland and Solway-Tweed River Basin Management Plans (SEPA, 2008). It is estimated that over 25% of Scottish lochs are at risk of failing to meet the WFD environmental objectives by 2015 due to forestry related activities (21 water bodies in total, consisting of an 'at risk area' of 170 km²) (SEPA, 2007a) and classified as sensitive to inappropriate afforestation and felling practices. A further 53 rivers (consisting of an at risk stream length of 652 km) are associated with a (statistically non-significant) threat from forestry (SEPA, 2007a). It is recommended that phased land use practices are used (e.g. phased felling) and that spatial planning is determined at a catchment scale to minimise the risk of diffuse pollution (SEPA, 2007a). Similar forestry pressures and measures are also common to upland parts of England and Wales, although the presence of woodland is generally viewed as a benefit, rather than a threat, to water body status.

The causes of diffuse pollution from forestry leading to potential non-compliance with WFD objectives are linked to a number of design and management aspects. These include:

Inappropriate site selection for afforestation, such as planting on acid-sensitive sites (Stevens *et al.,* 1994). Forestry is acknowledged to be a contributing factor in the acidification of surface waters in acid-sensitive parts of the UK. The principal way that forests affect surface water acidification is by the increased capture or 'scavenging' of acidic sulphur and nitrogen pollutants from the atmosphere by their aerodynamically rough canopies (FC, 2003). The risk of acidification is greatest for conifer forest due to their greater ability to scavenge acid deposition (Nisbet *et al.,* 1995), although Gagkas *et al.* (2008) showed that broadleaved woodland could also contribute to increased surface water acidification where woodland cover exceeds 30% of a catchment. It is estimated that 29% of acid-sensitive freshwaters in the UK receive deposition in excess of critical loads (based on 1995-97 acid deposition), although this is expected to continue to decline due to emission control (Hall *et al.,* 2004). The freshwater critical loads approach has been designed to control the acidification issue in forestry (FC, 2003).

Ground disturbance during forest establishment, harvesting and road building activities. Severe ground damage can result from forestry operations leading to increased sediment delivery, turbidity and downstream siltation (Marks and Leeks, 1998). Factors affecting the magnitude of impact include soil type, drainage and vehicle movements, as well as the presence of relic drains that discharge directly into watercourses.

Species mix/density, with high tree densities and some species casting heavy shade close to stream banks, severely reducing light penetration to watercourses. This can result in lower water temperatures and reduced in-stream productivity, as well as less river bank vegetation, increasing the risk of bank erosion and leading to wider, shallower river channels and greater siltation of spawning gravels (Broadmeadow and Nisbet, 2004; Kerr and Nisbet, 1996). Forest plans are addressing this issue by the gradual clearance of riparian conifer crops and conversion to open space or an open canopy of native broadleaved woodland.

Application of fertilisers and herbicides, with aerial applications of fertiliser to new or young conifer crops on nutrient poor upland soils presenting the greatest risk, especially within catchments draining to nutrient-poor standing waters (Nisbet, 2001; Swift, 1990). The infrequent nature of applications and strict guidelines on site suitability (e.g. proximity to watercourses and drainage ditches) and method of application (e.g. helicopter applications are strictly controlled and state-of-the-art guidance systems ensure accurate placement of fertiliser) help to minimise the risk. A study of plantation forestry in the catchment of the Clachaig Water at Muasdale in west Scotland showed that good practice measures were generally effective at protecting the freshwater environment from aerial phosphate fertiliser applications (Nisbet *et al.,* 2002). Similar findings were obtained from studies in Galloway (Lees and Tervet, 1994) and Sutherland (Nisbet, 2001). Measures are also in place to ensure that consideration is given to the impact of consecutive treatments in larger forests involving multiple owners (FC, 2003). Hand fertiliser applications present a lower risk, with the biggest threat associated with accidental contamination due to split fertiliser bags close to streams, e.g. when distributing bags across a site. Guidance on this aspect will be tightened in the next edition of the guidelines. Monitoring of a number of aerial urea fertiliser applications across Scotland indicated that application to more than 15% of a catchment area had the potential to cause ammonium concentrations in receiving streams to exceed the statutory limit of 0.78 mg NH_4-N l^{-1} for the protection of freshwater fish (Nisbet and Stonard, 1995b). This led to restrictions on the proportion of a catchment that can be treated at a given time.

Application rates of fertiliser to SRC are generally higher than to conventional forestry. Experimental results from a willow plantation showed that despite a high peak concentration of nitrate loss following fertiliser application in the establishment period

(70 mg l^{-1}, Andover soil series), nitrate losses over the whole crop rotation (average 18 mg N l^{-1}) were significantly less than a neighbouring standard arable crop rotation (winter wheat, winter wheat, winter barley, winter oilseed rape, with average leaching loss of 54 mg N l^{-1}) (Goodlass, *et al.,* 2007). These findings agree with those from other studies.

Few pesticide applications have been monitored in forests and woodlands but the greatest risk is associated with aerial insecticide applications to control major pest outbreaks (Nisbet, 2001). The main herbicide applied to forests is glyphosate at a concentration of 360 g l^{-1} and a rate of 5 l ha^{-1} once a year (May-Sept), just before replanting and for the following two years. The properties of this chemical, the method of application and use of broad buffer zones are thought to effectively control the risk of pollution. More recently, concern has been raised about the potential for pollution resulting from top-up applications of cypermethrin to control pine weevil damage on restock sites. Studies in Germany have shown run-off from cypermethrin use in forestry to have caused a number of pollution incidents (Zwick, 1992). This issue was evaluated in an intensive and extensive study of cypermethrin use in Wales in 2009, which found that the pesticide was present at potentially damaging concentrations in minor watercourses at some sites (Environment Agency, 2010). As a result, the controls on forestry practice to minimise the risk of cypermethrin spraying applications causing pollution will be further tightened in the next edition of the water guidelines. The Forestry Commission's chemical reductions policy is expected to lead to a declining trend in pesticide use in forestry and the selection of pesticides with least risk of off-site impacts (Willoughby *et al.,* 2004).

Harvesting/felling operations, which can disturb the soil and have the potential to increase water turbidity, sedimentation and acidification. Most pollution incidents resulting from forestry are associated with harvesting operations, usually linked to poor practice in timber extraction. Acidification is an issue in acid-sensitive areas, with forest harvesting having the potential to cause a short-term reduction in pH and increase in aluminium and nitrate concentrations in drainage waters (Brandt *et al.,* 2004). A study of two catchment streams in the upper Severn catchment by Reynolds *et al. (*1986) found that the harvested Hafren stream had double the nitrate concentrations of the moorland Gwy stream. In another study involving a Sitka spruce stand on wet, gleyed soils in North Wales, short-term fluxes of inorganic-N through the C horizon increased following felling from 10 to 70 kg N ha^{-1} yr^{-1}, levels comparable to leaching losses from intensive lowland agricultural systems (Stevens and Hornung, 1988).

Typically, cumulative N losses directly attributable to the effects of clearfelling in upland catchments are lower than from lowland agriculture at c. 20 kg N ha^{-1} in the 3-4 year post-felling period (Krause, 1982; Stevens and Hornung, 1990). The harvesting method itself is a factor influencing the extent of N losses. Conventional harvesting practice,

removing only the bole and leaving behind brash residues, can lead to increased mineralisation and nitrification rates, resulting in enhanced leaching in the short term (Silgram and Shepherd, 1999; Silgram *et al.,* 2005). Results by Titus and Malcolm (1992) showed that clearfelling led to higher leaching losses for nitrate when brash swathes were retained. However, losses were lower than those reported in the literature, with nitrate outputs less than inputs.

Clearfelling also presents a risk of phosphate contamination of watercourses. Soil type is a key factor with clearfelling on peaty soils most at risk of phosphate leaching (Cummins and Farrel, 2000).

Neal *et al.* (1998) undertook intensive and extensive studies of the impact of conifer harvesting across upland Wales and found variability in response attributed to differences in soil type and underlying geology. Good practice measures were found to be effective in controlling impacts, with a key measure being the need to constrain the proportion of an acid sensitive catchment felled within any three year period to <20%.

Felling and thinning of lowland broadleaved woodland can also enhance nitrate leaching losses to drainage waters but the impact is limited by the normal small scale of harvesting operations. Nitrate concentrations are generally much lower in groundwater beneath broadleaved woodland compared to lowland agriculture (Lilly *et al.,* 2001). The same relationship does not apply to lowland conifer forest in dry regions due to an evapo-concentration effect (Calder *et al.,* 2002).

The multinational research project, Water4All (Anon, 2005), proposed specific woodland management strategies for reducing nutrient losses from woodland to groundwaters, including:

- Alternatives to clearfell such as selection or group felling to promote continuous cover forestry and an increased diversity in tree age, light level and ground cover to maintain nutrient uptake.
- Promote natural regeneration to reduce the need for site cultivation and soil disturbance.
- Extend whole-tree harvesting to maximise nutrient removal on nutrient-rich sites.

Aside from the issue of the efficacy of the Forests & Water Guidelines, concern has been raised about monitoring of compliance and enforcement actions in situations where there has been failure to follow BMPs (IEEP, 2002). Most examples of non-compliance are associated with harvesting operations and sediment delivery, although these tend to be of relatively short duration and few in number (FC, 2008). Long term studies in Plynlimon have shown that progressive felling (harvesting and replanting operations affecting two-thirds of the forest over 19 years), resulted in very little impact on

streamwater quality (Neal *et al.,* 2004). Marks and Leeks (1998) found relatively few examples of sediment pollution in their review of reported pollutant incidences across England and Wales. Cited examples of poor forestry management causing diffuse pollution related to:

• **Forest road construction** on the Afon Rhyd (N Wales): Culvert construction across a stream led to silt contamination at a local treatment works (total suspended solid concentrations were recorded at 7580 mg l⁻¹) and disruption to the public water supply for two days.

• **Harvesting operations** using cable cranes: several examples were reported where logs had been allowed to drag along the ground surface during timber extraction, resulting in serious soil erosion and sediment loss. This was exacerbated when the timber had been dragged through watercourses causing changes to stream morphology.

• **Management of clearfelling operations** in a windblown area in SW Wales: skidding of felled timber caused the collapse of a culvert where an access road crossed a small tributary. The culvert became blocked and resulted in large inputs of particulate sediment into the watercourse and stream discolouration, which in turn raised concerns over fish health at a trout fishery further downstream.

Marks and Leeks (1998) found the most significant cause of ground damage to be due to insufficient brash cover on access routes for timber extraction. In one case at a site on the River Edw in Wales, this resulted in (i) discolouration of the river and its confluence with the River Wye (14 km downstream); (ii) high suspended solid concentrations (91 mg l⁻¹ at a point 5 km downstream of source) and (iii) siltation of the river bed at a level likely to present a significant threat to the ecology of the watercourse. Recommendations to the contractors to reduce sediment pollution included phased construction of access roads, construction of additional drains and silt traps and increased use of brash matting. These points were incorporated into the previous review of the Forests & Water Guidelines (FC, 2003). The risk of serious pollution resulting from non-compliance will always remain but regular review of the Guidelines, training updates and awareness raising should help to minimise the number of incidents.

Certain forestry management operations have the potential to increase the risk of diffuse pollution to water. In contextualising the scale of diffuse pollution from forestry, 25% of lochs in the Scotland River Basin were found to be potentially affected by forestry related activities. Similar forestry pressures apply to upland parts of England and Wales, although the presence of woodland is generally viewed as a benefit, rather than a threat, to water body status. Causes of diffuse pollution include inappropriate site selection and species mix/density, fertiliser and pesticide applications, and harvesting/felling operations. Applications of pesticide and fertiliser are already carefully targeted and controlled, and there exists little evidence to suggest widespread negative impacts.

Clearfelling represents a major disturbance and can pose a number of threats to water quality, but studies indicate that these can be minimised with careful management. The evidence indicates that broadleaved woodland generally protects water quality and is not a significant source of diffuse pollution. There are various examples of successful implementation of the Forests & Water Guidelines to control diffuse pollution, which are well reported in the literature. A small number of cases are reported each year of non-compliance causing diffuse sediment pollution, primarily associated with harvesting and road operations. Interpretation of any single incident must be treated with caution and contextualised. The risk of serious pollution resulting from non-compliance will always remain but regular review of the Guidelines, training updates and awareness raising should help to minimise the number of incidents.

3.2.1 Acid deposition

Can woodland help to protect water quality and/or associated biodiversity from harmful affects of deposition?

The 1989 Gothenburg Protocol set emission reduction targets for 2010 for sulphur dioxide (SO_2), nitrous oxides (NOx), ammonia (NH_3) and volatile organic compounds (VOCs) to abate acidification, eutrophication and ground-level ozone. In accordance with this protocol, UK emissions for SO_2, NOx, and NH_3 have fallen by 82%, 46% and 81%, respectively, since 1990 (2006 estimates reported by AEA Energy and Environment and published by Defra, 2009). However, it has been suggested that even if the Gothenburg Protocol and EU National Emissions Ceilings Directive targets are met (set at 297 kt NH_3 yr^{-1}), 49% of UK ecosystems (by area) will receive atmospheric N deposition in excess of the critical load for nitrogen eutrophication (Sutton *et al.,* 2004). Agricultural sources of ammonia contribute the vast majority (91%) of the current emission total of 315 kt NH_3 yr^{-1} and pose a challenge for emission reduction policy (Defra, 2009).

Emission and deposition of atmospheric ammonia to ecosystems is highly spatially variable. Emissions arise primarily from livestock farming and can be a threat to the biodiversity of natural and semi-natural habitats (Sutton *et al.,* 2004). Technical methods of reducing ammonia emissions are expensive and are limited in their effectiveness (Cowell and ApSimon, 1998). Patterns of N deposition are dependent on a number of factors, including rainfall (e.g. greater wet deposition in areas of high orographic rainfall), oceanic influences (e.g. the strength of the North Atlantic Oscillation (NAO) affecting transportation), and land use (deposition is greater to woodland compared to shorter vegetation). Recent work suggests that the latter factor could be exploited to protect at-risk conservation sites or water supplies from nitrogen deposition (Sutton *et al.,* 2004).

Carefully sited, sacrificial planting of woodland could be used to improve air quality for the benefit of downwind locations, or to encourage N deposition in areas that are less at risk from acidification and/or diffuse pollution to water. An example of this approach is

the spatial targeting of woodland around pig farms to reduce the high level of local ammonia emissions (Figure 1). The utilisation of spatially targeted woodland as a mitigation measure can be more efficient than conventional abatement techniques and may provide significant cost benefits (Sutton *et al.,* 2004). Woodland design, including size, shape and species mix, affect the efficiency of pollutant capture and therefore can be used to control the level of buffering provided and the risk of diffuse pollution reaching watercourses.
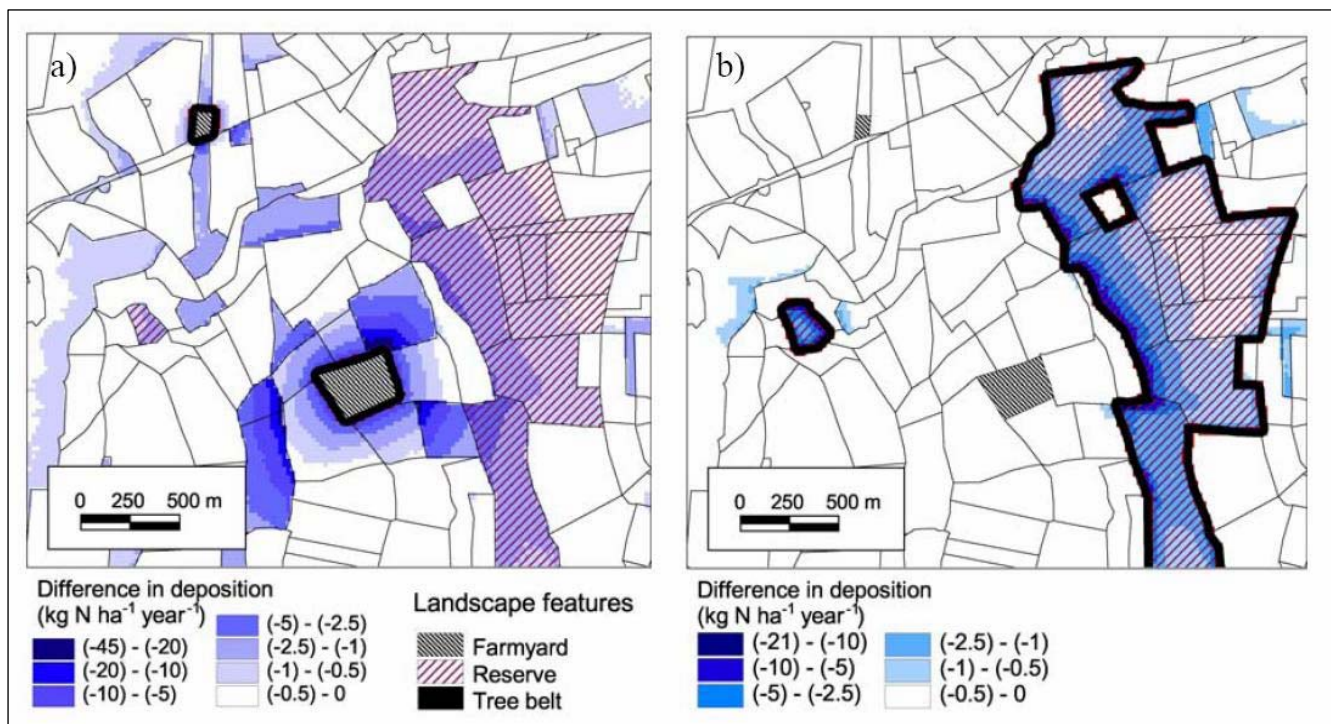
Figure 1. Woodland can be very efficient at capturing and removing pollutants from the atmosphere. Maps show model predictions for the effectiveness of a 50 m wide woodland strip placed either (a) around a farm or (b) around a nature reserve in reducing downwind ammonia deposition (From: Sutton *et al.,* 2004). © International Association for Landscape Ecology (UK).

Tree shelterbelts around farms can help capture ammonia emissions at source (e.g. from animal houses or manured and fertilised fields), while the turbulence created by their canopies can reduce deposition to the immediate surroundings. Maximising the benefits of such a scheme may include specific design considerations including:

- **Enterprise**: agroforestry can be particularly effective at reducing local pollutant emissions (Theobald *et al.,* 2004).
- **Species selection**: the scavenging capability of woodland is dependent on species type and the level of canopy closure. Prusinkiewicz *et al. (*1990) found that shelterbelts made up of mixed tree species (enhanced diversity) such as oak,

birch and pine took up nitrogen more effectively than single species woodland, while an open canopy (e.g. with more young trees) promoted greater air throughflow and associated scavenging.

- **Shape/structure**: an open canopy understorey can be better for woodland located immediately adjacent to the source, but a dense canopy understorey at the downwind edge is best for forcing polluted air through the main tree canopy.
- **Size**: wider strips of woodland appear to be more efficient for pollutant capture, with 2.1% of NH_3 recaptured from a 2 m high source and 10 m high trees at 5 m distance, compared with 7.1% recapture for a 60 m wide belt of trees (Theobald *et al.,* 2001, 2004). A series of small woodlands provides better protection for vulnerable sites compared to a few large woodlands because of the increased fraction of edge to disrupt airflow and promote deposition. Additionally, this concept may offer more flexibility in landscape planning, with the option of placing tree shelters/buffers either outside (e.g. bordering farmland) or inside the boundary of the designated area.
- **Location**: priorities for protection include SSSIs and SACs. Skiba *et al. (*2004) found that deposition downwind of pig and poultry farms was dependent on a number of factors, especially soil type. In existing mature woodland stands, responses may also be site specific, with Emmett *et al. (*1998) reporting that changes in N leaching losses with increased NH_4-N deposition were dependent on the N status of the soil-plant ecosystem.

Although scavenging of atmospheric pollutants by woodland can be an attractive option, care is required to ensure that the enhanced deposition to woodland does not result in pollution swapping and an increased risk of nitrate leaching and diffuse water pollution. For example, Forest Research data shows annual nitrate leaching losses of 1-3 kg N ha^{-1} from lowland and upland oakwoods in Wiltshire and Cumbria, 2 kg N ha^{-1} from young Sitka spruce in Perth and Kinross, 15 kg N ha^{-1} from upland, over-mature Scots pine in a high N deposition area in Derbyshire, and as much as 24 kg N ha^{-1} from a lowland site with Scots pine adjacent to an intensive pig farm at Thetford in East Anglia (Vanguelova *et al*. 2010).

Theobald *et al. (*2004) suggest that the benefits of woodland for ammonia abatement could be incorporated into the scoring system underpinning FC England's Woodland Creation Grant Scheme, thereby rewarding the farmer and encouraging uptake of this measure. A similar idea to that of using sacrificial planting for ammonia abatement is the spatial targeting of woodlands in urban air quality planning for the reduction of particulate matter concentrations (PM10) (Bealey *et al.,* 2007).

There is evidence to suggest that atmospheric deposition of pollutants such as NOx, NH₃ and SO₂ is greater to woodland compared to shorter vegetation. Recent work has shown that small but wide shelterbelts around pollutant sources (e.g. livestock rearing units) or

sensitive receptors (e.g. designated conservation sites) could be used to enhance local pollutant capture and protect vulnerable sites. More research is required to test the wider application of this approach using different tree species and stand structures. However, care is required in site selection to avoid locations where the enhanced deposition could threaten local water bodies.

How significant a problem is the contribution of enhanced deposition to woodland to diffuse pollution in the context of WFD objectives? and, What is the risk of woodland creation contributing to a decline in water quality through enhanced scavenging and diffuse pollution?

Forestry is acknowledged to be a contributing factor in the acidification of surface waters in acid sensitive parts of the UK. The principal way that forests affect surface water acidification is by the increased capture or 'scavenging' of acidic sulphur and nitrogen pollutants from the atmosphere by their aerodynamically rough canopies (FC, 2003). The critical loads approach is used to identify freshwaters at risk of acidification and all new forest planting and restocking within or adjacent to exceeded areas require an assessment of the susceptibility of local waters to a forest scavenging effect before plans are approved (Figure 2).

The effect of woodland creation on the scavenging of atmospheric pollutants can be split into three main stages:

•   Establishment, characterised by low scavenging due to limited canopy coverage and low tree height;
•   Growth/development phase, when scavenging reaches a maximum post canopy closure and as canopy increases in height, although N leaching risk is relatively low due to high crop demand; and
•   Mature/old-age phase, when scavenging remains high and N leaching risk increases due to reducing N demand.

The timing and duration of these stages varies with woodland type, with broadleaved woodland being the slowest to mature. Conifers typically reach canopy closure at age 15-20 years (Nisbet *et al.,* 1995) and therefore the size of the scavenging effect for a newly planted conifer forest will be dependent on the nature of the future pollution climate. The lower scavenging ability of broadleaves compared to conifers and longer time to reach canopy closure means that this type of woodland creation is less likely to contribute to freshwater acidification. Possible exceptions could include large-scale planting within acid-sensitive catchments, woodlands sited immediately downwind of emission sources, and planting schemes involving more productive species at a higher density, such as under Short Rotation Woodland (SRW) systems. These aspects are best addressed on a site by site basis as part of the normal assessment of environmental impacts accompanying grant applications for new woodland.
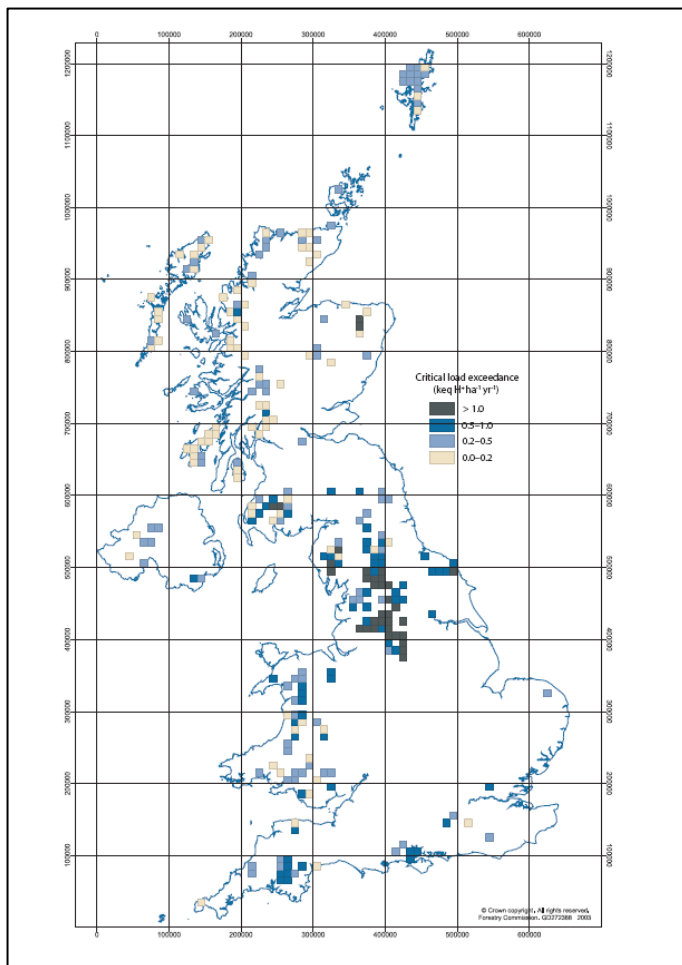
Figure 2. The freshwater critical loads exceedance map is used to identify areas at risk from the enhanced capture of acid pollutants from the atmosphere by forest canopies (based on 1995/97 acid deposition) (from Forestry Commission, 2003).

The use of the critical loads methodology for assessing the threat of acidification by forestry has received some criticism (Skeffington *et al.,* 2007). A comparison of observed versus predicted acid sensitivity based on critical loads showed agreement in only 65% of cases (n=84), i.e. 20 sites were predicted as sensitive where Acid Neutralising Capacity (ANC) data suggested they were not, while 15 sites predicted as non-sensitive were observed to be acid-sensitive (Short and Merrett, 2001). However, this assessment did not address the precautionary approach adopted by the Forests & Water Guidelines (Forestry Commission, 2003) in basing the critical loads assessment on high flow streamwater samples, when conditions tend to be at their most acidic. The critical loads approach is being re-evaluated in the ongoing revision of the Guidelines in light of WFD requirements and concerns over mismatches between critical loads exceedance and fish population status in certain acid-sensitive catchments in Galloway.

It is widely acknowledged that acid deposition is the primary cause of surface water acidification. This has led to a range of policies being introduced over the last twenty years aimed at achieving significant reductions in pollutant emissions. UK emissions of sulphur dioxide have declined substantially (by 89%) since their peak in 1970, reducing from 6,370 kt to 706 kt by 2005. There has also been a significant reduction (48%) in UK nitrous oxide emissions from 3,130 kt in 1970 to 1,627 kt in 2005, while emissions of ammonium have declined by a smaller margin (17%) from 383 kt in 1970 to 318 kt in 2005 (Defra, 2007b).

On a national scale, deposition of non-marine sulphate has followed that of emissions, declining by 60% between 1987-2001 compared to a 70% decline in emissions during this period. The decline in measured nitrogen deposition has been smaller, ranging from 50% for dry deposition of nitrogen dioxide to little change in wet deposition of oxidised nitrogen and total deposition of reduced nitrogen. Concerns regarding the impacts on water quality from enhanced acid deposition by forests have therefore lessened in recent years. However, some water bodies are likely to remain at risk for some time due to localised high deposition resulting from factors such as altitude and aspect, as well as N status (Short and Merret, 2001). Areas above 300 m are thought to be at greatest risk due to the increased duration of cloud cover and capture of occult deposition. Continued restrictions on the scale of forest cover above this altitude may be required until further reductions in pollutant emissions are realised.

Emission control policies appear to be succeeding in promoting the continued chemical recovery of acid-sensitive waters across the UK, although there is scope for further improvement as emissions continue to decline and soils re-equilibrate to a lower pollution climate. Long-term monitoring studies show evidence of significant and rapid chemical recovery across most sites (UKAWMN, 2010). Evidence of biological recovery is weaker and more variable, which is not unexpected in view of lag effects, including the continued impact of acid episodes and slow recolonisation, especially where populations have been lost or barriers affect species migration. Many sites have undergone slight but significant biological change involving the appearance or increased abundance of some acid-sensitive, epilithic diatom and macroinvertebrate species, consistent with the observed improvement in water chemistry. A comparison of paired forest and moorland sites shows that the forest streams tend to have higher acid anion concentrations and remain more acidic. However, despite being more impacted by acid deposition, the chemical time series do not reveal any major dissimilarity in recovery between forest and moorland streams.

The results from other acid water monitoring studies are in line with those of the UKAWMN. For example, long-term monitoring since 1991 of ten forest and two moorland catchment streams in upland Wales by the Forestry Commission and the Environment Agency, shows a significant decline in non-marine sulphate at all sites and a significant

rise in pH, alkalinity and alkalinity-based ANC at around half the sites (unpublished data from FC and EA; Figure 3). Similarly, a study of 37 stream and loch sites across 4 regions of Scotland by Harriman *et al. (*2003) found evidence of significant chemical and some biological recovery between 1976-2000. They concluded that both forest and moorland streams showed generally similar and rapid responses to reductions in pollutant deposition.
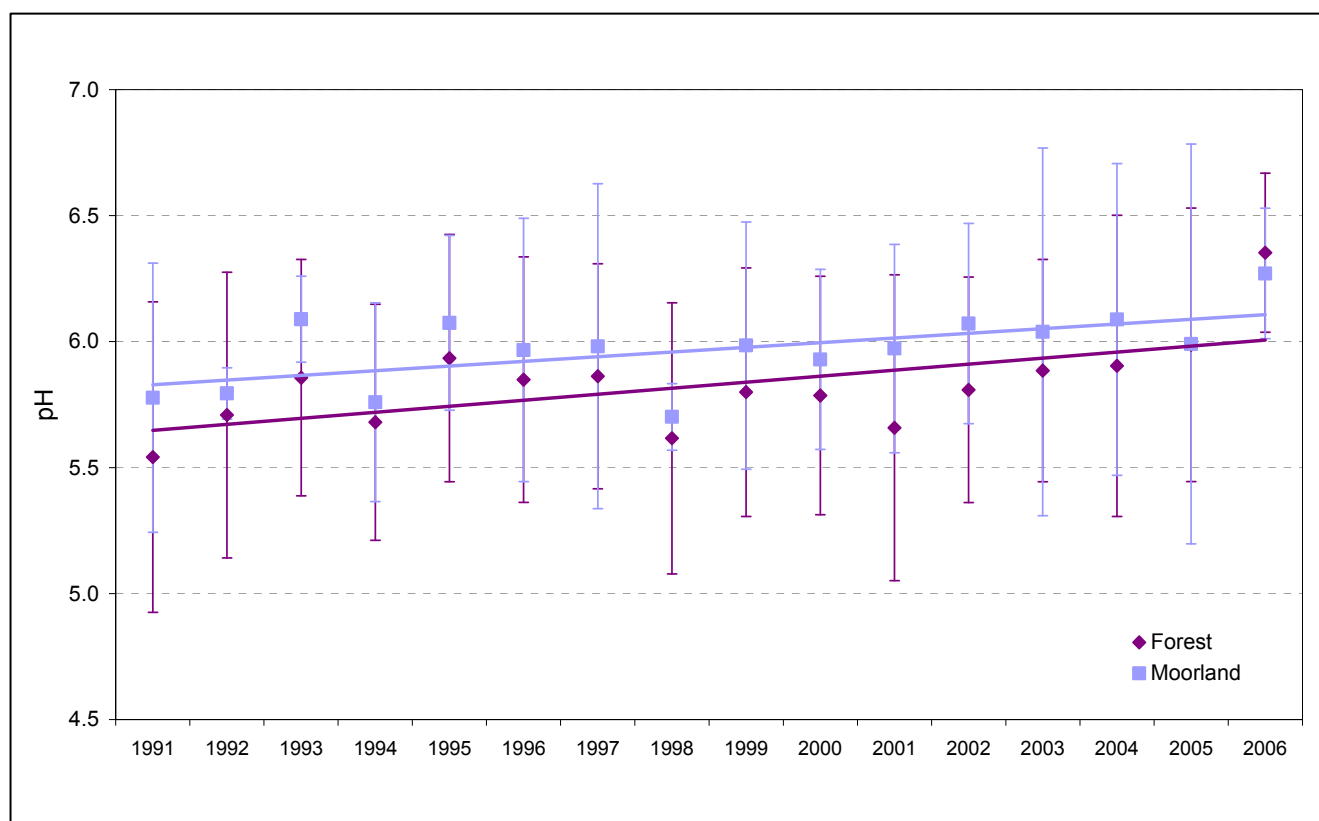
Figure 3. Acidified streams draining forest and moorland catchments appear to be recovering at similar rates in response to ongoing emission reductions, suggesting that existing measures may be controlling the contribution of forestry to acidification. Plot compares the mean response of stream pH in ten forest and two moorland, acid sensitive catchments in upland Wales (unpublished data from FC-EA acid water monitoring network).

Ferrier *et al. (*2001) found clear evidence of chemical recovery in nearly all of the studied 48 forest and moorland lochs in the Galloway Region in south Scotland, based on repeated water quality surveys between 1979 and 1998. The results suggested that approximately 75% of the possible improvement in ANC had already occurred during this 20-year period. Evidence of recovery was also obtained by Helliwell *et al. (*2001) in their assessment of water chemistry changes between 1984-99 in the Rivers Cree, Bladnoch and Luce in Galloway.

While Scarr *et al.* (2002) found weak evidence of chemical recovery in forest and moorland streams at Llyn Brianne in mid Wales, a more recent assessment of the longer-term data by Ormerod and Durance (2009) identified a clear recovery signal. Reductions in winter acidity in terms of hydrogen ion concentration were broadly similar in acid forest and moorland streams over the 25-year study period, although aluminium concentrations only declined in the moorland streams. The forest streams remained too acid to support acid-sensitive invertebrates, while there was some evidence of recovery in acid moorland streams.

Reynolds *et al.* (2004) found stronger evidence of chemical recovery in Beddgelert Forest in north Wales. An assessment of 18 years of data (1982-2000) for three forested and one moorland stream showed that while the forest streams remained more acidic, all displayed a similar increase in pH (0.5 units), although there was a greater decline in hydrogen ion concentration in the forest streams. The recovery trends in acidity related variables were considered to be similar in catchments under moorland, mature forest and within partially clearfelled/restocked forest.

These results provide good evidence of continuing chemical recovery and encouraging signs of some biological recovery in acid-sensitive waters across the UK. However, further monitoring is essential to demonstrate that sustainable forest management underpinned by best practice measures in the Forests & Water Guidelines is controlling the contribution of forestry to acidification and will continue to do so in the future. Since forest streams tend to be more impacted by acid deposition and thus more acid than moorland ones, the time scale for achieving a chemical status capable of supporting acid-sensitive species may be longer. This has implications for the achievement of WFD objectives.

Opportunities exist for promoting native riparian woodland as a means of aiding the biological recovery of acidified waters. The clearing back of dense conifer shading and opening out of streamsides has been shown to greatly enhance aquatic and riparian habitats (Broadmeadow and Nisbet, 2002). There is therefore a reasonable expectation that the targeted clearance of riparian conifer stands casting heavy shade could aid upstream fish migration and the biological recovery of streams showing chemical improvement in response to ongoing emission reductions.

One area of remaining uncertainty is the longer-term effects of atmospheric N deposition and the possibility of increased breakthrough of nitrate due to nitrogen saturation (Dise *et al.,* 1998; Curtis *et al.,* 2005). Nitrogen deposition continues to exceed soil acidity and nutrient critical loads in many parts of the country and there is a concern that this could lead to increased leaching of nitrate. Nitrate breakthrough would promote acidification and possibly reverse recent trends in streamwater recovery. Woodland management has an important role to play through its affect on nitrogen release by soil disturbance,

uptake by tree growth and removal in harvested products. Concern has been raised that the amount of N retained within woodland biomass and soils remains high and potential future disturbance such as due to clearfelling could lead to nitrate release and pose an increased risk of acidification (Tietema *et al.,* 1997).

The ability of forest stands to take up N is related to growth demand and therefore forest productivity (Turner, 1977). In the early stages of forest development, nutrient accumulation in biomass is high as foliage and roots develop. N increment rates in woody tissue peak at canopy closure and remain stable for a prolonged period (until maturity), but rates of N uptake then characteristically decrease (Miller, 1981) potentially leading to increased N leaching. Experimental evidence by Stevens *et al. (*1994) showed that nitrate concentrations in soil water increased in ageing stands. Accompanying results from streamwaters bordered by stands of different ages also appeared to show a similar relationship. This agrees with other catchment studies that have found higher nitrate concentrations in streamwaters draining older, mature conifer plantations, and that seasonality in concentrations can increase with conifer age (Reynolds *et al.,* 1994; Stevens *et al.,* 1993; Hornung *et al.,* 1987). The drive to diversify forest age and species structure could therefore potentially promote acidification by increasing the extent of older-aged forest stands. However, this is more of an issue for the design and management of existing forests rather than for woodland creation. Climate change is likely to exert an impact by affecting N uptake, soil N availability and leaching rates (Nisbet, 2002).

Relatively little research has considered the effects of tree age on N losses from broadleaf woodland. A study by Gagkas *et al. (*2008) found a relationship between percent broadleaved woodland cover and nitrate and aluminium concentrations within streams draining acid-sensitive areas, but was unable to assess the effect of forest age. Instead, there was evidence of a significant species effect, with the relationship dominated by catchments with a high percentage cover of alder. Alder is a N-fixing species and thus more likely to promote nitrate leaching due to N supply exceeding demand, especially in areas receiving moderate to high N deposition.

The concept of a critical C:N threshold defining the point of saturation has been included in a number of simple models of N leaching losses in forests, including PnET, SMART, MAGIC and VSD (Rowe *et al.,* 2006). However, most of these rely on simple N breakthrough functions and Emmett *et al. (*1997) has highlighted the need to develop more sophisticated models of N dynamics. Kros *et al. (*2004) found that soil type, tree species, N deposition, forest area and tree height were all significant explanatory variables for patterns in soil solution nitrate concentration. Rowe *et al. (*2006) found that grassland and deciduous woodland began leaching at relatively low C:N values compared with heathland and coniferous woodland, which could suggest that woodland types differ in their sensitivity to atmospheric N deposition. These differences are supported by other

European observations by Gundersen *et al. (*1998). Evidence of nitrogen saturation in the UK and elsewhere, however, remains patchy and the subject of continuing research. For example, a rapid and large reduction in drainage water N content was observed in the Dutch and German atmospheric N reduction experiments within the NITREX project (Bredemeier *et al.,* 1998), suggesting that any reduction in emissions should lead to immediate benefits in terms of water quality.

Forestry is acknowledged to be a contributing factor in the acidification of surface waters in acid sensitive parts of the UK due to the enhanced scavenging of acid deposition. The critical loads approach is used to identify freshwaters at risk and all new forest planting and restocking within or adjacent to exceeded areas require an assessment of the susceptibility of local waters to this effect before plans are approved. International agreements have resulted in major declines in pollutant emissions and acid deposition since the 1970's and emission control policies appear to be succeeding in promoting the continued chemical recovery of acid-sensitive waters. Evidence of biological recovery is weaker and more variable. Despite being more impacted by acid deposition, long-term monitoring studies do not reveal any major dissimilarity in chemical recovery between forest and moorland streams.

As the extent of critical loads exceedance reduces in line with declining pollutant emissions and deposition, the risk of pollutant scavenging by woodland creation contributing to exceedance and water acidification will continue to lessen. Areas above 300 m are thought to be at greatest risk due to the increased duration of cloud cover and capture of occult deposition. Continued restrictions on the scale of conifer forest cover in at-risk catchments may be required until further reductions in pollutant emissions are realised. The lower scavenging ability of broadleaves compared to conifers and longer time to reach canopy closure means that this type of woodland creation in general is much less likely to contribute to future freshwater acidification. Possible exceptions could include woodlands sited immediately downwind of emission sources and involving more productive species and higher density planting, such as for SRW systems.

Continued monitoring is essential to demonstrate that sustainable forest management underpinned by best practice measures in the Forests & Water Guidelines is controlling the contribution of forestry to acidification and will continue to do so in the future. One outstanding issue is the impact of N deposition and the threat of nitrogen saturation. Since forest streams tend to be more impacted by acid deposition and thus more acid than moorland ones, the time scale for achieving a chemical status capable of supporting acid-sensitive species may be longer. This has implications for the achievement of WFD objectives.

3.2.2 Nutrients

Is there a role for woodland on land that is more susceptible to nitrogen loss?
In 2004, nitrogen losses from agricultural land were estimated to account for 61% of the nitrate entering surface waters in England and Wales (Defra, 2004). Increasing nitrate concentrations across Europe have been linked to increasing proportions of arable land upstream of surface measurement gauges (EEA, 2004). Relative proportions of N losses from woodland (particularly lowland deciduous) are expected to be much lower e.g. modelled N-losses from forestry accounted for only 1.2% of total N-losses in Scotland in 2004, compared to an estimated 73.5% from agriculture (Anon, 2006). The relative contributions of different sources to N and P concentrations and loads in the Yorkshire Ouse were modelled in the EU EUROHARP project (Silgram, 2007; Silgram *et al.,* 2008) using the ADAS EveNFlow model. The results suggested that when combined, all non-agricultural sources accounted for less than 10% of the riverine N load, with the majority of that being associated with inputs from upload moorland rather than from woodland.

Spatial targeting of woodland to reduce nitrogen losses has received recent research interest at a national scale in programmes such as AFFOREST and other GIS based projects concerned with catchment planning. Land conversion to farm woodland or SRC has the potential to substantially reduce N losses relative to conventional arable or grassland. For example, annual mean N leaching losses for woodland in the Marlborough catchment in Southeast England were estimated to be less than a sixtieth of that for arable (26.4, 15.5 and 0.4 kg N ha⁻¹ yr⁻¹ for arable, grassland and woodland, respectively) based on a modelling study (SHETRAN) by Koo and O'Connell (2006).

Silgram (2005) compared nitrate leaching losses between fields in the Nitrate Sensitive Areas (NSA) scheme, which ran from 1989-2003, with reference areas in adjacent coniferous and deciduous woodland of differing ages and species composition (Figure 4). Based on 60 site-years of data, mean annual leaching losses for agricultural fields subject to strict NSA rules limiting N fertiliser applications, were 40 kg ha⁻¹ for winter cereals, 48 kg N ha⁻¹ for oilseed rape, 66 kg N ha⁻¹ for potatoes and 17 kg N ha⁻¹ for woodland. The latter value is consistent with the results reported in the wider literature for woodland, which typically lie in the range 0-24 kg N ha⁻¹ yr⁻¹.

Using the above data, Silgram *et al. (*2005) recommended that the annual nitrate pool potentially available for leaching (incorporated within the NEAP-N model embedded into the ADAS MAGPIE system (Lord and Anthony, 2000)) should be 6-8 kg N ha⁻¹ for most lowland woodland and for upland woodland where atmospheric N deposition is <20 kg N ha⁻¹. This pool increases to 15 kg N ha⁻¹ for lowland woodland close to pig, poultry, dairy or industrial units, for upland woodland where atmospheric N deposition is >30 kg N ha⁻¹, and for conifer stands >30 years old. These values are comparable with ranges of 2.9-15 kg N ha⁻¹ yr⁻¹ for unimproved grassland and 0.7- 22.6 kg N ha⁻¹ yr⁻¹ for

wetlands. The results of the NSA scheme suggest that agricultural land management practices alone will be insufficient to meet good water status and targeted land use change will need to be considered. In view of the modest anticipated impacts of the recently revised Nitrate Vulnerable Zone (NVZ) measures reported under the public consultation process in 2008, such conclusions, which infer the need for increases in (and targeting of) woodland areas, remain valid today.
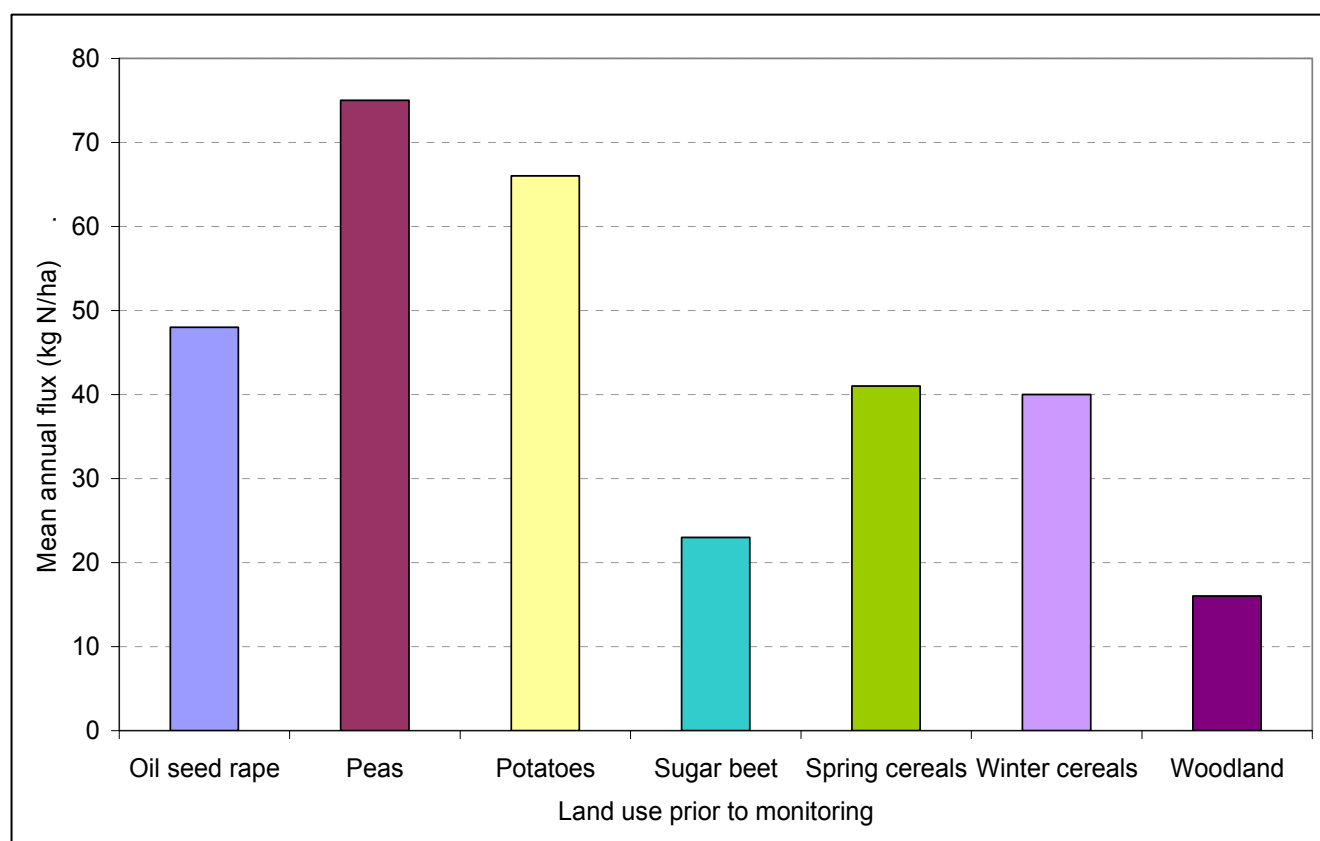
Figure 4. Over-winter nitrate leaching is significantly lower beneath woodland compared to following a range of arable crops (From Silgram *et al.,* 2005).

Land use change from arable farming to woodland will induce major changes in the nitrogen cycle (Compton *et al.,* 1998; Jussy *et al.,* 2002; Koerner *et al.,* 1999). Simulations of land use change in the Netherlands (Rijtema and de Vris, 1994) and afforestation in a Danish catchment (Bastrup-Birk and Gundersen, 2004) showed substantial reductions in nitrate leaching where land had been converted to woodland. Furthermore, in a study of nine afforested sites in Denmark, nitrate concentrations reduced substantially over a 10 year establishment period (Hansen *et al.,* 2004; Vesterdal *et al.,* 2002) (Figure 5).
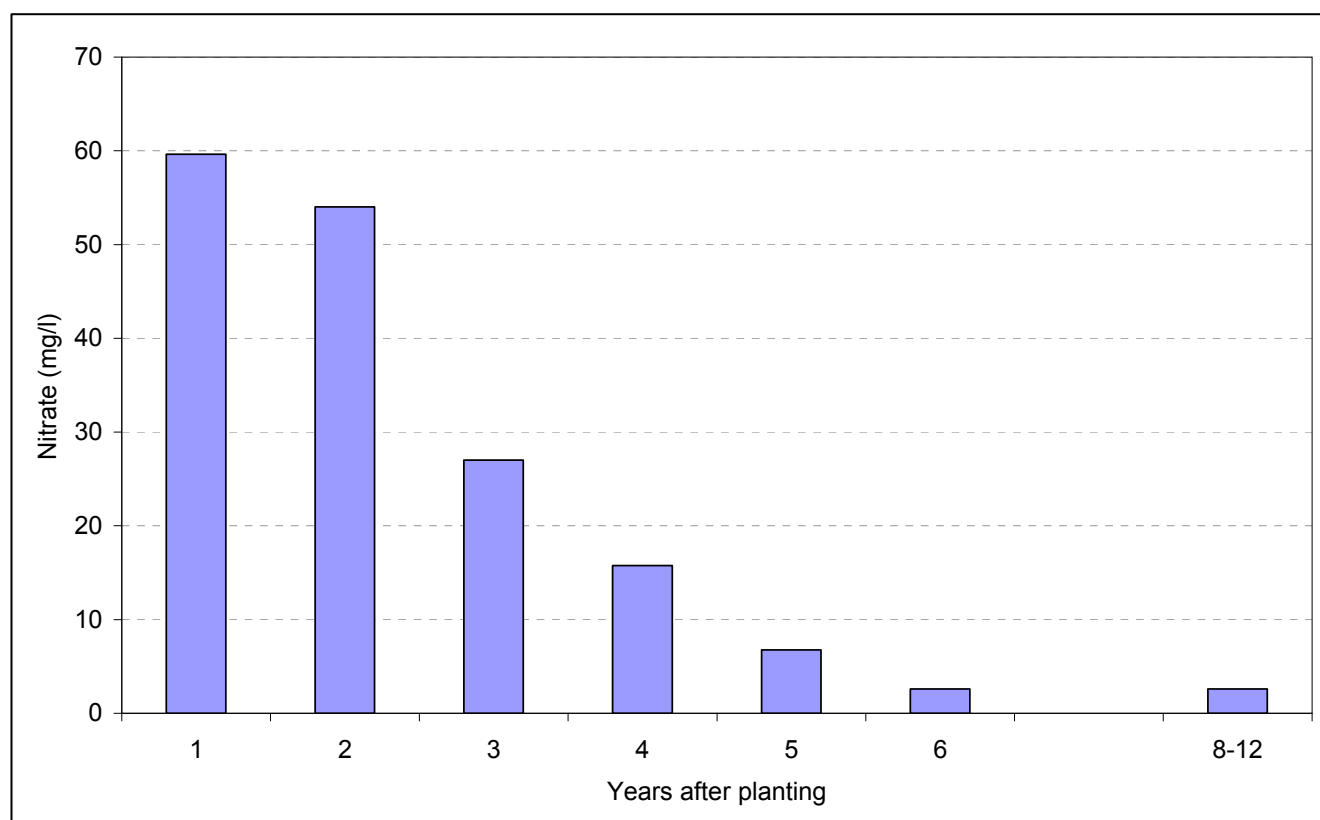
Figure 5. Woodland planting can be very effective at reducing nitrate levels in groundwater. Plot shows the average response in nitrate concentrations in drainage water at 75-90 cm depth in the soil following afforestation of former arable land at nine sites in Denmark (from Hansen *et al.,* 2004).

There is evidence to suggest that N loss from poorly drained soils can be reduced through afforestation (e.g. Addy *et al.,* 1999). Woodland planting has also been suggested as an effective measure to reduce nitrate leaching from well drained sandy soils, where agricultural production is reliant on recurrent, large N fertiliser inputs due to the inherently nutrient-poor status of these soils (SNH, 2009). A number of long-term investigations in Poland have shown woodland biogeochemical barriers (woodland strips/tree shelterbelts) to be effective at reducing nitrate leaching from adjacent fields (Ryszkowski *et al.,* 1999) and thereby exerting a purification effect on the chemistry of groundwaters (Cooper *et al.,* 1987; Bartoszewicz, 1990; Bartoszewicz and Ryszkowski, 1996; Ryszkowski and Bartoszewicz, 1989; Ryszkowski *et al.,* 1997, 2002; and Ryszkowski, 2000), as well as helping to protect crops from wind and advective frosts, control erosion, conserve moisture and provide shelter for livestock (Ryszkowski and Kędziora, 2007). Concentrations of nitrate in groundwater within shelterbelts, or pine and birch woodland patches, adjacent to cultivated fields were reduced by 76-98% of the input. The efficiency of N removal by shelterbelts was found to be influenced by woodland age, width of strip, season and depth to water-table (Ryszkowski and

Kędziora, 2007). One exception concerns the use of alder, which is a nitrogen-fixing species and therefore more likely to promote nitrate leaching due to nitrogen supply exceeding demand, especially in areas receiving moderate to high nitrogen deposition.

The AFFOREST project features the development of a Decisions Support System (DSS) tool to aid planning decisions. The tool can optimise on a number of different objectives, one of which is the minimisation of nitrate leaching risk (Gilliams *et al.,* 2005). A literature search failed to uncover an actual application of the spatial tool for woodland planning, but in principle this tool could be evaluated in a future UK-based demonstration project.

Short-term (1-5 years) enhanced N losses can occur from forests and woodlands as a result of soil disturbance accompanying woodland establishment (Atkinson, 1989) or due to tree felling or windblow (Stevens and Hornung, 1988; Harding *et al.,* 1992). However, the impact of such perturbations is relatively small over a complete forest or woodland rotation and is further limited by the generally localised nature of these effects. One case where forests may not yield a nitrogen benefit is where conifers are planted in dry regions of the country. A study by Calder *et al. (*2002) found that the high water use of such forests led to a disproportionately large concentrating effect with the result that nitrate concentrations in groundwater were similar to those draining arable crops (Figure 6). The Forest & Water Guidelines address this risk by recommending that large-scale conifer planting should be avoided within Nitrate Vulnerable Zones receiving <650 mm annual rainfall.

Spatial targeting of woodland to reduce nitrogen losses has received recent interest in research programmes such as AFFOREST. Land conversion from arable land to farm woodland and SRC appears to have significant potential for limiting N losses. Within farms, there is evidence to suggest that N loss from poorly drained soils can be reduced through afforestation. Well drained sandy soils that require additional large N inputs to sustain commercial agricultural production may also benefit from land use change to woodland. Biogeochemical barriers such as tree shelterbelts have been shown to be effective in reducing concentrations of nitrate and other pollutants in long-term experiments. Narrow shelterbelts are thought to be more effective cleansers than dense woodland stands, and require less land area. There is a need for research to assess the cost-effectiveness of shelterbelts for reducing nutrient losses and the practicability of integrating

their use into the UK farming environment.
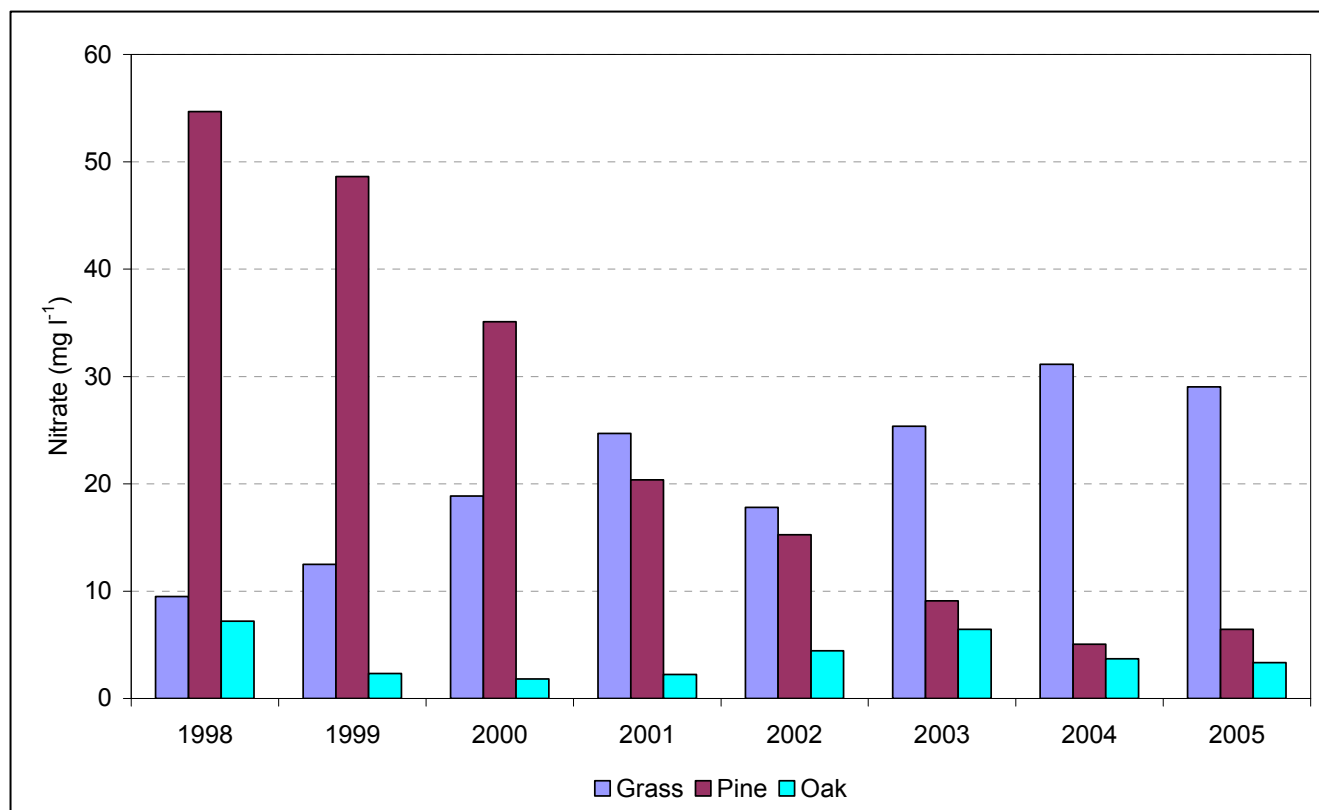
Figure 6. High nitrate concentrations can occur beneath conifer woodland in dry areas. Plot shows high nitrate concentrations in soil drainage waters beneath a Corsican pine stand at Clipstone Forest in the Midlands, which sharply declined following clearfelling in 2000 (and subsequent regeneration of birch). Data are compared with nitrate concentrations under a grass ley, which show a rising trend following the farm's withdrawal in 2000 from a moratorium on N fertiliser applications (under the NSA scheme). Also shown, are nitrate concentrations under oak woodland, which remain low throughout the monitoring period (from Calder *et al.,* 2002).

Is there a role for woodland to act as nutrient soaks near surface waters?
The establishment of riparian woodland buffer strips can act as potential nutrient "soaks" near surface waters. However, while the benefits of these for nutrient retention are widely accepted in principle, there is currently no consensus on their relative efficacy compared to that of wet grassland. Effectiveness will depend on design, management and site factors, with width a key consideration in terms of cost-benefit. Empirical studies have demonstrated variable results linked to differences in previous land use history, depth of water table and soil type (e.g. Addy *et al.,* 1999). Some have found woodland buffers to be more effective at removing nutrients than grassland (Osborne

and Kovacic, 1993; Hubbard and Lowrance, 1997; Kovacic *et al.,* 1991; Schulze *et al.,* 1995), whilst others have shown the opposite to be the case (e.g. Haycock and Burt, 1993; Lowrance *et al.,* 1995; Schnable *et al.,* 1996; Correll, 1997).

The comparative ability of vegetation to remove nitrate from groundwater is likely to differ between species. For example, N-fixers such as Red Alder could be expected to enhance nitrate concentrations, while more productive species like some willow and poplar hybrids would enhance nutrient uptake (Addy *et al.,* 1999). Experimental work by Schultz *et al. (*1995) showed that fast-growing species were best at stream-side due to their quick establishment, providing filtering and stabilising effects within the first three years of planting. The use of willow was particularly effective in soil stabilisation due to its ability to root sprout and form a dense root structure.

Schultz *et al. (*1995) also considered the use of multi-species riparian buffer systems to provide a spectrum of rooting systems and surface roughness aimed at maximising nutrient removal and sediment trapping. Buffer areas composed of separate tree, shrub, grass and bioengineering (willow stakes and dead tree fascines) strips reduced nitrate concentrations by more than 80% between adjacent fields and a stream in Central Iowa (12 to 2 mg NO_3-N l^{-1}) (Figure 7). A minimum buffer width of 29 m (either side of the stream) was recommended. In contrast, Vought *et al. (*1994) suggested a 10-20 m width of riparian woodland would be sufficient to remove the majority of nitrate and phosphate pollutants present in surface run-off.

It has been postulated that deciduous woodland is generally more effective in constraining nitrate and/or ammonium losses than coniferous woodland (e.g. Carlyle, 1986; Kinniburgh and Trafford, 1996), with the higher growth and nutrient uptake rates of conifers offset by the greater scavenging ability of their canopies and thus N deposition loadings. Older, unmanaged riparian woodland is likely to have a lower N uptake than younger, managed stands (see above).

Riparian and floodplain woodland have been proposed as potential nutrient soaks adjacent to surface waters. Various studies demonstrate the nitrate reduction potential of woodland buffers, although the debate over whether trees or grass provide the greatest protection for surface waters remains unresolved. Some studies suggest a combination of grassland and woodland to be best, but this option has not been assessed economically as an alternative to implementing each individually. However, riparian and floodplain woodland are thought to offer a greater range of multiple benefits, including to aquatic biodiversity and flood risk management. The incorporation of fast-growing tree species as energy crops for wood fuel may make this a more attractive measure to farmers for controlling diffuse pollution.
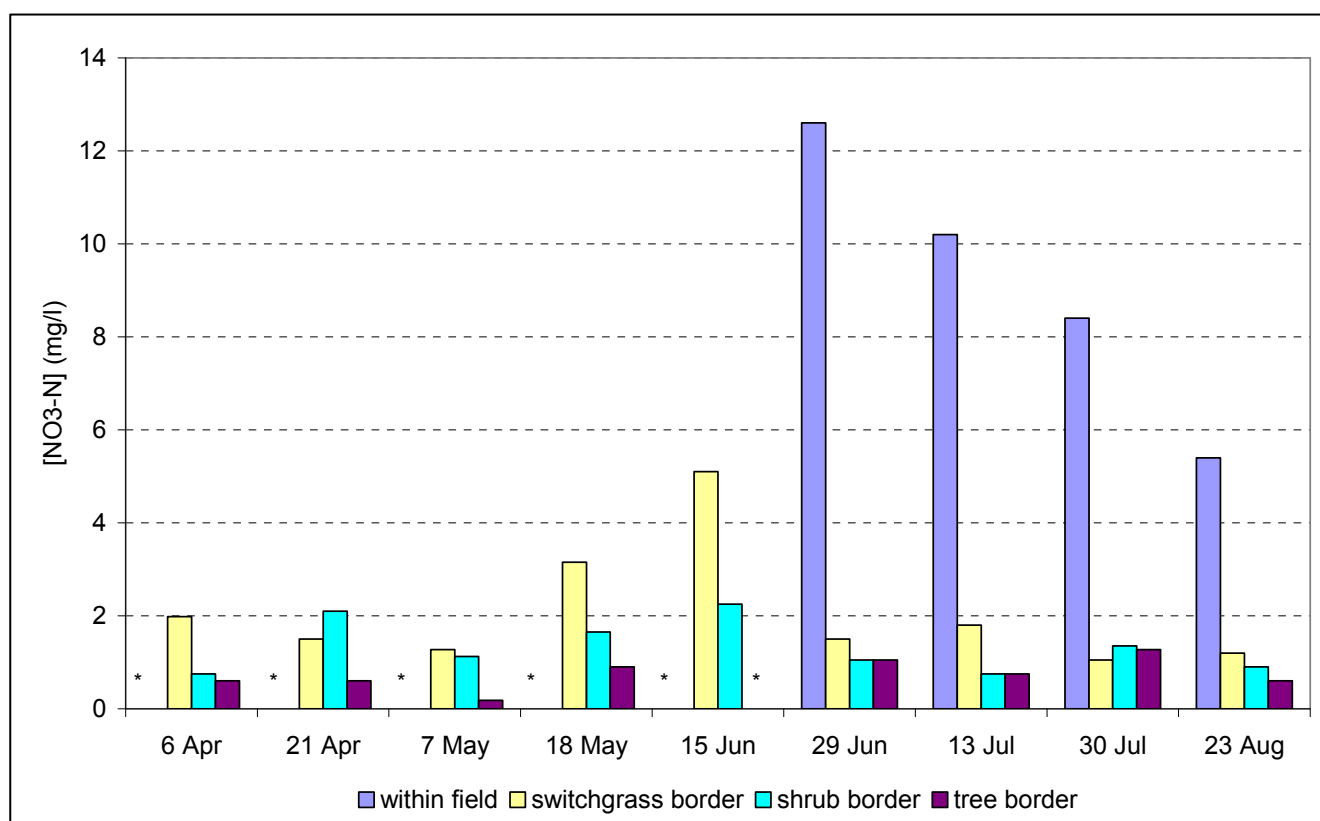
Figure 7. Buffer areas can be very effective at nutrient removal. Plot compares nitrate concentrations in drainage waters during the growing season under different types of buffer vegetation with those within the adjacent cropped field (from Schultz *et al.,* 1995); * missing data.

Are there any woodland measures that could be deployed in the Nitrates Action Programme?

The latest NVZ designations cover approximately 67% of England, 3% of Wales and 15% of Scotland. Current NVZ farm limits are set relative to the agricultural area of the farm and do not include areas of ungrazed woodland. However, the Forests & Water Guidelines (FC, 2003) recommend that management restrictions and N limits applicable under the NVZ rules are also adhered to within woodland areas, although N levels are generally adequate and woodland fertiliser needs nil or minimal.

The Nitrates Action Programme contains no reference to woodland measures (inclusive of SRC). Current management restrictions required in NVZs and optionally applied to forestry are not thought to have a major impact on woodland operations. On the contrary, it has been suggested by some agencies (e.g. Wildlife and Countryside Link,

and Woodland Trust) that the NVZ Action Programme could be further strengthened by promoting other land use measures to reduce N loadings (Wildlife and Countryside Link, 2007; House of Commons, Environment, Food and Rural Affairs Committee, 2008). This could include uncultivated buffer strips (grass, scrub and trees) adjacent to surface waters and targeted woodland creation (Wildlife and Countryside Link, 2007; House of Commons, Environment, Food and Rural Affairs Committee, 2008). The general absence of fertiliser inputs to woodland and low nitrate concentrations in drainage waters, especially under broadleaved woodland, mean that woodland creation could be an effective local measure for reversing the rising nitrate levels in some groundwaters (Nisbet *et al.,* 2004). Land use change to woodland would be particularly effective when targeted to land near to boreholes, on soils susceptible to nitrate leaching, or on surface water pathways of nitrate movement to streams - such as within riparian buffer zones. Consideration should be given to incorporating such woodland measures into a future revision of the Nitrates Action Programme, supported by a programme of research to strengthen the evidence base and develop guidance.

Energy woodland crops such as SRC could be a particularly attractive option for mitigating nitrate leaching in NVZs by maximising nitrogen uptake and providing a high yielding crop for farmers. However, SRC requires regular N additions to maintain productivity and Goodlass *et al. (*2007) showed potential high losses of nitrate in the establishment and removal years of an SRC plot of willow (maximum losses of 140 mg l^{-1}, <3 mg l^{-1} and 70 mg l^{-1} for establishment, harvesting and removal phases respectively). These compare with maximum values of approximately 80 mg l^{-1} for a typical arable crop rotation, although when averaged over the whole life-span of an SRC crop (15-30 years), nitrate leaching losses are very low in relation to more intensively-managed arable land. The results of this study are supported by the findings of a Swedish study by Arronsson *et al. (*2000) where, during the main growth phase when the crop received fertiliser applications of up to 153 kg N ha^{-1}, average nitrate concentrations leaving the root zone remained low (<0.05 mg NO_3-N l^{-1}). Thus, despite repeated fertiliser additions and site disturbance during harvesting phases, the risk of nitrate leaching from SRC appears relatively small (e.g. Lord *et al.,* 2007). Nevertheless, Goodlass *et al. (*2007) recommend that to minimise N losses SRC stands should be maintained for as long as possible (i.e. 15-30 years).

The relatively low nitrate losses that characterise woodland as a land use means that there is a good case for incorporating woodland creation based measures into the Nitrates Action Programme. Possible measures include the establishment of uncultivated woodland buffer strips alongside surface waters or targeted planting around wells/boreholes or on soils prone to nitrate leaching. Planting SRC could be a particularly attractive option for maximising nitrate removal and providing a high yielding crop. Despite modest fertiliser additions to maintain productivity and the inevitable disturbance caused during harvesting, over the lifetime of the crop, nitrate outputs

appear to be much lower than for commercial arable rotations. Current NVZ farm limits do not include areas of ungrazed woodland, and although it is recommended that management restrictions on fertiliser applications imposed within agricultural land in NVZs are also complied with, this is not a legal requirement.

Is there a role for woodland in final treatment systems on farms?

The known purification functions (phytoremediation) of SRC and SRW have raised the potential for use of these measures for final water treatment on farms. Research programmes such as Water Renew, Wilwater and ArtWET have all shown encouraging results or are still ongoing. Much of this work has been based across the wider EU and so the specific applicability of research conclusions to UK conditions, and the issue of how UK policy may be used to support such schemes is still unclear. Woodland buffer strips have particular promise in reducing sediment and nutrient delivery to rivers.

Sugiura *et al. (*2008a) describe experimental findings from the EU LIFE Water Renew project. The aim was to couple wastewater management with renewable energy, which is an endeavour that has been found to be commercially viable in the US and Sweden, but not fully understood in terms of relevance and effectiveness under UK conditions. The UK experiments assessed the removal of nutrients from sewage effluent (often described as wastewater polishing, but also referred to as vegetation filtering (Aronsson *et al.,* 2000), dendroremediation (Rockwood *et al.,* 2004) or slow rate systems (Paranychianakis *et al.,* 2006)) applied as a fertiliser to SRC during the establishment year. Initial results from the first year using controlled irrigation to maintain field capacity on heavy clay soils, found the SRC species of willow, poplar and eucalyptus to be well adapted to a WaterRenew system in the UK (Sugiura *et al.,* 2008a).

Less investigated, however, is the ability of SRC or SRW buffers to remove pathogens and faecal indicator organisms (FIO). For example, Entry *et al. (*2000) reported little change in FIO numbers on passage through a vegetated filter strip (VFS) following an application of pig wastewater, whilst Dillaha *et al. (*1988; 1989) found higher concentrations in the run-off from VFS compared to neighbouring land. The latter suggests that in some circumstances VFS could become sources rather than sinks for pathogens. The poor results could be due to FIO's being preferentially bound to finer clay and silt particles that are less easily captured by vegetation and slower to sediment out (Edwards, 2003). Defra-funded work is currently underway in the UK to evaluate the efficacy of grass buffer strips for reducing the entry of pathogens to surface waters.

Constructed wetlands may also be used in the treatment of farm waste, including dairy manure; effluent/wastewater; run-off from concentrated, cattle feeding operations; and pig and poultry manure (Knight *et al.,* 2000). The efficiency of woodland-wetland systems in FIO removal and improving BOD is currently being investigated within the ARTWet program at several sites in France, but results are not yet available.

The known purification/phytoremediation functions of SRC and SRW have raised the potential for their use as final water treatment systems on farms. Research programmes such as Water Renew, Wilwater and ArtWET have either shown encouraging results or are still ongoing. They appear to be most effective at removing sediment and nutrients but not so good at treating Faecal Indicator Organisms. Much of this work has been based in the wider EU and so the specific applicability of the techniques to UK conditions, and how UK agri-environment policy might be adapted to support such functions, remain to be determined.

3.2.3 Pesticides

How significant a role can targeted woodland creation play in reducing pesticide concentrations in surface and ground waters? And, Are specific measures over and above those designed to reduce nutrient loss to water bodies required to address pesticide pollution?

The contamination of water bodies with agricultural pesticides can pose a significant threat to aquatic ecosystems and natural resources (e.g. Dabrowski *et al.,* 2002). The use of woodland in reducing pesticide concentrations may be split into three categories: edge of field woodland shelterbelts to reduce spray drift; riparian woodland buffer areas to intercept pesticides in run-off; and constructed wooded wetlands to treat contaminated waters. Woodland itself is thought to generally pose little risk of pesticide pollution due to the relative small and infrequent amounts of pesticide applied and the continuing drive to develop and promote alternative non-chemical forms of pest control (Willoughby *et al.,* 2004).

The use of shelterbelts can be a highly effective measure, achieving reductions in spray drift of between 60 to 90% (Ucar and Hall, 2001; Lazzaro *et al.,* 2008) (Figure 8). A review by Reichenberger *et al. (*2007) found natural (living) windbreaks to perform better than artificial ones, with medium-dense windbreaks offering optimum porosity and hence the best protection. Effectiveness can be complicated by local airflow patterns (Ucar and Hall, 2001), which are influenced by tree species and leaf stage. The EC FOCUS Groundwater Scenarios Working Group recommend for regulatory risk assessment purposes, drift reduction values for tree shelterbelts of 25% for bare trees, 50% for intermediate foliage and 90% for full foliage (FOCUS, 2004). This is consistent with Walklate (2001), who reported typical drift reduction efficiencies of 86-91% for a 7 m high windbreak of alder trees.

Riparian woodland buffer areas can also provide effective protection for streams and groundwaters from pesticide applications on adjacent land. Lowrance *et al. (*1984) found riparian woodland to be particularly efficient at both intercepting aerial drift of pesticides and trapping pesticides bound to sediment in run-off. Furthermore, pesticide residues may be removed from drainage waters through a number of natural processes within

woodland soils, including by tree uptake (Lowrance *et al.,* 1984). Both a mature, managed woodland buffer (50 m wide) and a newly restored woodland buffer (38 m wide) achieved almost complete pesticide reduction (Lowrance *et al.,* 1997; Vellidis *et al.,* 2002). However, few publications have quantified pesticide load reductions by riparian woodland buffers and there have been no studies in the UK. It is also notable that the width of riparian woodland buffers studied is much greater than those normally present in the intensively-managed European agricultural landscape and would require a large area of agricultural land to be set aside (Reichenberger *et al.,* 2007). European studies show that natural bank vegetation typically provides little resistance to pesticide run-off and erosion inputs to streams due to inadequate ground coverage and width (Bach *et al.,* 1994). Fabis *et al. (*1994) found that 32-90% of solutes that infiltrated into 4.5-20 m wide bank vegetation strips reached the stream via rapid interflow.

Studies in the USA have assessed the effectiveness of riparian woodland buffer zones at protecting streamwaters from aerial pesticide applications to forest stands on the adjacent land. For example, a major study by Dent and Robben (2000) investigated the impact of aerial applications of herbicides and fungicides to forest areas draining to 23 different sized streams across three geographical regions in Oregon. They found that the presence of overstorey riparian woodland buffers gave almost complete protection, with no evidence of substantial adverse effects on either bank vegetation or on streamwater quality in the studied streams. However, sampling was limited to pre and immediately post pesticide application (15 minutes, 2 hours, 4 hours, 8 hours and 24 hours after application) and did not consider any delayed effects e.g. following a major rainfall event.

The EU LIFE project ArtWET assessed the efficiency of bioengineering control methods based on a range of artificial wetland prototypes. Sites included vegetated ditches and wet woodland microcosms. It was concluded that a combination of high vegetation density and low-flow rates in vegetated ditches could achieve efficiencies of 90% for the removal of aqueous phase insecticides originating from spray drift (Dabrowski *et al.,* 2005) and 60% for herbicides (Gregoire *et al.,* 2009). However, it is unclear whether the ditches were vegetated with trees, grass, or other plants. The studies involving experimental wet woodland microcosms in the Antony and Loche regions of France are ongoing with no results reported to date.

The above measures are likely to be effective at reducing both pesticide and nutrient losses to water bodies, although their efficacy of action is expected to vary, e.g. in terms of width and structure of riparian woodland buffer, shelterbelt or wetland. Further work is required to evaluate the role of these controlling factors in order to improve guidance on the best design and management for pollution control.
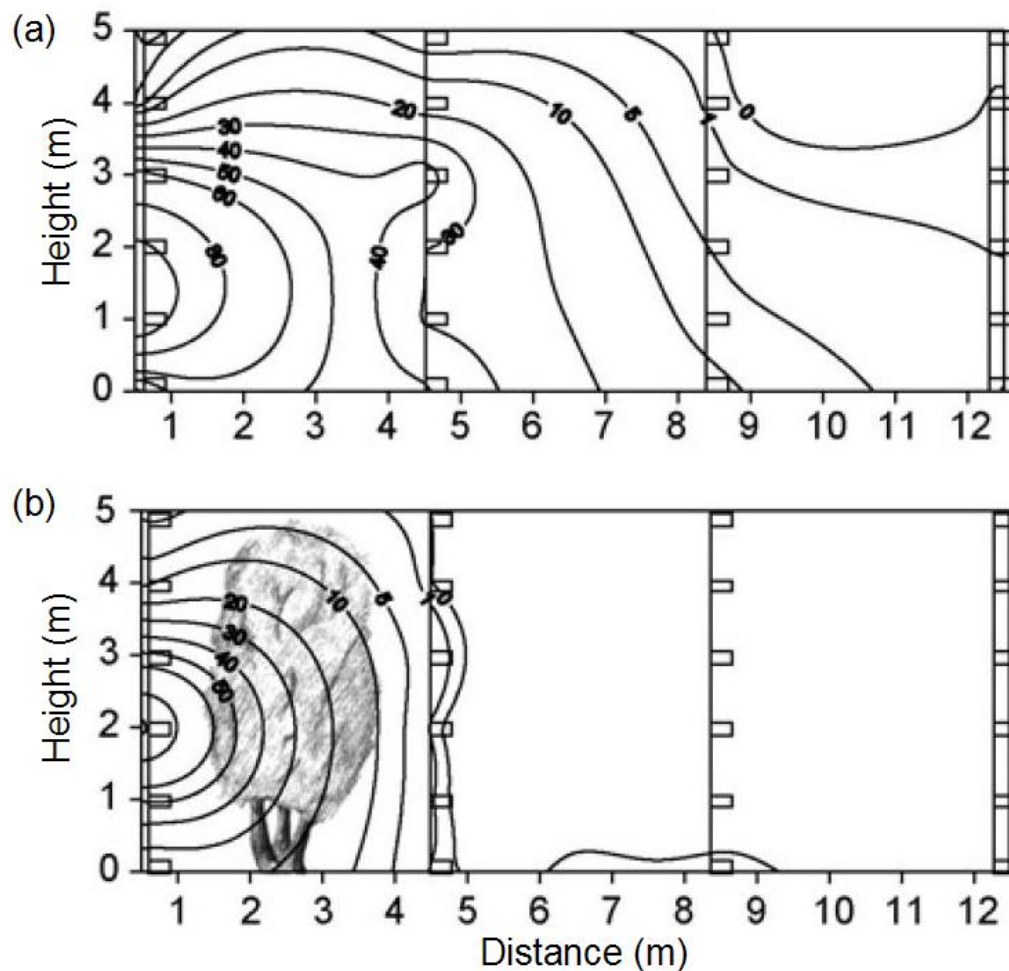
Figure 8. Woodland shelterbelts can be very effective at reducing pesticide spray drift. Plots compare pesticide deposition levels (mg/run/m^2) downwind of a pesticide application to a field bordered with (bottom) or without (top) a tree/hedge shelterbelt (7-8 m high, single line of trees, comprising mixed species; including London plane, sumac, elm, *Viburnum* and *Prunus*). All distances in metres; application by tractor-mounted sprayer. Reprinted from Agriculture, Ecosystems and Environment, Vol 123, Lazzaro, Otto and Zanin, Role of hedgerows in intercepting spray drift: Evaluation and modelling of the effects, pp 317-327, Copyright (2008), with permission from Elsevier.

Targeted woodland creation can be an effective measure for reducing the risk of pesticide pollution, although quantitative evidence is lacking for the UK. The use of woodland in reducing pesticide losses can be split into three categories: edge of field windbreaks/shelterbelts to reduce spray drift; riparian woodland/buffer areas to intercept pesticides in run-off; and constructed wetlands to treat contaminated waters. Studies have shown windbreaks and riparian buffers to give almost complete protection

when designed correctly but the potential for using wooded wetlands awaits the results from ongoing experiments in France. Woodland creation based measures are likely to be effective at reducing both pesticide and nutrient losses to water bodies, although their efficacy of action is expected to vary e.g. in terms of width and structure of riparian woodland buffer, shelterbelt or wetland.

3.2.4 Reducing run-off and soil erosion

What woodland measures could be deployed to control run-off and soil erosion? and,How may woodland be used at a landscape scale to control soil erosion?
It is widely acknowledged that soils under woodland are usually well protected and improved (FC, 1998). Measurements generally display consistently lower sediment losses for watercourses draining woodland compared to other land uses (Figure 9).
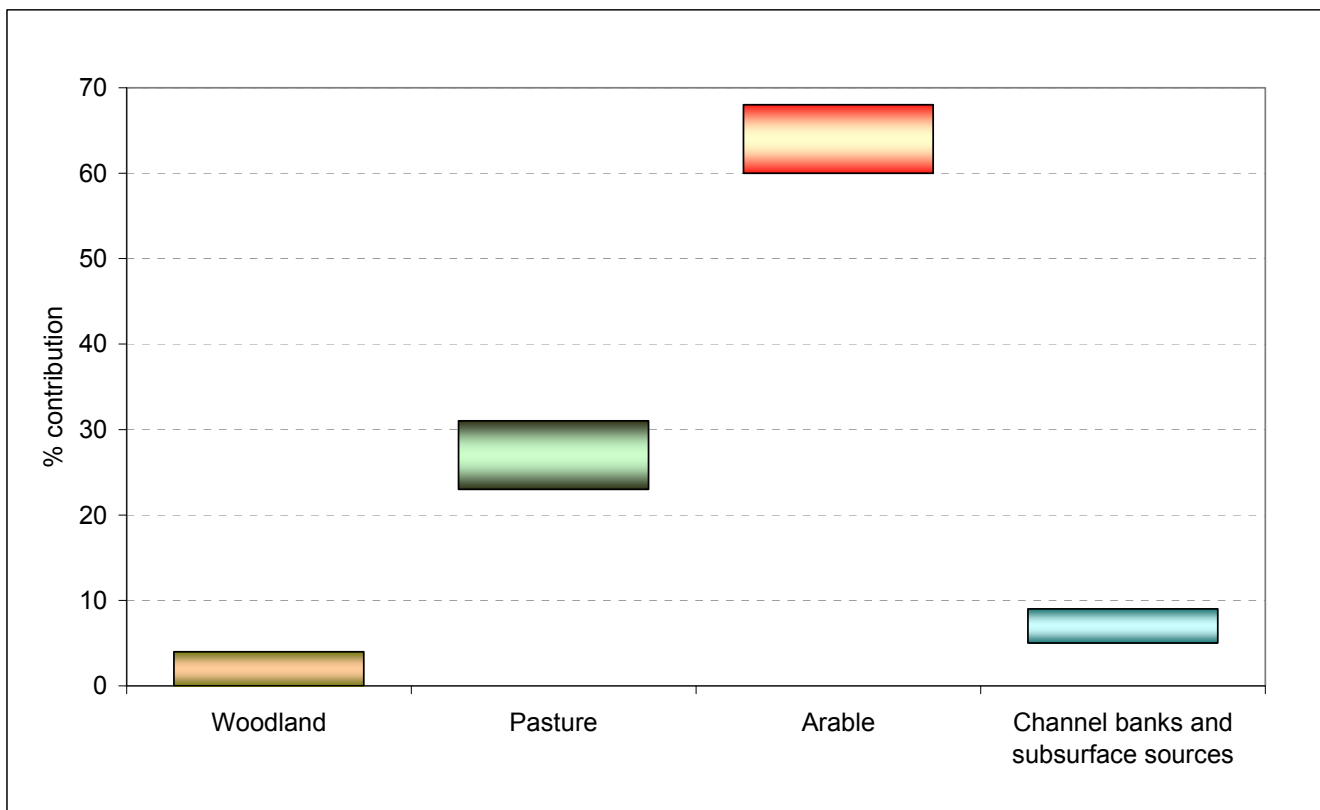
Figure 9. Well managed woodland is usually associated with low sediment losses. Plot shows the relative contribution of different sediment sources (land uses) to sampled fine sediment from the bed of the River Frome in Southwest England (after Collins and Walling, 2007).

Nisbet *et al. (*2004) describe the main ways that woodland can reduce soil erosion as:

•   providing physical shelter from the wind,
•   reducing water run-off due to higher water use
•   protecting the soil from compaction and surface sealing, thereby increasing the entry of rainwater into the soil
•   improving soil strength and stability through encouraging the build-up of soil organic matter and via the action of tree roots

There are a number of options for using woodland at a landscape scale to help reduce soil erosion and sediment delivery (Nisbet *et al.,* 2004):

1.   The planting of woodland on vulnerable soils can protect these from disturbance by removing key pressures such as overgrazing, poaching by livestock, damaging cropping practices or human trampling.

2.   The establishment of woodland along run-off/sediment pathways can interrupt and reduce the transport of sediment to watercourses. Once surface run-off occurs, it quickly converges to form rills and gullies, such as down tramlines in cereal and potato fields (Silgram *et al.,* 2007, 2009). Studies at Pont Bren in Wales have shown that woodland shelterbelts can be very effective at intercepting and reducing surface run-off by enhancing soil infiltration. Infiltration rates were up to 60 times higher under young native woodland shelterbelts compared to adjacent heavily grazed pasture, with 90% of the improvement occurring within two years of stock removal and tree planting (Carroll *et al.,* 2004). Other locations where this benefit can be put to good effect include the planting of woodland on infiltration basins or swales to improve the retention of polluted run-off from farm steadings or road/track ways, or within sustainable urban drainage systems (SUDS).

3.   The creation of riparian woodland buffer areas can be a very effective measure for intercepting run-off and trapping suspended sediment. The use of VFS has been widely reported in the USA and are regularly recommended in national BMP programmes to reduce diffuse pollution (Edwards, 2003). Their operational efficiency and maximum effective length is location specific, dependent on slope/microtopography (degree of flow convergence), soil properties (e.g. texture and infiltration rate), climatic factors (rainfall intensity and duration), and adjacent land use (Edwards, 2003) (Figure 10). Recommended widths for buffer areas range from 3-200 m with 5-15 m most commonly adopted.

Several papers report clear positive benefits from VFS, primarily in relation to sediment retention (Lowrance *et al.,* 1986) with benefits less marked for soluble

substances such as nitrate (Chaubey *et al.,* 1995). It has been suggested that the efficiency of sediment trapping by VFS is inversely related to sediment particle size (and density), with one model indicating that the trapping efficiency of clay sediment in a 15 m length VFS to be 47%, compared with 92% for silt (Abu-Zreig, 2001). Phillips (1989), Haycock and Pinay (1993) and Hubbard and Lowrance (1994) found that a combination of woodland and grassland buffers (as an understorey or adjacent strip) enhanced sediment removal. Defra-funded research is underway in the UK to evaluate the effect of buffer strip width on the cost-effectiveness of this measure in controlling diffuse pollution. Cost-effectiveness is being evaluated by considering the land taken out of agricultural production verses the environmental benefit in terms of reduced siltation and effects on fisheries and biodiversity.
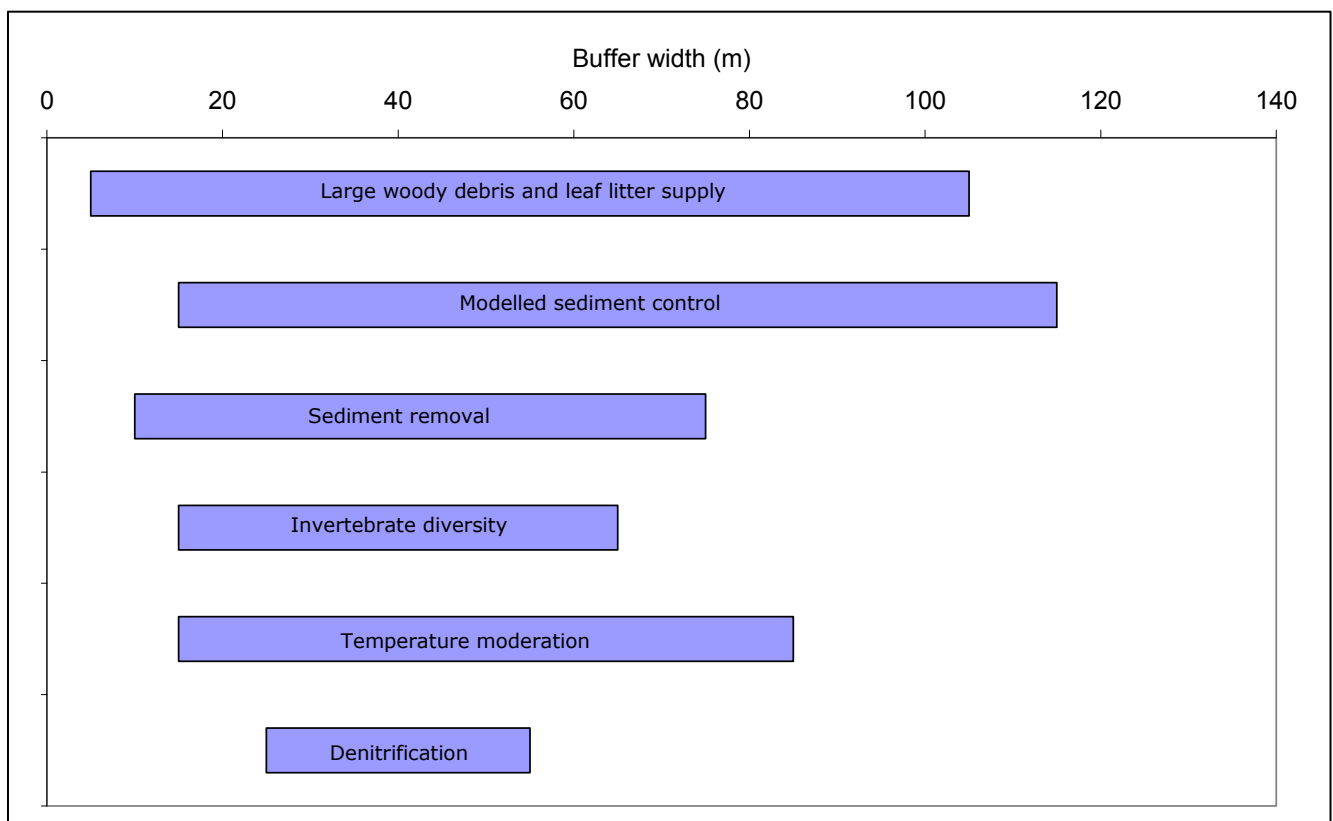
Figure 10. Riparian woodland buffers provide a number of water functions, including sediment removal. Plot shows a range of buffer widths reported in the literature as being required for the adequate performance of specific buffer functions (from Broadmeadow and Nisbet, 2004).

Riparian woodland has the added advantage of protecting stream and river banks from erosion by the strengthening action of tree roots. Zaimes *et al. (*2008) studied the relative contribution of stream banks to total sediment and

phosphorus losses under different riparian land uses across Iowa. Such losses tend to be highly variable but can dominate loads in some areas (Kronvang *et al.,* 1997). Anthony and Collins (2006) calculated that stream banks across the UK contributed a total of 394.1 tonnes or 15% of the national gross sediment yield. Walling *et al. (*2003) in a study of interstitial fine sediment in samples retrieved from salmonid spawning gravels in the south-west of England estimated that channel bank sources were responsible for as much as 84% of the total load. Measurements generally show consistently lower losses and greater bank stability for watercourses lined by riparian woodland compared to other land uses. Options for speeding up the protection of actively eroding river banks include the use of bioengineering solutions such as the intensive planting of willow stakes.

4.   Finally, the action of riparian and floodplain woodland in encouraging out-of-bank flows and slowing down flood flows promotes sediment deposition and retention, reducing downstream siltation.

A pilot study demonstrating how to use these woodland measures to assist sediment control was undertaken by Nisbet *et al. (*2004) in the catchment of Bassenthwaite Lake in the Lake District in northwest England. A two-stage strategy was adopted involving the identification of the main sediment sources and pathways followed by an evaluation of opportunities for targeted woodland planting to alleviate the problem. Details of this approach are described in Appendix 2.

There are a number of options for using woodland to control run-off and reduce soil erosion and sediment delivery. These include targeted woodland planting to protect erosion sources, the use of shelterbelts or buffer areas to interrupt the transport and delivery of sediment to watercourses, and the restoration of riparian and floodplain woodland to protect river banks and enhance sediment retention by slowing down flood flows and promoting out-of-bank flows. Studies show that these measures can be very effective as part of a whole-catchment approach to tackling sediment problems, although most of the supporting evidence is based on overseas work. Further research is needed to test the measures under UK conditions and improve guidance on their design and management to maximise benefits (e.g. in terms of width of shelterbelts and buffers for different soil and slope combinations).

Could Environmental Stewardship be further developed to encourage woodland as a pathway interceptor of run-off and associated eroded sediment?
There are several measures within Environmental Stewardship (ES) that have the potential for development to encourage the use of woodland to help reduce surface run-off and associated nutrient and sediment losses. Following CAP reform, the Single Payment Scheme (SPS) was expected to result in the natural regeneration of trees and scrub. However, a recent review (Silcock and Manley, 2008) suggests that this potential

has not been realised, which might mean that in some cases, the effects of Good Agricultural and Environmental Condition (GAEC) and cross compliance have resulted in wider woodland establishment being inadvertently discouraged.

Within existing ES rules, there appear to be several opportunities which could encourage the adoption and utilisation of woodland as a diffuse pollution mitigation measure. Currently, points are awarded for land under Entry Level Stewardship associated with the maintenance of existing hedgerows, but this does not extend to the creation of new hedgerows. Hedgerows are a form of living windbreak (or shelterbelt) and perform multiple beneficial ecological and environmental functions. The environmental functions include the capture of sediment and interception of pesticides and other diffuse pollutants.

Buffer strips are also recognised within the ES scheme options, but only for grass strips, with no reward for the establishment of woodland buffers. Points are awarded irrespective of location within the landscape i.e. a buffer strip adjacent to a farmhouse would, in principle, receive the same score as one bordering a field of potatoes next to a river. The former would have a lower environmental protection benefit, but as currently framed, the scheme rules would provide the same economic benefit to the farmer in both cases.

The Higher Level Stewardship scheme has regional aims to increase woodland cover, but as with ES, at the farm scale there is no incentive to target scheme measures to where they can most benefit the freshwater environment. Potential improvements to both stewardship schemes are therefore desirable and could consider:

- Incentives (points or payments) for the creation of tree shelterbelts, hedgerows and riparian woodland buffer areas.
- Weighting of the points system to favour the targeting of these measures to the most effective location within farm landscapes.

Concerns have been highlighted regarding the application and interpretation of cross compliance and GAEC measures. It is thought that requirements such as minimum levels of maintenance; avoiding the encroachment of unwanted vegetation on agricultural land; and protection of permanent pasture (land which may previously have been designated for woodland establishment), could discourage farmers from allowing the natural regeneration of woody vegetation in desirable areas (Silcock and Manley, 2008). Natural regeneration has traditionally taken the form of small-scale encroachment of trees and scrub in field corners, along field edges and across marginally productive land. Potential benefits to water include forming a buffer to adjacent watercourses, reducing erosion and intercepting run-off. However, these concerns may be unwarranted due to a lack of

awareness or poor implementation of cross-compliance rulings by farmers (Silcock and Manley, 2008).

Despite the national area of farm woodland showing an increasing trend with time, qualitative findings by the Land Use Policy Group suggest that SPS is unlikely to have a major effect on woodland expansion (Silcock and Manley, 2008). Barriers to woodland expansion associated with SPS have been attributed to: confusion regarding eligibility, rules and inspections, leading to greater caution in decision-making and scheme implementation; lack of awareness amongst farmers and advisers of the full range of options for woodland expansion; and scheme complexity with multiple rules and operators.

General barriers to woodland expansion on farmland include:

- The comparatively low economic returns from woodland/forestry as opposed to agriculture.
- Length of the required investment period.
- Potential higher reward and increased flexibility for alternative uses of marginal land.
- Grazing pressures from deer affecting the success and costs of establishment and regeneration in certain areas.
- Cultural factors, including the protection of cultivated lands.
- Land ownership.
- Perceived reduction in land capital values.
- Desire to preserve 'traditional' landscape views.
- Lack of experience and knowledge about farm woodland management.

Identified recommendations for the pro-active support of natural regeneration and woodland planting on farmland within SPS include: more inspections to ensure effective implementation; increasing the flexibility in eligibility (recent changes under the CAP Health Check (2008) now permit SPS to be claimed on land planted with woodland); and improving compatibility/coherence between SPS and cross compliance (Silcock and Manley, 2008). Currently, EC regulation 1782/2003 requires Member States to establish rules which prevent the ratio of land under permanent pasture to total agricultural land decreasing by more than 10% from the reference year of 2003. This regulation currently appears to limit the extent to which new woodland areas can be promoted, and so closer legal scrutiny of the regulation is needed to explore whether any opportunity exists by which woodland areas might fall outside the scope of this legislation.

The Scottish Rural Development Programme (SRDP) includes support for a number of woodland based Land Managers' and Rural Priority options, although as with ES, more needs to be done to target woodland planting for water benefits. For example, funding

support is available for small-scale woodland creation on agricultural land, but while this recognises improving water quality as one of the outcomes, there is no incentive to direct planting to where it can be most effective. There is much scope for better targeting of these options, including the expansion of specific Challenge Funds, which are currently limited to promoting woodlands in and around towns for people. These deficiencies have been recognised in the First Stage Review of the SRDP (Cook, 2009) and the Scottish Government intends to implement changes to deliver more focused regional priorities. SEPA are promoting a Priority Catchment approach in future schemes that may help to advance the concept of woodland planting in the right place for diffuse pollution and flood mitigation, as well as delivering wider environmental and other benefits. In Wales, the Glastir Scheme is still under development but will support the creation of water interception strips (shelter belts) and streamside woodland/hedgerow planting and management. Within Glastir Woodland Creation (open from November 2010), there are currently no plans to target woodland creation at a strategic scale but the most effective tree planting actions will be incorporated into the design of individual schemes.

ES has the potential for further development to encourage the use of woodland to intercept surface run-off and reduce associated sediment losses. The creation of shelterbelts and riparian woodland buffers are not currently included in the scheme but do appear to offer potential benefits for both water and ecology. The introduction of the SPS was expected to result in the potential for regeneration of trees and scrub on marginal lands due to falling livestock numbers, but a recent review suggests that little change is evident so far. A number of issues were highlighted that may have already, or may in future, discourage farmers from allowing natural regeneration on their land. Addressing these concerns and associated recommendations would encourage the targeted planting of woodland to deliver significant water benefits. Similar deficiencies and opportunities also apply to the SRDP and to a lesser degree Glastir in Wales.

3.3 Water resources

Will the hydrological impact of new woodland affect the available resource or low river flows?

Trees can use more water than other types of vegetation but whether they do and by how much is dependant on many factors, including tree species, location and local climate, soil and geology, woodland management and design, scale of woodland, and the type of land cover being replaced (Neal *et al.,* 1991; Nisbet, 2005; Calder *et al.,* 2008) (Figure 11). The higher water use is mainly due to the interception and subsequent evaporation of rainwater by their aerodynamically rougher canopies, but also to potentially higher transpiration rates sustained by deeper rooting on drier sites.

Research world wide generally shows that forests, especially evergreen, use more water than shorter types of vegetation, resulting in lower water yields (McCulloch and

Robinson, 1993; Calder *et al.,* 2008). A seminal study was the work of Bosch and Hewlett (1982), who in their review of 94 catchment studies from across the world established a significant relationship between % forest cover and water yield. A 10% increase in conifer or broadleaved forest cover within a given catchment was associated with a 40 mm and 25 mm decrease in water yield, respectively. Related research by Calder and Newson (1979) on the water use of upland conifer plantations in the UK derived a similar rule of thumb that for every 10% of a catchment covered by a closed canopy conifer forest, there would be a potential 1.5-2.0% reduction in water yield. However, this rule cannot be applied to drier lowland areas due to the closer match between rainfall and evaporation losses and much lower water yields. Under these conditions, studies show that conifer forests can have a disproportionately larger effect, amounting to a 7-10% reduction in water yield per 10% forest cover in some years (Calder *et al.,* 2003).
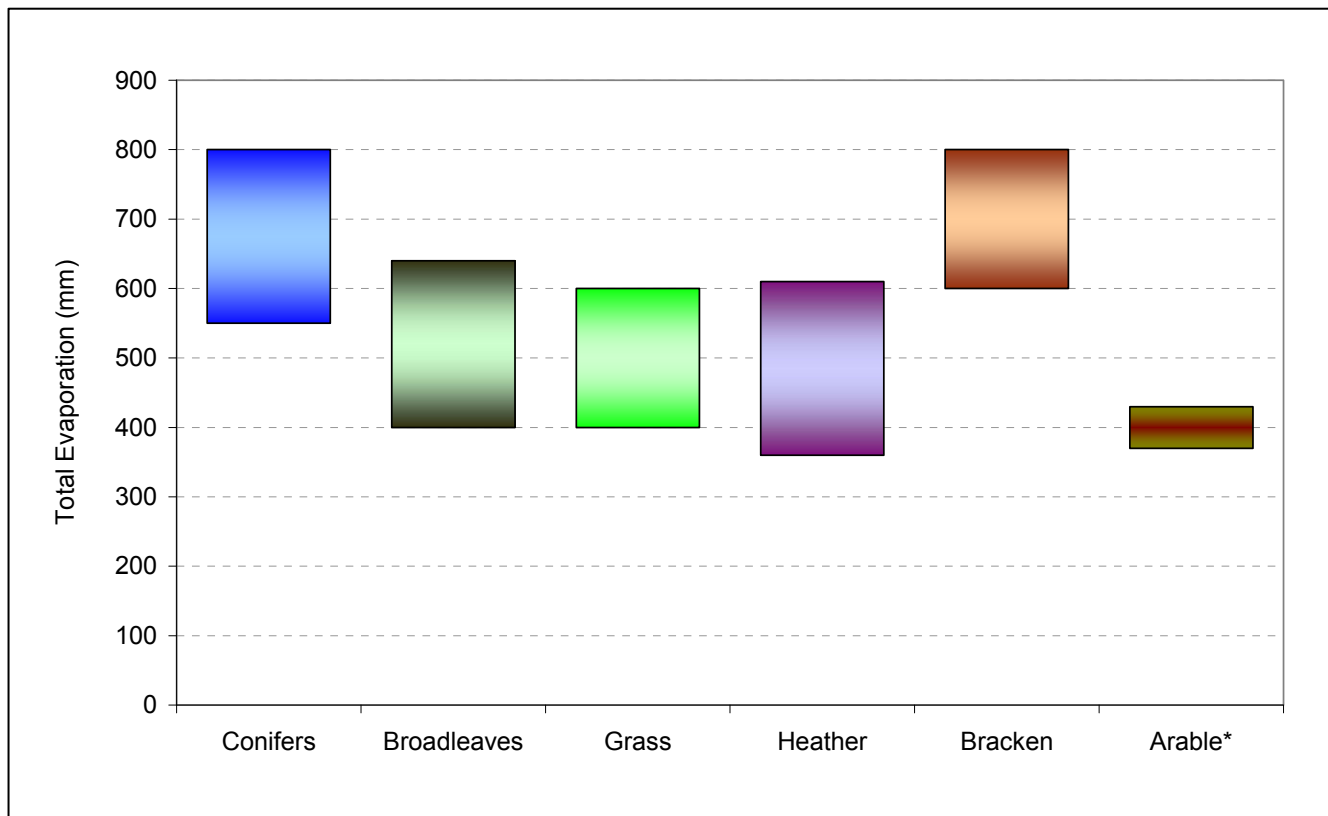
Figure 11. Trees generally use more water than other types of vegetation. Plot compares typical range of annual evaporation losses in mm for different land covers receiving 1000 mm annual rainfall in UK (from Nisbet, 2005). * Assuming no irrigation

Few studies have examined the relationship between broadleaved woodland and water yield in the UK and those that have give conflicting results. The work of Green *et al.* (2006) on the water use of oak woodland on sandstone in Nottinghamshire found that

groundwater recharge was 1.4-3.2% less for every 10% woodland cover, compared to a grass ley. In contrast, Roberts *et al. (*2001) and Harding *et al. (*1992) showed that recharge was 1.3-2.5% greater than grass under beech and ash woodland on chalk at a site in Hampshire and 1.4% greater for ash on clay in Northamptonshire, for every 10% of a catchment covered by woodland. The difference in results between these studies is thought to be due to soil/geology and species related factors (Roberts and Rosier 2005; Wullschleger, 1998).

A number of studies have used the above results to model the impact of broadleaved woodland planting schemes on local water resources. Calder *et al. (*2002) predicted that a planned three-fold expansion of broadleaved woodland (from 9% to 27% of area) to create the Greenwood Community Forest in Nottinghamshire would lead to a maximum reduction in groundwater recharge of between 3-6%, assuming all planting involved oak on sandstone. Drawing on the results from studies both on chalk and sandstone, Price (2005) concluded that the impact on the average annual water yield of an increase in native broadleaved woodland cover from 4% to 40% of the public water supply catchment at Loch Katrine in central Scotland, would range from +1% to −4% (average of −2% for mixed broadleaves).

The measured impacts and established relationships between woodland and water yield cannot be transferred directly to the within-year distribution of river flows, especially flow extremes (Nisbet and Stonard, 1995a). High and low flows are strongly influenced by soil and geological factors, which determine the routing and timing of water draining/flowing through a catchment. The impact of woodland on both flood and drought flows remains a contentious issue, with studies presenting conflicting results.

Research on low flows in the UK has focused on upland conifer forests due to their greater impact on water yield. An analysis of 21 gauging stations from forested catchments with long-term flow records in Scotland and Northern Ireland by Black and Cranston (1995) found evidence of a decline in low flows in 11 cases, an increase in two and no significant change in eight, although none of the changes were related to the proportion of forest cover present. In contrast, a study of long-term flow records for two extensively afforested catchments in South Scotland by Nisbet and Stonard (1995a) found no evidence of any effect due to forest growth through time. Other UK studies have also failed to find any evidence of a significant relationship between upland conifer forests and low flows (Gustard *et al.,* 1989; Kirby *et al.,* 1991). Similarly, a review of 28 catchment studies from across Europe by Robinson *et al. (*2003) concluded that while effects of upland conifer forests on low flows have been recorded at a local scale, forestry in general probably has a relatively small influence on drought flows across Europe. Few studies have assessed the impact of broadleaved woodland on low flows but those reviewed by Robinson *et al. (*2003) revealed no detectable effect.

In conclusion, planting new woodland could potentially reduce the available water yield but with little impact expected on low flows. Large scale planting of conifer woodland poses the greatest risk, especially within dry lowland areas. Planting native broadleaved woodland is likely to have a relatively minor impact on water yield and low flows, although there is a need to strengthen the evidence base in the UK.

Is there adequate information for an EIA to include impacts on water resources?

A wide range of models has been developed to predict the water use of forests and the impact on water resources. These range from simple empirical type models based on an annual or daily time step (Calder and Newson, 1979; Harding *et al.,* 1992; Calder *et al.,* 2003) to more physically realistic, complex, multilayer process models operating at an hourly or shorter time scale (Roberts and Rosier, 1992; Evans *et al.,* 2006). The process models have a larger number of parameters and require the most input data in terms of climate, vegetation and soil factors.

The Penman-Monteith equation is widely regarded as the most rigorous approach for estimating transpiration and forms the core of many process based models (Harding *et al.,* 1992). Interception losses are separately modelled using single or multiple layer canopy process models (Rutter *et al.,* 1975; Gash, 1979; Calder, 1987). These tend to be useful research tools for investigating evaporation processes at the stand level but their reliance on detailed meteorological data above the forest canopy on an hourly or more frequent basis limits their wider application. Efforts have been made to extend the use of these complex models by using weather generators to provide the required met data (Evans *et al.,* 2006). One of these is ForestEtp, which has been shown to perform well in predicting the impact of Sitka spruce on water yield in the Coalburn catchment study in North England (Pellenq *et al.,* 2004).

Simplified versions of process models that rely on some empirical relationships have been incorporated into broader scale models for application at a landscape level. In the UK, the Meteorological Office has developed the MORECS (Thompson *et al.,* 1981) and MOSES (Met Office Surface Energy Scheme) (Essery and Clark, 2003) models for providing grid based estimates of evaporation and/or carbon exchange across the national land surface. When linked to GIS, these models can give catchment based estimates of evaporation for different land classes, which could be used as a guide for assessing impacts of woodland planting on water resources. However, in these models, values are only generated for broad woodland classes such as broadleaved or conifer woodland and therefore cannot address the influence of important factors such as tree species, tree age and woodland structure. There are also issues over gross simplifications such as the assumption by MOSES of a uniform 3 m soil depth and inability to account for geological influences such as the unusual hydraulic properties of chalk (Finch *et al.,* 2004).

The most widely used form of model in the UK for estimating woodland impacts on water resources is the simple daily water use model. A number of versions of the model exist but the main difference in applications relates to the choice of parameter values. The best known is the HYLUC model as described by Calder (2003), which uses semi-empirical parameters to estimate actual transpiration from daily Penman potential transpiration values and interception loss from daily rainfall. Transpiration values are moderated by available soil water and both transpiration and interception values are allowed to vary seasonally. The model was found to perform well against observed data in the study by Calder *et al. (*2003) involving woodland on sandstone in Nottinghamshire but the choice of parameter values has been questioned in an application to beech woodland over chalk in Hampshire (Roberts *et al.,* 2001). The main limitation is that parameter values are only available for a few conifer and broadleaved woodland tree species derived from a small number of sites in central and southern England. A similar approach to HYLUC underpins the daily water balance model IRRIGUIDE (Bailey and Spackman, 1996), which was developed jointly by ADAS and the Meteorological Office. Results compare favourably with measurements (Silgram *et al.,* 2007), and although originally developed as a tool for farm advisers, it is now more widely used as a research tool for modelling nitrate leaching losses from NVZs and in water quantity projects such as those associated with climate change scenarios.

To conclude, adequate information and models are available to guide an EIA of the impact of woodland planting on water resources but expert judgement is required to tailor their application to specific site conditions. Further measurements and model testing are necessary to cover a wider range of species and site types, and to demonstrate fitness for purpose.

3.4 Flood alleviation

In what circumstances can woodland be used to reduce flood frequency or severity?

Forests and woodland have long been associated with an ability to slow down run-off and reduce downstream flooding (McCulloch and Robinson, 1993). However, while there is evidence of a forest impact on flood flows at a local level (< 100 km^2) and for smaller flood events (Robinson *et al.,* 2003; O'Connell *et al.,* 2004), forest hydrology studies in the UK and world wide generally provide little support for a significant effect on extreme flood flows at a wider landscape level (Robinson and Dupeyrat, 2003; Robinson *et al.,* 2003; FAO, 2005; Calder and Aylward, 2006). This may be partly due to the relatively short lengths of available data records, but also the difficulty of isolating a forestry effect from the mix of land uses and activities present within larger catchments. For example, research has shown that forest related hydrological effects are very difficult to discern when <20% of a catchment is affected (Cornish, 1993).

Nisbet and Thomas (2006) highlighted three mechanisms whereby trees could help alleviate flooding; by their greater water use, due to the higher infiltration rates of woodland soils, and by the greater hydraulic roughness of floodplain and riparian woodland. The first two are considered below, while the third is addressed by the next question.

The higher water use of conifers offers some scope for reducing flood run-off but the effect is expected to decline with size of flood event. Calder (1990) noted that interception loss as a proportion of rainfall reduced with increasing storm size, reaching a maximum of 6-7 mm day^{-1}. Losses for individual large storms generating floods are therefore likely to be <10% for completely conifer forested areas (Nisbet and Thomas, 2006). The lower interception loss of broadleaves means that their effect will be even smaller, especially for flood events during the leafless period when the risk of flooding is usually greatest.

The ability of forest and woodland soils to reduce overland flow by receiving and storing more rainfall, the classic 'sponge effect', could have a larger impact on flooding. For example, studies at Pont Bren in Wales found that infiltration rates were up to 60 times higher within young native woodland shelterbelts compared to grazed pasture (Bird *et al.,* 2003) (Figure 12). These results are supported by other studies (Eldridge and Freudenberger, 2005).

Recent modelling predicts that planting shelterbelts across the lower parts of grazed grassland sites could reduce peak flows by between 13 and 48%, which is supported by field data from manipulation experiments (Jackson *et al.,* 2008). These benefits could apply to woodland planting as part of future sustainable farmland drainage systems. However, other modelling studies suggest that land use conversion to woodland has a relatively small effect on flood flows. For example, work by Park and Cluckie (2006) in the River Parrett catchment in Southwest England predicted that conversion of grassland or arable areas to woodland would have no effect on flood risk. Similarly, a study in the Laver catchment in North England found that converting 25% of the area to broadleaved woodland would only reduce a 1-in-100 year event by 1-2% and delay the flood peak by 15 minutes (JBA, 2007). The contrasting findings are thought to be due to differences in modelling approach and in particular, to the way the models handle the effects of land use change on evapotranspiration and soil processes. For example, neither the River Parrett or River Laver studies addressed the impact of woodland planting on the low infiltration rates of soils damaged by agricultural activities, where the benefit of woodland could be expected to be greatest.

The role of the woodland sponge effect also applies to SUDS, with woodland planting having the potential to enhance the water infiltration and retention functions of these key sites, in addition to providing a wide range of other benefits.
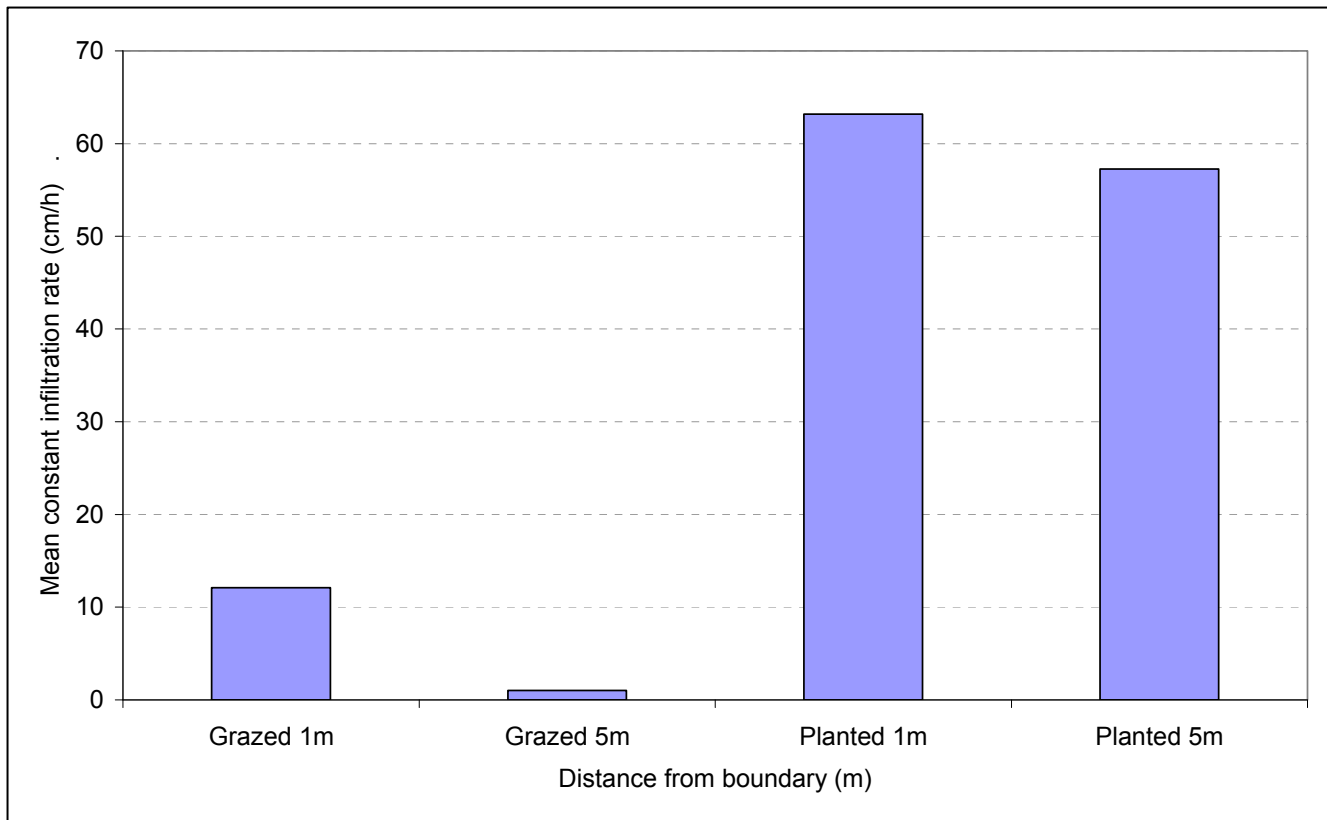
Figure 12. Woodland can help to increase the entry of rainwater into the soil, reducing rapid surface run-off. Plot compares mean soil infiltration rates along a transect between sheep grazed pasture and a recently planted woodland shelterbelt (2-7 years after planting) at Pont Bren in mid Wales (from Caroll *et al.,* 2004, Can tree shelterbelts on agricultural land reduce flood risk? Soil Use and Management, with permission from Wiley).

Although there is evidence of a forest impact on flood flows at a local level (<100 km[2]) and for smaller flood events, forest hydrology studies in the UK and world-wide generally provide little support for a significant effect on extreme flood flows at a wider landscape level. However, it is difficult to draw a definitive conclusion from such work due to the limited data records in relation to the rarity of extreme flood events, the contrasting local effects of different forestry practices on flood run-off, problems with upscaling local field based measurements, and the difficulty of isolating a forestry effect from the mix of land uses and activities present within larger catchments. Future research needs to try and clarify the impact of forestry across the full spectrum of flood flows.

Is there any/sufficient evidence that appropriately located floodplain woodland and riparian buffer strips be promoted and further encouraged to reduce flooding?

The strongest case for forestry being able to attenuate more extreme floods at the large catchment scale is provided by modelling studies on the impact of floodplain and riparian woodland. Work by Thomas and Nisbet (2006) showed that the increased hydraulic roughness associated with planting native floodplain woodland along a 2.2 km grassland reach of the River Cary in Somerset could reduce water velocity by 50% and raise the flood level within the woodland by up to 270 mm for a 1 in 100 year flood (Figure 13). Temporary flood water retention within the reach increased by 71 % and the downstream progression of the flood peak was delayed by 140 minutes. These results were considered significant for reducing downstream flood risk by potentially desynchronising flood flows and providing more time for issuing flood warnings.
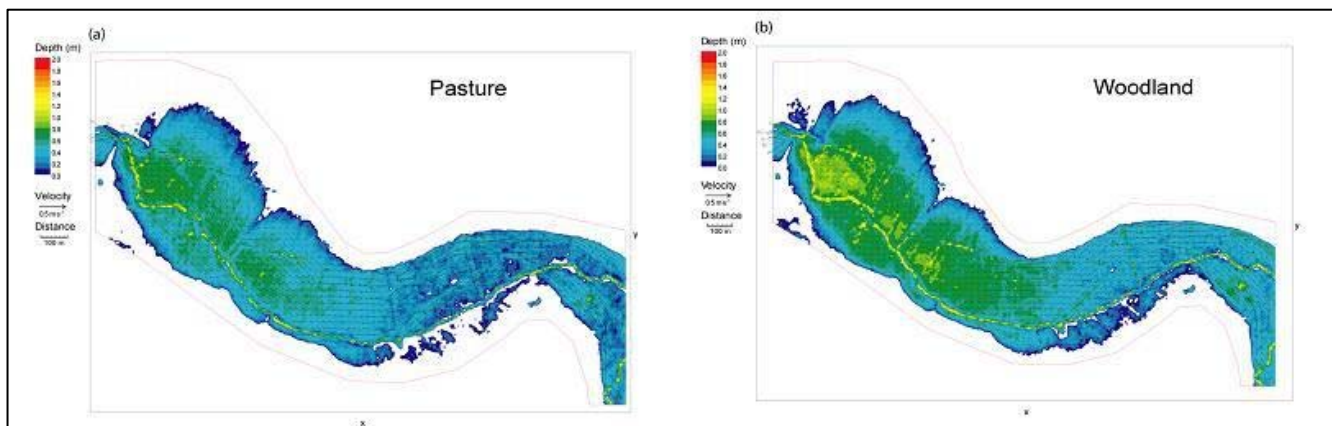
Figure 13. Floodplain woodland can be effective at delaying flood flows, potentially reducing downstream flood risk. Maps compare model predictions of flood depth and water flow velocity for a 2.2 km reach of the River Cary, Somerset under floodplain woodland vs grassland; arrow length is proportional to velocity (Thomas & Nisbet, 2006)

A second modelling study at Ripon in North Yorkshire predicted that planting floodplain woodland at four sites in the River Laver catchment totalling 40 ha in area (<1% of catchment) could delay the progression of a 1 in 100 year flood by around one hour. This had the potential to reduce the flood peak at Ripon by 1-2% by desynchronising the flood contribution from the adjacent tributary, the River Skell (Figure 14). A much greater reduction was expected with a larger planting area (Nisbet and Thomas, 2008).

Further support for the role of floodplain woodland in delaying flood flows is provided by laboratory flume tests (Xavier *et al.,* 2007), model applications (O'Connell *et al.,* 2007) and literature reviews (EA, 2007). Other modelling studies have found floodplain

woodland to have little effect on extreme flood flows. Work by Jacobs Babtie (2006) in the catchment of Glen Urqhart in North Scotland predicted that large-scale planting would reduce a 1 in 200 year event by only 0.8%, although the flood peak would be delayed by one hour. However, this study only looked at the effect of planting the whole floodplain and acknowledged that more targeted planting within tributary catchments could have a greater impact by desynchronising flood flows. Similarly, the above mentioned modelling study by Park and Cluckie (2006) in the River Parrett catchment predicted that the conversion of a 200 m wide riparian/floodplain zone along the main river to woodland (3% of catchment) would have no effect on flooding. Some of the variation in model results is due to differences in selected parameter values, especially the size of Manning's 'n', which defines the hydraulic roughness of the vegetated floodplain and river channel. More measurements are required to refine this parameter for different woodland types and structures. Alternatively, other more sensitive models are being developed that use drag force and friction, rather than a single Manning's n value to represent the effect of vegetation on river flows (Xavier *et al.,* 2007).
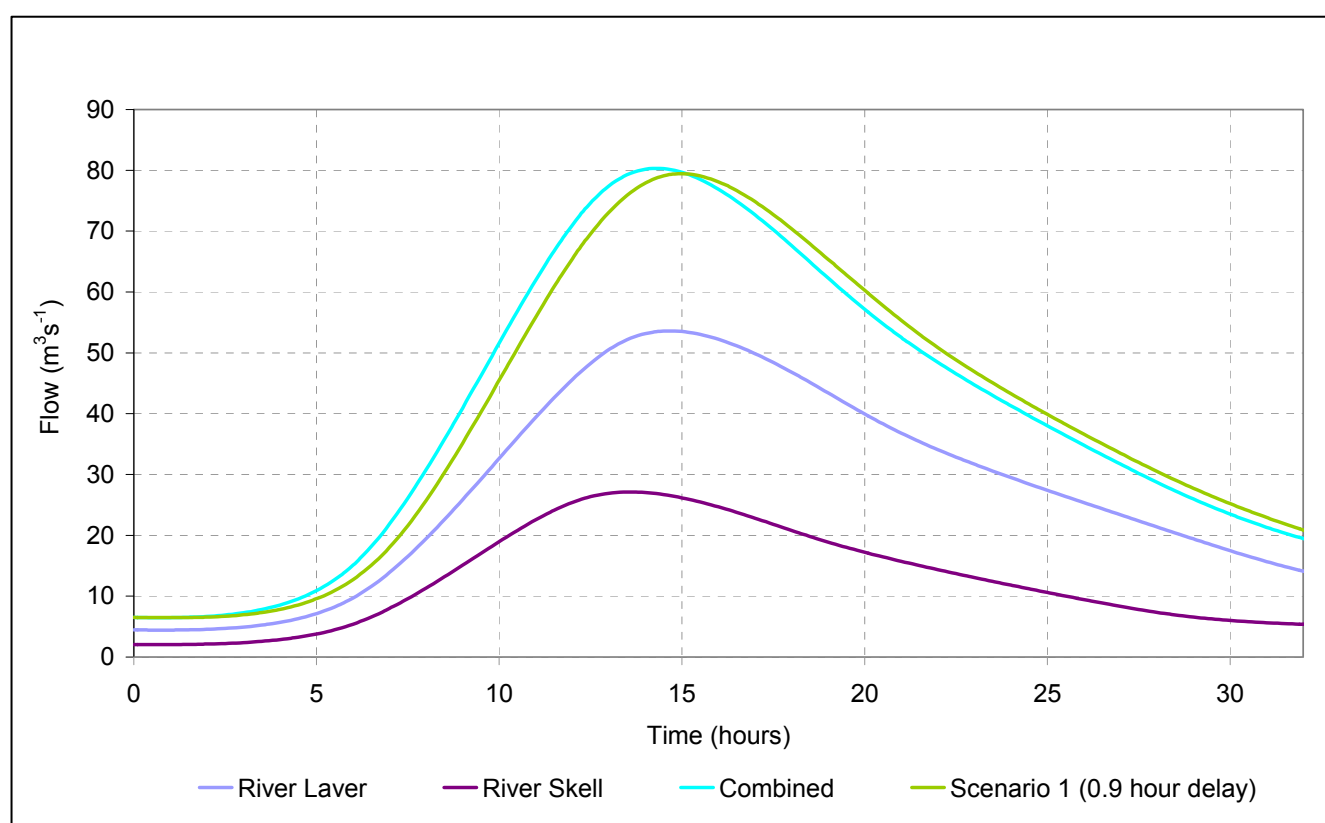
Figure 14. When appropriately located, planting floodplain woodland could help to desynchronise flood peaks from different tributaries, so reducing downstream flood risk. Plot shows the modelled effect of planting 40 ha of floodplain woodland (Scenario 1) in the River Laver catchment in North Yorkshire on the combined flood peak with the River Skell, just above Ripon (from Nisbet and Thomas, 2008).

Riparian woodland acts in a similar way to floodplain woodland but on a different scale. In addition to the hydraulic roughness associated with bankside and adjacent trees in the riparian zone, the presence of large woody debris (LWD) dams within the stream channel act to delay flood flows, promote out-of-bank flows and increase flood storage. Studies show that these porous dams can significantly delay flood peak travel time, although the effect reduces with increasing size of event and poorer condition of the dams (Gregory *et al.,* 1985; Linstead and Gurnell, 1999; Macdonald *et al.,* 2003). A recent study on a tributary of the River Usk in South Wales by Thomas and Nisbet (2006) found that individual LWD dams could delay the downstream passage of a 1-in-100 year flood peak in tributary streams by an average of 2-3 mins. Anderson *et al. (*2006) showed that riparian vegetation reduces wave velocity, which would be expected to lengthen catchment response times and, consequently, decrease peak discharge. However, to be effective at a larger catchment scale would require extended reaches of riparian woodland and associated LWD dams along tributary streams.

Despite the positive evidence in support of floodplain and riparian woodland having the potential to reduce extreme flood peaks, there is little or no 'hard' field data to back up the model predictions and flume results, primarily due to a lack of field studies. The recent Defra funded multi-objective demonstration project 'Slowing the flow at Pickering' will help to address this gap, as will the Scottish Government's Research Strategy on natural flood management.

Overall, there appears to be significant scope for using woodland to help reduce flood risk. The greater water use of conifers and the woodland sponge effect appear to be most effective at the local catchment scale and for small and moderate flood events, while modelling studies predict that floodplain and riparian woodland have the greatest potential for attenuating large floods within downstream towns and cities. Although studies are required to test model predictions, there is probably sufficient evidence to promote floodplain and riparian woodland planting to reduce flood risk in appropriate locations, especially when other benefits are factored into the calculation.

Are there any other benefits besides flood relief?
Many studies identify floodplain and riparian woodland as providing a wide range of other benefits (Kerr and Nisbet 1996; Hughes *et al.,* 2001; Hughes, 2003; Bronstert and Kundzewicz, 2006). One of the most frequently cited is enhanced biodiversity. Floodplain, and to a lesser degree riparian woodland represent rare, complex and diverse habitats, which fall within the wet woodland Habitat Action Plan. This sets clear national targets for the restoration and expansion of wet woodland in England and Wales by 2015. Another is the ability of floodplain and riparian woodland to reduce diffuse pollution, primarily by enhancing siltation and sediment retention (Jeffries *et al.,* 2003), nutrient (phosphate and nitrate) removal (Gilliam, 1994) and fixing heavy metals (Gambrell 1994). A related water benefit is improved hydromorphology, including: the

action of tree root systems in stabilising river banks and providing underwater shelter; inputs of LWD promoting pool formation and increasing habitat diversity; increased canopy shading preventing lethal water temperatures during hot weather and restricting weed growth (Broadmeadow *et al.,* 2009); and the potential enhancement of low river flows from water stored in pools, side channels and wetland soils (McGlothlin *et al.,* 1988). Other benefits are listed as carbon sequestration, wood fuel and timber, and improved landscape. There is significant potential to promote wood fuel for fossil fuel substitution, with opportunities to maximise this benefit through the planting of SRC or SRW. These would have the added advantage of speeding up the development of hydraulic roughness and therefore the effectiveness of these systems for flood mitigation.

Many studies identify floodplain and riparian woodland as providing a wide range of other benefits, including enhanced biodiversity, reduced diffuse pollution, improved hydromorphology, a reduction in thermal stress to fish through shading, carbon sequestration, wood fuel and timber, and improved landscape. There is significant potential in the floodplain to promote wood fuel for fossil fuel substitution, with opportunities to maximise benefits through planting SRC or SRW, although care is required to avoid locations where this could threaten water resources.

If yes, in what circumstances and through what mechanisms could floodplain woodland be used?

The scope for using floodplain and riparian woodland to reduce flood risk should be considered alongside other potential land use and land management measures within the catchment flood management planning process. Floodplain and riparian woodland are unlikely to replace existing hard flood defences but form a part of a package of integrated measures to tackle known flooding problems. Since there will usually be a significant delay between woodland planting and the development of dense woodland vegetation with high hydraulic roughness, the main role of floodplain and riparian woodland is likely to be in helping to climate proof present and new defences. Alternatively, they could provide a sustainable option to assist the protection of smaller communities at risk of future flooding where it is not cost effective to build new flood defences. The planting of SRC or SRW could greatly accelerate the development of hydraulic roughness and therefore offer in the future, greater flexibility for flood management, as well as providing a higher yielding crop generating wood fuel.

Opportunities for planting floodplain and riparian woodland within flood risk catchments have been mapped in relation to constraints and other benefits (Broadmeadow and Nisbet, 2009) (Figure 15). This information can be used when designing/considering appropriate measures to manage flood risk during the development and review of Catchment Flood Management Plans (CFMP). Zoning of these areas would help to target incentives to support planting. If the impact of floodplain woodland is limited to delaying

the downstream passage of the flood peak, its contribution to flood alleviation will be restricted to those sites where there is the potential to desynchronise flood flows from tributary systems. This will require care in site selection to ensure that planting does not have the opposite effect of increasing the flood peak by synchronising flood flows from individual tributaries.

Priority Areas for Potential New Woodland

- Floodplain
- Wider catchment
- Riparian
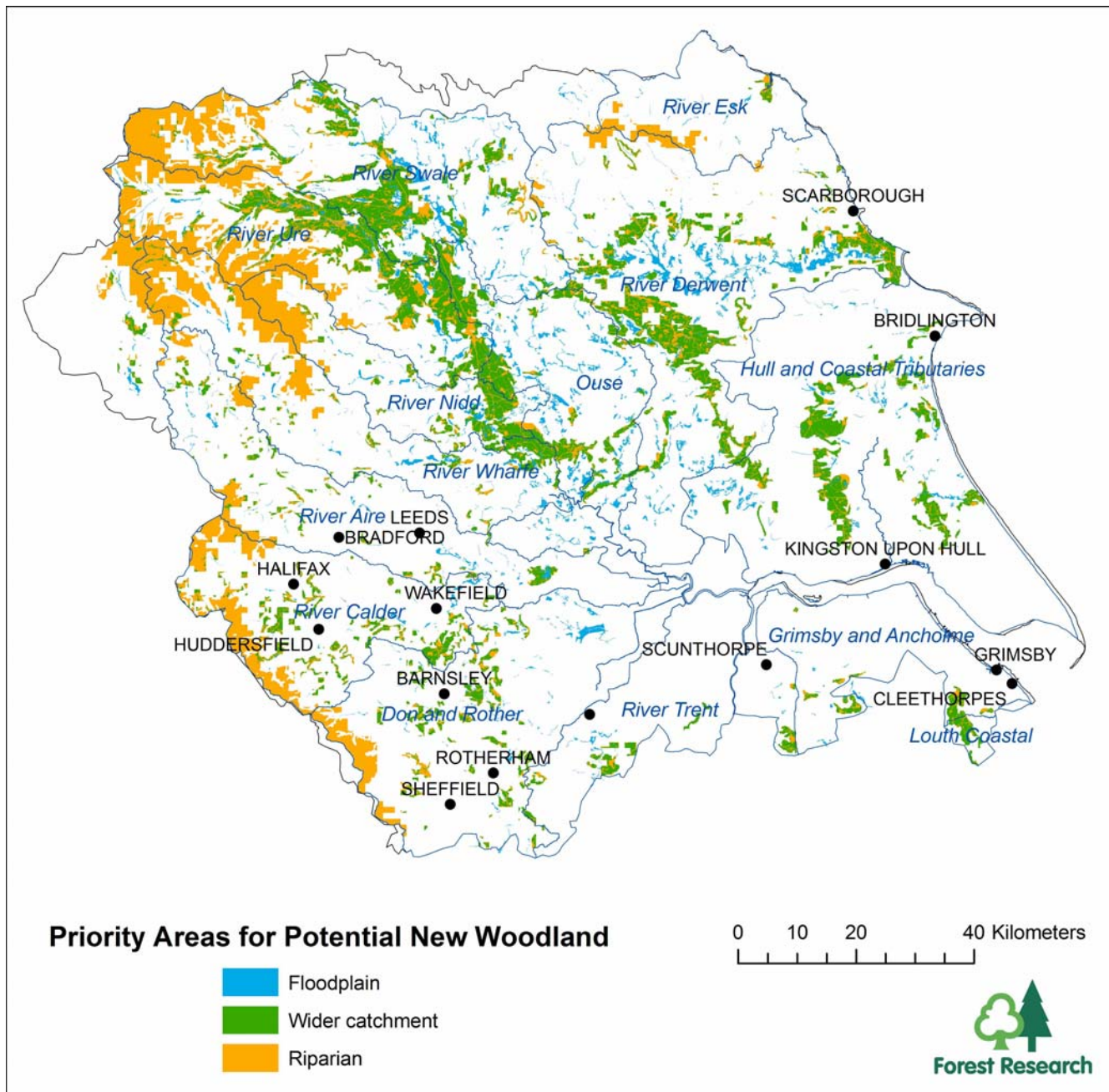
Figure 15. Regional mapping can help identify opportunities for planting floodplain woodland to reduce downstream flood risk. Map shows opportunities for planting floodplain, riparian and other woodland within the Yorkshire and Humber Region in Northeast England to deliver a range of water benefits, including improved flood management (from Broadmeadow and Nisbet, 2009).

The RDP England (RDPE), Better Woodlands for Wales (BWW) and SRDP are likely to be the main mechanisms for supporting floodplain and riparian woodland planting in the respective countries. Notably, FC(E) introduced in the Yorkshire and The Humber Region in 2010 an additional contribution of £2,000/ha under the English Woodland Creation Grant to encourage new planting in areas contributing to flood risk management. However, Nisbet *et al. (*2011) found that while this level of enhanced grant is sufficient to promote riparian and wider woodland planting in selected locations, it appears to be insufficient to secure woodland planting on higher valued agricultural land such as within the floodplain. The creation of natural floodplain woodland with multiple channels and backwater ponds is thought to offer the greatest value for flood alleviation but provides minimal direct income and results in a marked reduction in the capital value of the land. Landowners will therefore need to receive additional payments for this ecosystem service and effort spent promoting the resulting benefits.

Achieving the required scale of woodland planting to deliver a significant reduction in downstream flood risk is likely to require a much higher level of grant support than is currently generally offered. There will also often be a need to co-ordinate planting by a number of smaller landowners. One option would be to introduce a special 'Challenge fund' or locational premium (as in Yorkshire and the Humber but at a higher rate) to target the most effective locations for planting. However, State Aid Rules limit the proportion of woodland planting costs that can be public funded, which restricts the scope for compensating landowners for their losses. Alternatively, supplementary funding could be provided from regional flood levy's or direct payments from national flood defence budgets, although State Aid Rules may also apply here. The planting of SRC or SRW would be more financially attractive with the landowner receiving energy crop payments and income from selling woody biomass for power generation.

The scope for using floodplain and riparian woodland to reduce flood risk should be considered alongside other potential land use and land management measures as part of the catchment flood management planning process. Floodplain and riparian woodland are unlikely to replace existing hard flood defences but form part of a package of integrated measures to tackle known flooding problems. Opportunity mapping and zoning of land can help identify preferred locations for woodland planting. The country RDPs are likely to be the main funding mechanisms but achieving the required scale of woodland planting to deliver a significant reduction in downstream flood risk will require a much higher level of grant support than is currently offered. One option would be to introduce a special 'Challenge fund' or locational premium to target planting to the most effective locations.

In what circumstances would we not encourage woodland on the floodplain?
There are some circumstances constraining the use of floodplain or riparian woodland to manage flood risk. The first concerns the backing-up of floodwaters upstream of the woodland, which could threaten local properties. Modelling work shows that the effect depends on the channel gradient and can extend over a distance of 300-400 m or more, although the enhanced flood depth gradually declines over this distance, being greatest at the woodland edge (Nisbet and Thomas, 2008) (Figure 16). The risk can be controlled by carefully siting woodland to avoid locations where properties or infrastructure lie within the affected zone. Since the dimensions of the zone will be determined by the channel gradient, width of the floodplain and nature of the woodland planting, identifying suitable locations needs to be guided by modelling work.
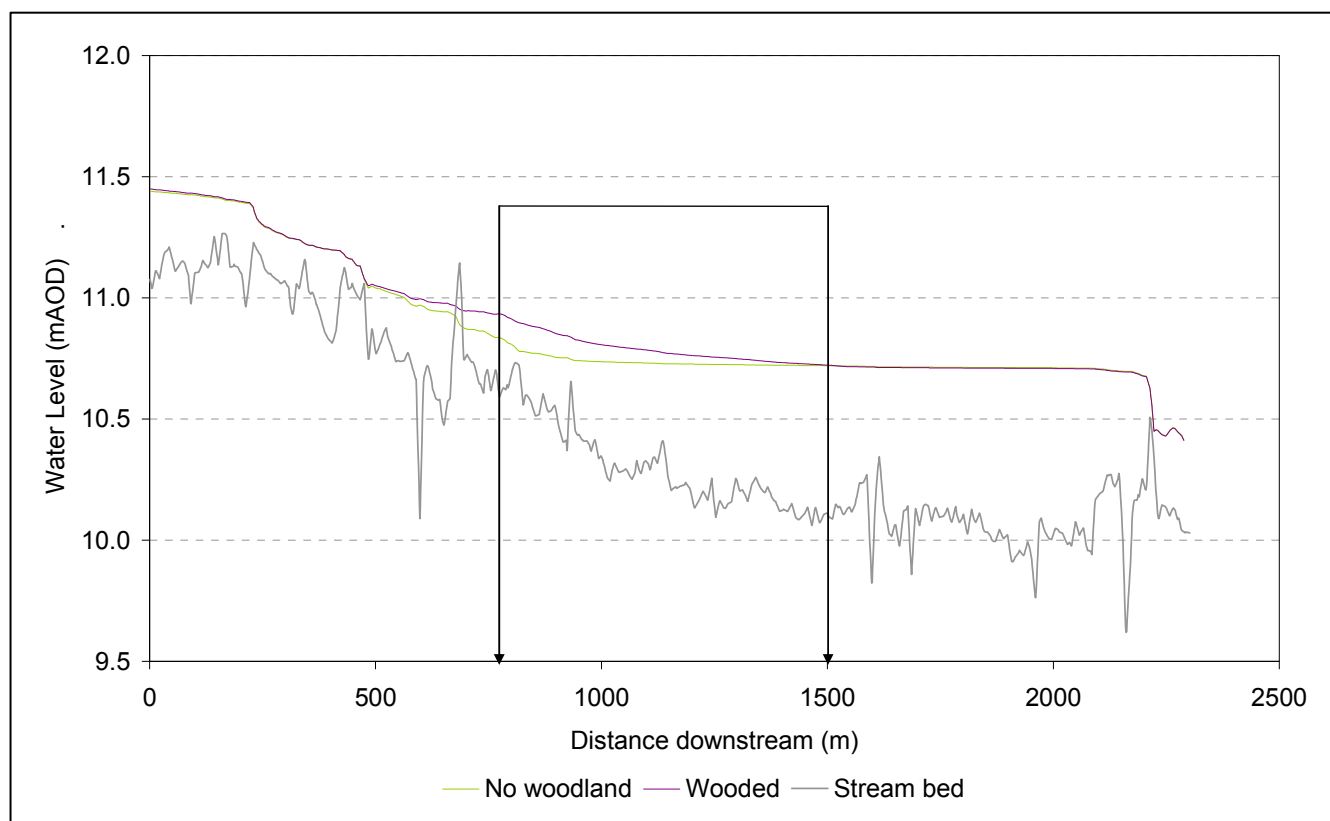
Figure 16. Floodplain woodland can cause a backing-up of floodwaters. Plot shows the modelled extent of this effect upstream of a 50 ha block of floodplain woodland in the River Cary catchment in Somerset; arrows show upstream and downstream limit of woodland (from Thomas and Nisbet, 2006).

A second constraint relates to the risk of LWD being washed downstream and blocking key structures such as bridges and culverts. There are a number of examples of LWD contributing to major flood events and causing problems for flood management.

However, questions remain about the ability of floodplain and riparian woodland to retain or release LWD. For example, it is possible that past problems have resulted from the clearance of woodland and the loss of its trapping function. There is a need for research to assess LWD dynamics and the stability of LWD dams, but in the interim a precautionary approach is warranted and catchments with a history of LWD contributing to flooding by blocking known pinchpoints in downstream towns and cities should be avoided for any major upstream planting in the floodplain. The effectiveness of measures designed to trap LWD such as the planting of transverse woodland strips or hedgerows in appropriate locations merits study.

Another constraint is the presence of existing flood defences, which help to contain and convey floodwaters quickly downstream. The planting of floodplain or riparian woodland within these flood zones could have an adverse effect by synchronising and so enhancing flood flows. Woodland could also weaken flood embankments due to windblow and pose problems for maintenance by restricting access. Planting beyond flood embankments is more acceptable but would provide little benefit for flood attenuation due to being disconnected from all but very extreme flood flows. Even when flood flows top embankments and inundate adjacent woodland, the standing nature of floodwaters severely limits the scope for any flood lag effect. This also holds for planting within managed washlands, although woodland may provide a more flood tolerant land use with higher biodiversity compared to open wetland. Armbruster *et al. (*2004) provides a detailed review of the tree species best suited to washlands to withstand flooding.

The need to protect open wetland habitats also restricts the scope of woodland planting, as will the presence of buried archaeology that could be damaged by tree rooting or windblow. Planting below flood risk sites would obviously confer no benefit for flood management, while Grade 1 or 2 agricultural land is likely to be too expensive and better suited to food production. Lastly, catchments with insufficient water to maintain ecological flows or water demands may be unsuitable due to the potential high water use of woodland, although this could be largely controlled by appropriate species selection.

The main circumstances where the planting of floodplain and riparian woodland should not be encouraged are where the backing-up of floodwaters upstream of the woodland could threaten local properties, there is a risk of LWD being washed downstream and blocking key structures such as bridges and culverts, or where there is a threat to existing flood defences, buried archaeology or important open wetland habitats.

3.5 Riparian management

How can woodland aid/hinder good ecological status in surface waters?
The five main risks to achieving good ecological status in the 7816 surface water bodies of England and Wales are geomorphological changes due to river engineering (43%) and diffuse pollution from nitrate (29%), phosphate (28.7%), pesticides (17%), and

sediment delivery (16.4%) (Environment Agency, 2005a). Riparian woodland can potentially play an important role in mitigating against all of these (Parrott and MacKenzie 2000). Firstly, the binding action of tree roots can help to strengthen and stabilise river banks, reducing erosion and bank collapse (Broadmeadow and Nisbet, 2004; Luke *et al.*, 2007). This leads to narrower, deeper river channels with less siltation and more shelter for fish. Riparian woodland can also protect river banks by restricting access by livestock to preferred reaches where the damaging effects of trampling can be better controlled and managed. The entry of LWD makes an important contribution to improving river channel morphology by creating debris dams and associated pools. These promote the retention of organic matter, increasing in-stream processing and productivity to the benefit of stream ecology. LWD dams can also reduce and delay downstream sediment movement and thereby help to control siltation (Hassan *et al.*, 2005).

Another way that riparian woodland reduces sediment levels is by intercepting sediment entrained in surface run-off from the adjacent land (Broadmeadow and Nisbet, 2004). The action of herbaceous vegetation and dead wood in slowing down run-off and trapping sediment, combined with the high infiltration rates of woodland soils, helps to reduce sediment delivery to watercourses. Sediment retention also aids the removal and fixation of bound pesticides and phosphate, so reducing the risk of diffuse pollution. Nutrient removal is further enhanced by tree uptake and through microbial processes within riparian woodland soils (Broadmeadow and Nisbet, 2002; Haggard and Storm, 2003; Luke *et al.*, 2007). These, including microbial denitrification, can play an important role in nitrate removal and maintaining a supply of clean, oxygenated water (Soulsby *et al.*, 2005). For riparian woodland to be most effective in reducing diffuse pollution however, land drains from the adjacent land need to terminate before the woodland edge to maximise contact between drainage waters and riparian soils.

The ability of riparian woodland to moderate the stream microclimate is expected to become an increasingly important benefit to stream ecology (Hannah *et al.*, 2008; Malcolm *et al.*, 2008; Broadmeadow *et al.*, 2010). Some species of fish such as salmon and trout are very sensitive to water temperature and thus are believed to be at risk from climate warming. A study by Broadmeadow *et al.* (2010) in the New Forest in southern England found that water temperatures in open grassland sections on hot summer days regularly exceed the lethal limit of 25 °C for brown trout, while they rarely rose above 20 °C in shaded wooded sections (Figure 17). This confirms the important role of riparian woodland in providing a cool water refuge for protecting fish and other aquatic life from summer warming. Trees also benefit fish by providing a food source through the direct input of terrestrial invertebrates that fall from the canopy and indirectly through leaf litter, which supports macroinvertebrate communities (Broadmeadow and Nisbet, 2004; Danger and Robson, 2004).
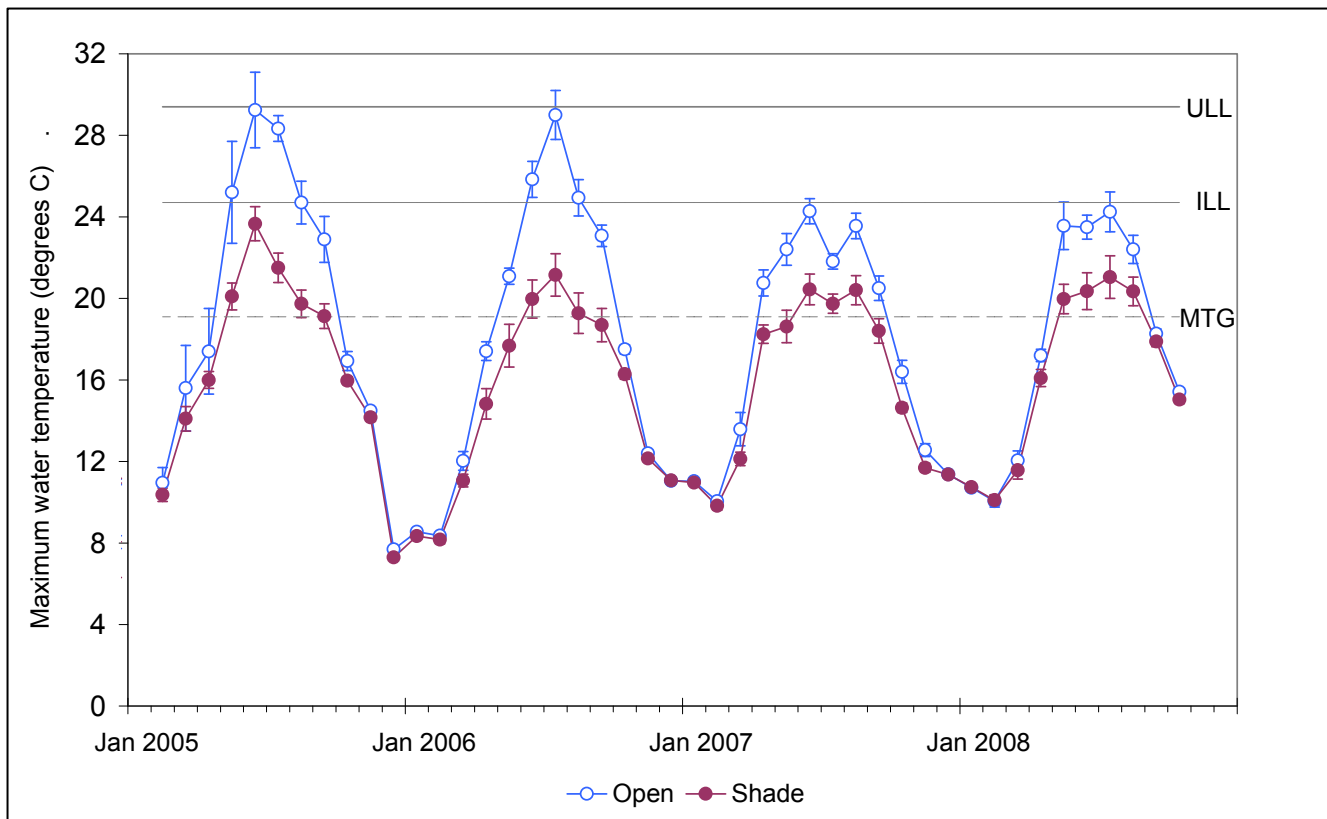
Figure 17. Woodland shade is expected to become increasingly important for reducing thermal stress to fish. Plot compares measured annual variation in water temperature between shaded and open stream reaches in the New Forest in southern England in relation to temperature limits for salmonid fish: ULL = Ultimate lethal limit; ILL = Incipient lethal limit; MTG = Maximum temperature for growth (from Broadmeadow *et al.,* 2010).

Another benefit of shading is in controlling weed and filamentous algal growth, and possibly the spread of invasive weeds. Algal growth has been implicated in the poor status of some freshwater pearl mussel populations, while mussel densities have been found to be positively related to the level of riparian woodland shade (Lucey, 1993; Gittings *et al.,* 1998). The felling of bankside trees has been implicated in the decline of some freshwater pearl mussel populations in Germany (Young *et al.,* 2001), while the restoration of native woodland has been advocated as a way of mitigating the potential adverse effects of climate change on surviving populations (Hastie *et al.,* 2003).

Riparian woodland has also been associated with some negative impacts on stream ecology (Broadmeadow and Nisbet, 2004; Malcolm *et al.,* 2004). The main one concerns the effects of excessive shading, largely associated with conifer plantations planted too close to streamsides. This can lead to bare stream banks, increased erosion and

siltation, and channel widening, resulting in impoverished stream habitat. A related issue is the increased risk of bank disturbance from windblown trees. This is greatest for conifer crops in exposed areas, especially where adjacent stands are felled up to one stream bank. Windblow is also cited as a problem for planting trees close to flood embankments, although a study by MacDonald *et al. (*2003) found little evidence of decreased bank stability resulting from blown trees.

The impact of LWD dams associated with riparian woodland is another cause for concern. Many view these dams as a barrier to migrating fish and have traditionally removed them from affected streams. However, studies have shown that LWD is very beneficial to stream ecology and dams only restrict fish movement if they become sealed with sediment and fine wood material (Broadmeadow and Nisbet, 2004). Other problems associated with LWD mainly affect river and flood management and are covered under related questions.

Finally, the potential high water use of some riparian tree species could pose a problem for maintaining ecological flows in drought prone areas. In particular, willow and poplar trees can maintain high evaporation losses when well supplied with water and therefore could contribute to the cessation of summer low flows along smaller streams and rivers, especially where flows are at risk from over-abstraction. However this could be offset by the increased water storage associated with LWD dams. No studies have appeared to quantify the impact of riparian woodland on river flows.

In summary, riparian woodland has generally been found to protect or enhance good ecological status, with exceptions mainly linked to poorly designed and managed conifer plantations within upland areas. The benefit of riparian woodland for mitigating the impact of climate warming on the freshwater environment is likely to become increasingly important and thus there is a strong case for developing appropriate models to help guide the optimum design and management of riparian woodland for this purpose (e.g. in terms of species choice, woodland structure and woodland cover).

How can riparian woodland management contribute to improving morphological status?

The WFD recognises that the morphological condition of water bodies is a key element of ecological status. A modelling tool 'MimAS' has been developed in the UK to assess the morphological status of rivers and the impact of various pressures or alterations. The tool uses a concept of 'system capacity' and a set of Morphological Condition Limits. One of the alterations considered by the tool is the loss of riparian vegetation or a reduction in its condition. A complex (>3 dominant vegetation types), continuous or semi-continuous cover (>50%) of natural woody vegetation is generally considered to represent the best riparian vegetation for protecting morphological status. Exceptions include open wetlands and riparian zones above the natural tree line.

The FC Forests & Water Guidelines (Forestry Commission, 2003) are in line with the river MimAS tool by recommending that riparian woodland management should aim to establish and maintain an open, native woodland canopy based on an intricate mix of five vegetation habitat types: open ground, occasional large trees, trees with open glades, scrub thicket and closed canopy woodland. They describe how species choice, structure and width of riparian woodland influence the ecological integrity and diversity of aquatic habitats and how these are best managed to protect ecological status. A key need is to determine the desired level of shade in relation to the requirements of different water users and to manage this accordingly by interventions in the form of thinning, pollarding, coppicing or felling. In general, the level of shade should be sufficient to allow the development of a more or less continuous cover of ground and bankside vegetation, which is best achieved by aiming for a 50% cover of dappled shade from trees and shrubs. A long-term programme is underway across Britain to clear back older-aged conifer plantations from streamsides and restore riparian areas to native woodland, in line with WFD objectives for improving morphological status. More detailed guidance on riparian woodland management for protecting morphological and wider ecological status is provided by FC (1990, 1994), Parrott and MacKenzie (2000) and Broadmeadow and Nisbet (2002).

A complex, continuous or semi-continuous cover of natural woody vegetation is considered to represent the best riparian vegetation for protecting morphological status. Riparian woodland management has an important role to play in maintaining the desired structure of riparian vegetation by regular interventions in the form of thinning, pollarding, coppicing or felling. A long-term programme is underway across Britain to clear back older-aged conifer plantations from streamsides and restore riparian areas to native woodland, in line with WFD objectives for improving morphological status.

Are there specific measures that might promote this benefit?
As already noted, regular management of riparian woodland is required to sustain the optimum vegetation structure for supporting good ecological status. Thinning, pollarding, coppicing and selective felling are the main measures used to control the level of shade to maintain an open woodland canopy with occasional old, large trees and a cover of ground vegetation. Appropriate species choice is also important, for example avoiding planting large blocks of heavy shading species such as oak and alder and instead interspersing these with lighter foliage species such as birch, rowan and willow (Broadmeadow and Nisbet, 2002). LWD should be retained within streams, especially where stable dams are formed, and only removed if it presents a significant barrier to fish movement (e.g. where dams become infilled with sediment) or poses a flood risk. Such management interventions may not be cost effective or beneficial to landowners and therefore often neglected without financial support. Woodland grants are available from the FC for sustaining the environmental and social benefits provided by woodland but only now are these starting to be targeted at riparian woodlands or water benefits.

Alternative payments for woodland restoration and woodland maintenance remain untargeted for delivering water benefits, such as under Higher Level Stewardship within Joint Character Areas.

For larger forests, Forest Design Plans in State Forests and Forest Plans within the private sector outline the felling, thinning and restocking work to be carried out over a 20 year period. These plans need to be approved by the FC, who check that the work will meet the standards of their environmental guidelines, including those for water. This provides a way of co-ordinating/integrating the felling and restoration of riparian zones within and between existing forests to achieve good morphological status of river water bodies. In Scotland, a data base has been constructed for all woodlands lying within 100 m of watercourses draining to water bodies considered to be at risk of failing good morphological status. The data base shows the forest plans and management agreements in place and allows the progress in felling work and the restoration of native riparian woodland to be monitored against the desired time scale, in line with WFD objectives.

Regular management of riparian woodland is required to sustain the optimum vegetation structure for protecting morphological status. This requires financial support in the form of Woodland Management or Improvement Grants. Forest Design Plans in State Forests and Forest Plans within the private sector have an important role to play in of co-ordinating, integrating and monitoring conifer felling and restoration work in riparian zones to achieve good morphological status of river water bodies within the desired time scale, in line with WFD objectives.

Are there any woodland measures that could be developed to benefit surface water ecology?

The Forests & Water Guidelines (FC, 2003) describe a large range of measures designed to control risks and maximise benefits for surface water ecology. A separate section addresses riparian woodland and the establishment of a buffer area both in existing forests and new planting to protect the riparian and aquatic zones from disturbance. Key aspects of the design of the riparian buffer to benefit the freshwater environment are management, width, species choice and structure. A 20 m wide buffer of open, native woodland, providing 50% dappled shade, is recommended for protecting good water status on larger streams and rivers. The inclusion of a grassland edge has also been shown to benefit sediment retention (Daniel and Gilliam, 1996).

As noted above, regular management of riparian woodland can enhance the benefits for surface water ecology. A programme of thinning, pollarding, coppicing or selective felling will not only help to maintain ground flora important for the filtering and trapping of suspended sediment but also improve tree growth and the uptake of nutrients. Another

benefit of management is to achieve a balanced woodland age structure, including some older trees to maintain inputs of LWD to stream channels.

Measures to encourage the planting of new riparian woodland buffers within agricultural and urban landscapes probably offer the greatest potential to benefit surface water ecology. The general absence or poor condition of riparian woodland in these landscapes presents widespread opportunities for new planting. Consequently, there is a need to target woodland creation to where it can do most benefit. Preferred locations include along water bodies failing good status due to diffuse pollution or morphological pressures. Mapping of risk factors, pollutant sources and constraints can help to guide site selection, as can opportunities for providing added value, such as contributing to flood risk management or 'growing' a woodland habitat network for biodiversity gain. Blocking of land drains would help to dissipate polluted run-off and promote pollutant retention and uptake by riparian woodland buffers, so increasing their effectiveness in tackling diffuse pollution.

Support for planting new riparian woodland is provided by FC England's Woodland Creation Grant, although a minimum limit of 15 m is set for the width of new stands. However, smaller areas can be funded under the Higher Level Stewardship scheme. There is also support for planting riparian woodland within the Rural Priority options under the SRDP and by BWW grants in Wales. Most of these schemes receive 'standard' woodland grant payments but there is scope for extending and further developing the use of additional funding contributions to help promote and target planting to where water benefits are greatest.

The Forests & Water Guidelines describe a large range of measures designed to control risks and maximise benefits for surface water ecology. A key measure is the regular management of the riparian zone to benefit the freshwater environment, with the aim being to maintain a 20 m wide buffer of open, native woodland, providing 50% dappled shade, for protecting good water status on larger streams and rivers. Measures, including funding to encourage the planting of new riparian woodland buffers within agricultural and urban landscapes probably offer the greatest potential to benefit surface water ecology.

Could woodland, coppice or energy crops be used to increase effectiveness as a buffer and/or increase the productivity of the land?

As already noted, coppicing can increase the effectiveness of riparian woodland buffers by maintaining the optimum vegetation structure for river morphology and sediment trapping, and by enhancing tree growth and thereby nutrient uptake. Coppicing is also an effective measure for increasing hydraulic roughness and delaying flood flows. Additional gains can result from SRC for energy crops by further promoting vegetation roughness and productivity. The planting of high yielding willow and poplar clones has

been shown to be very effective at removing nutrients and reducing the oxygen demand of sewage effluent (Britt *et al.,* 2002; Berndes, 2006; Sims and Riddell-Black, 1998; Sugiura *et al.,* 2008b). Similarly, the rapid growth and multi-stemmed nature of these crops makes them ideally suited to flood risk management. Available payments for the planting of energy crops and income generated by selling the harvested biomass also makes this an attractive option for landowners.

SRW offers similar benefits to SRC for promoting nutrient uptake but is probably less effective at delaying flood flows due to the lower hydraulic roughness associated with single stemmed trees. However, the latter will be at least partly offset by the longer crop rotation (8-20 years) and thus extended presence of the woodland under SRW compared SRC (typically 4 year rotation). The impact of the frequent cropping under SRC could be controlled through appropriate design, ensuring that harvesting work is correctly phased to maintain maximum roughness.

It is important to note that both forms of energy crop present a number of threats to stream ecology. These include the risk of ground damage and increased erosion and sediment delivery due to more frequent harvesting operations, especially under SRC systems compared to conventional forestry (Armstrong, 1999). Heavy shading will eliminate ground vegetation and therefore reinforce the need to include a grass edge to promote sediment trapping. Other threats include the potential increased water use of energy crops, which can threaten water resources and the maintenance of ecological flows in rivers (Calder *et al.,* 2009). This could be managed by species choice, with a recent modelling study by Calder *et al. (*2009) suggesting that Fraxinus excelsior (Common ash) could generate a higher water yield than grass, although biomass yields are likely to be less than for more exotic tree species associated with a high water use, such as eucalyptus. However, water use rates may have been overpredicted since Eastham *et al. (*1990) found that the water use efficiency (ratio of biomass produced per unit volume of water evaporated) increased in densely planted biomass plantations and rising carbon dioxide concentrations may further enhance this factor in the future. Energy crops could also reduce the carbon content of organic-rich riparian soils, which needs to be considered when assessing the impact on the overall carbon budget, as part of a whole life-cycle analysis.

Coppicing and energy crops can increase the effectiveness of riparian woodland buffers by maintaining the optimum vegetation structure for river morphology and sediment trapping, by enhancing tree growth and thereby nutrient uptake, and by increasing hydraulic roughness and delaying flood flows. However, these systems also pose a number of threats to stream ecology, including an increased risk of ground damage, erosion and sediment delivery due to more frequent harvesting operations, and reduced water supplies and ecological flows due to higher water use.

3.6 Climate change

Observational records and model projections indicate that freshwater resources have the potential to be strongly impacted by climate change (Bates *et al.,* 2008). The UK Climate Impacts Programme's (UKCIP) most probable climate change scenario suggests a gradual warming across the whole of the UK, with summer and winter temperatures rising by some 2-3ºC by the end of this century. Winters are predicted to be around 20% wetter, while summers could be 20% drier in the south and 5% wetter in the north. These changes are likely to affect both the timing and volume of river flows and extent of groundwater recharge, with knock-on effects for water quality and streamwater ecology.

Are there any species or locational considerations in relation to targeting new woodland to protect water?
One of the key water impacts linked to climate change is the increased risk of flooding due to wetter winters and more frequent extreme rainfall events (Nisbet, 2002). While new flood defence schemes typically allow for a 20% enhancement of flood flows (Environment Agency, 2005b), sites reliant on existing schemes or without protection face a rising threat of flood damage. Consequently, attention is increasingly turning to the potential role of land use and land management as a way of managing flood risk at the catchment scale. The opportunities provided by woodland creation to help attenuate local and larger-scale flooding are likely to become increasingly attractive in appropriate locations and best addressed within CFMPs. Species choice can be an important consideration for enhancing the effectiveness of woodlands for reducing flood generation or conveyance, e.g. by affecting water use and vegetation roughness (Nisbet and Thomas, 2006).

Species choice is expected to be even more important when addressing the impact of climate change on water supplies. The projected decrease in summer rainfall and increased evaporation, especially in southern and eastern Britain, represents a serious threat to future water supplies. Water demand already exceeds supply during dry summers in the south and is predicted to rise by 15-27% between 1990 and 2021 due to population growth and warmer temperatures (National Rivers Authority, 1994). The high water use of conifer woodland can cause a disproportionately large reduction in river flows and groundwater recharge in drier regions of the country due to the smaller quantity of rainfall and thus effective drainage. Since reductions of 7% or more are possible for every 10% of an aquifer where conifer replaces grass or arable land, large-scale planting of new conifer woodland should be avoided within areas of low water availability (Nisbet, 2005).

The lower water use of broadleaved woodland poses much less of a threat and could enhance water supplies in some locations (Roberts and Rosier, 2005). The main risk of broadleaved woodland reducing water yield is on sandy soils within dry regions, such as

the Triassic Sandstone Aquifer in the English Midlands. In contrast, woodland planting may increase water yield on clay soils or soils overlying chalk, especially involving lighter foliaged species such as ash. However, the overall impact of new broadleaved woodland on water yield and groundwater recharge is likely to be relatively small and therefore can probably be ignored except where planting occurs on a large scale within a given catchment or aquifer.

The only other exception concerns the planting of SRC or SRW crops. Studies in southern England show that poplar and willow planted as SRC can have a high water use when well supplied with water, reducing recharge volumes on average by at least 6.0% per 10% SRC cover compared to cereals in the final year before cutting (Hall *et al.,* 1996). Planting of these energy crops on any sizeable scale is therefore probably best avoided in locations where water demand is expected to exceed available supplies. Hall (2003) provides guidelines on identifying suitable locations in England and Wales for planting SRC where the benefits for biomass production are expected to outweigh the hydrological impacts. Southeast England is most at risk, with the guidelines recommending that only a small proportion of a catchment should be planted where the annual precipitation is <600 mm, due to SRC using all of the effective precipitation. The only caveat is for sites with shallow soils, where the lack of water will severely restrict both SRC water use and productivity, such that recharge volumes are likely to be similar to those for grass or arable crops.

Recent modelling suggests that extensive planting of SRW crops could also threaten water supplies in dry regions (Calder *et al.,* 2009) (Figure 18). Planting of potentially higher yielding exotic species such as eucalyptus or southern beech was predicted to have serious implications for water resources in areas receiving <800 mm rainfall, reducing the mean annual water yield by 2080 for a given area of SRW from a mean of 86 mm under grass to a mean of only 9 mm under the exotic species, based on a low emissions scenario. However, this was in sharp contrast to planting native ash as SRW, which was predicted to increase water yield by 2080 by a margin of 1.5 to 20.2% per 10% cover, compared to grass. If these predictions prove to be correct, this would represent a very attractive land use option for mitigating the impacts of climate change in terms of both water and energy production.

It is important to note that important gaps remain in our knowledge of the impact of climate change on tree water use, especially for trees grown under SRW systems, where very little experimental data is available and none for the UK. A major uncertainty concerns the effect of rising CO_2 levels on tree water use efficiency. Stomatal conductance and water use are generally reduced at higher CO_2 (Broadmeadow and Randle, 2002), with reductions of 19-40% having been recorded in experimental studies for a range of species (Lodge *et al.,* 2001; Hungate *et al.,* 2002). Another issue is the impact of increasing soil water stress due to summer drying on evaporation rates, which

is predicted to lead to a convergence in water yields from woodland and grass through time (Calder *et al.,* 2009).
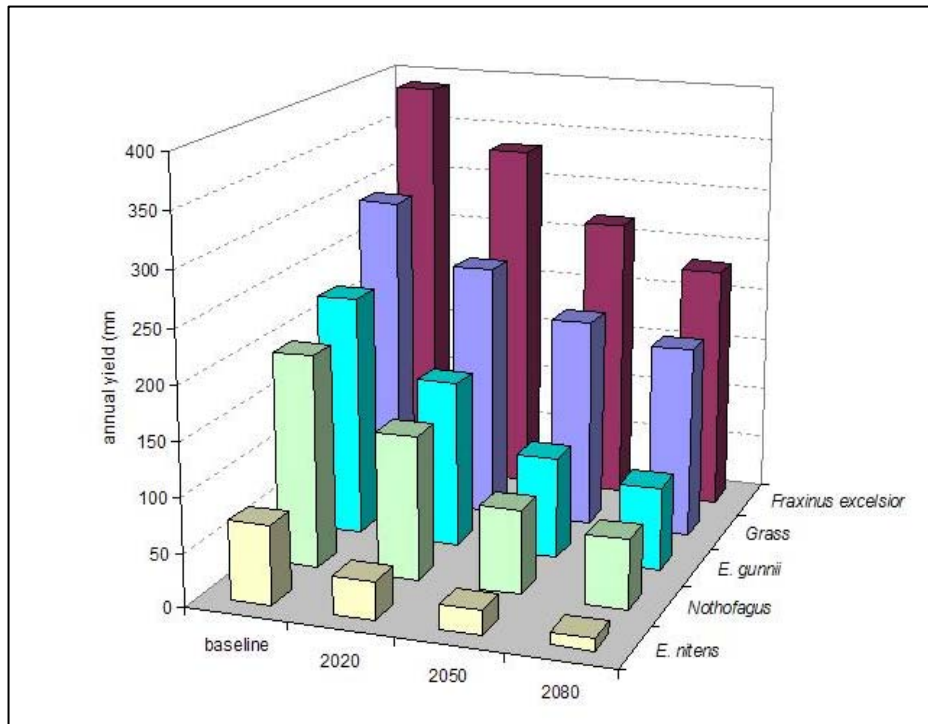
Figure 18. Extensive planting of exotic tree species such as eucalyptus as SRW could have serious implications for water resources. Plot compares model predictions of annual water yield for different tree species with grass at Alice Holt in South England for UKCIP02 Low Emission climate change scenarios (from Calder *et al.,* 2009).

As already noted, the ability of riparian woodland to moderate stream temperature is likely to become increasingly important for managing the impact of climate warming on the freshwater environment. Smaller streams and rivers in southern Britain are probably most at risk from water temperatures exceeding lethal limits for sensitive fish species such as trout and salmon (Broadmeadow *et al.,* 2010). While groundwater dominated systems will be less sensitive to warming, drier summers and increasing water demand are likely to reduce the thermal buffering from these cooler waters. Fisheries in northern parts may benefit from warmer waters enhancing growth and productivity but spawning in upland streams could be adversely affected by rising temperatures exceeding the optimum thermal range for egg development. Riparian woodland shade could also become more important for managing the spread of invasive species, which may be favoured by climate change.

As well as posing a threat to maintaining water supplies in drought prone areas, the high water use of conifer woodland can indirectly threaten water quality due to an

evaporation-concentration effect (Calder *et al.,* 2002). The greatest impact appears to be on nitrate levels, with the low rate of recharge beneath conifers leading to rising nitrate concentrations in groundwater, which could eventually exceed drinking water standards. To minimise this risk, the Forests & Water Guidelines recommend avoiding large scale new planting of conifers within Nitrate Vulnerable Zones receiving <650 mm annual rainfall. The extent of this area is likely to increase with climate change.

Another water quality issue concerns the impact of climate change on surface water acidification. Wetter and cloudier winters could increase the scavenging of acid deposition by woodland, especially conifers, as well as promote the leaching of base cations. This may offset the benefits of emission control and delay the recovery of acidified waters. Consequently, constraints on new conifer planting within acid-sensitive areas are likely to remain for some time. However, this effect may be countered by higher soil temperatures increasing mineral weathering rates and soil buffering capacity. Increases in forest productivity due to warming and higher CO_2 are also likely to enhance nitrate uptake and possibly reduce nitrate leaching, helping to reduce the risk of nitrate saturation and thus acidification (Emmett and Reynolds, 1996).

In conclusion, climate change could have wide ranging impacts on water quality and quantity. New woodland planting can help to moderate some of these, such as managing the predicted rise in flood risk and controlling the threats posed by warmer water temperatures. However, woodland expansion also poses some problems, mainly linked to the high water use of conifers and some broadleaves, especially when grown as energy crops. Good design and attention to species choice can help to minimise these threats. In light of the complexity of the issues and lack of data, continuation of monitoring and research will be very important.

In what circumstances can WFD and climate change mitigation measures be complimentary?

Since most forests and woodland promote carbon sequestration, new woodland planting will generally help to mitigate climate change (Morison *et al.,* 2008). Sequestration is potentially greatest for higher yielding conifer species or broadleaves grown under SRC or SRW systems. In contrast, woodland benefits for water are likely to be greatest for native broadleaved woodland and therefore this type of planting tends to be more complementary to meeting both WFD and climate change mitigation objectives. Funding measures designed to expand riparian and floodplain woodland probably offer the greatest synergy by reducing flood risk, retaining diffuse pollutants, improving river morphology, mitigating rises in water temperature and increasing carbon storage (Scott *et al.,* 2004), as well as providing a number of other benefits, especially for biodiversity.

There is potential to maximise complementarity through planting of SRC and SRW in appropriate locations as part of riparian and floodplain woodlands. Providing drought

prone sites are avoided, energy crops can offer additional advantages for water protection, flood risk management and climate change mitigation by enhancing pollutant uptake and sediment retention, more rapid establishment of vegetation roughness (especially for SRC) and increased carbon sequestration, as well as a more attractive and faster economic return for landowners.

Targeted planting of broadleaved woodland to intercept run-off such as within infiltration basins, downslope field boundaries and within SUDS also presents complementary benefits for reducing diffuse pollution, flood attenuation, carbon storage and soil protection.

The water and other benefits arising from the planting of native broadleaved woodland tend to be more complementary to meeting both WFD and climate change mitigation objectives. Measures designed to expand riparian and floodplain woodland probably offer the greatest synergy by reducing flood risk, retaining diffuse pollutants, improving river morphology, mitigating rises in water temperature and increasing carbon storage, as well as providing a number of wider benefits, especially for biodiversity.

In what circumstances might woodland creation and management for climate change mitigation have a detrimental effect on meeting WFD objectives?
The main circumstance where woodland creation for climate change mitigation could have a detrimental effect on meeting WFD objectives concerns the large scale planting of conifer woodland or energy crops. The large potential biomass yields of these woodland types promotes carbon sequestration but at a cost of high water use and markedly reduced ecological flows and water supplies. Lower recharge also indirectly affects water quality due to the evaporation concentration effect. This can manifest itself by rising nitrate concentrations exceeding water standards, especially in areas receiving <650 mm annual rainfall. In addition, energy crops pose risks of increased soil damage and sediment delivery associated with frequent harvesting operations (especially for SRC), which will usually be constrained to winter periods due to biodiversity issues. However, these risks can be minimised by good woodland design and management.

An expansion of upland conifer woodland for carbon sequestration could result in greater scavenging of acid deposition and thus increased surface water acidification within acid-sensitive areas. Climate change could accentuate this trend due to higher rainfall, longer duration cloud cover and more storm events. Measures designed to increase biomass yields from existing woodland and forests such as the extraction of harvesting residues could also contribute to increased soil and water acidification. The growing pressure to harvest tree stumps for wood fuel poses a range of threats, including an increased risk of ground damage leading to erosion and siltation, as well as greater acidification due to the increased removal of soil base cations (Forest Research, 2009). More work is needed to quantify these risks and assist with identifying suitable sites for stump harvesting.

An intensification of management practices within existing forests to enhance tree growth for carbon sequestration could present increased risks to the freshwater environment. For example, more intensive cultivation, drainage, fertilisation or harvesting regimes could increase ground damage, sediment delivery and nutrient run-off, with the potential to result in diffuse pollution. This risk could be further enhanced by wetter winters and more frequent storms due to climate change, leading to increased soil waterlogging and higher peak flows. However, the application and further development of good practice offers significant scope for reducing the threats to soil and waters.

The main circumstance where woodland creation for climate change mitigation could have a detrimental effect on meeting WFD objectives concerns the large scale planting of conifer woodland or energy crops. Planting presents a potential high cost to water in terms of increased water use and reduced ecological flows and water supplies, as well as an increased risk of diffuse water pollution resulting from an intensification of forestry practices such as the greater harvesting of woody residues.

3.7 Contaminated land and waste

When planted and managed as part of a controlled programme, trees and woodland can play an important role in the rehabilitation of derelict land, including landfill sites. Benefits include visual remediation, reducing 'fit for use' restoration costs, reducing mobilisation and leakage of contaminants and, in some cases, treatment (phytoremediation) of contamination (Figure 19).
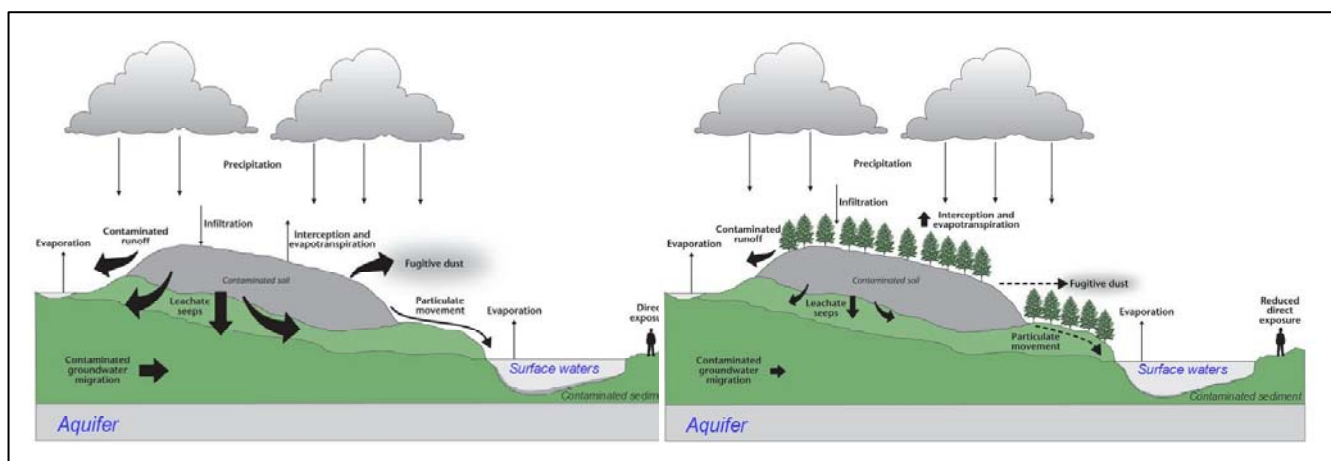
Figure 19. Woodland creation can play an important role in the rehabilitation of contaminated land. Conceptual diagram compares relative fluxes and pathways of contaminants for wooded vs non-wooded sites (from Hutchings, 2002).

Is woodland being utilised to its full potential in protecting good status or lowering the risk to water bodies from contaminated land?

There are up to 300,000 ha of contaminated land in England and Wales (Environment Agency, 2005a), some of which may have the potential to pollute both surface waters and groundwaters. Remediation efforts have tended to focus on soil rather than water (Rivett *et al.,* 2002), with many sites requiring chemical treatment or soil removal to permit revegetation. Partially treated or lighter contaminated sites are well suited for conversion to woodland, with the benefits of using trees and woody biomass in remediating contaminated land being well documented (Jones Jr. *et al.,* 2001; Pulford and Watson, 2003; French *et al.,* 2006; Strycharz and Newman, 2009).

Trees can assist remediation in a number of ways: by helping to enrich the soil with organic matter, which is important for immobilising many contaminants (Hutchings, 2002); by providing a semi-permanent landcover, reducing the risk of soil disturbance and erosion (ibid.); by reducing surface run-off/groundwater recharge and thus the potential for leaching of contaminants to water (ibid.); and by the active uptake of contaminants and fixation in woody biomass (Dickinson *et al.,* 2009). There is also a role for planting woodland adjacent to contaminated land, which can help to reduce the offsite migration of contaminants by intercepting polluted run-off and by reducing wind erosion and trapping airborne contaminated soil. At a more basic level, woodland provides an effective way of screening contaminated sites and discouraging access.

Although woodland offers potential in helping to manage and remediate contaminated land, it may not be suitable for all sites. For example, the tendency for some types of woodland to acidify the soil could enhance the mobilisation of certain metal contaminants within inadequately buffered materials. Heavy shading could also pose a problem by restricting the growth of ground vegetation and exposing bare soil to increased erosion. The risk of fire releasing and spreading contaminants may also be a concern. Most of these threats, however, can be controlled by good woodland design and management practices.

Woodland is not being utilised to its full potential to reduce the risks to water bodies from contaminated land. Only a minor fraction of the 300,000 ha of contaminated land in England and Wales has been restored to woodland. Trees can assist remediation by: enriching the soil with organic matter, which is important for immobilising many contaminants; by providing a semi-permanent landcover, reducing the risk of soil disturbance and erosion; by reducing surface run-off/groundwater recharge and thus the potential for leaching of contaminants to water; and by the active uptake of contaminants and fixation in woody biomass.

How can meeting such objectives best be realised/targeted?

A key need is to raise awareness among policy makers and planners of the benefits of using woodland for managing and remediating contaminated land. The establishment of regional demonstration sites and provision of appropriate guidance would greatly help in this regard. Major difficulties include the lack of information on the nature of the contamination on many sites, high spatial variation in the level of contamination, securing the long-term management of such sites and agreeing responsibilities and costs. Public sector ownership can provide longer-term security but the transfer of responsibilities presents problems and needs to be carefully managed. Although each site is different, classification into broad categories in terms of the nature of the contamination or previous land use would help to rank sites and translate approaches between common site types. Individual sites would require a detailed site assessment to determine the potential for woodland remediation and to plan accordingly. Long-term monitoring and evaluation is often overlooked or deficient but has a very important role to play in determining and demonstrating success, building an evidence base, and identifying best practice. Partnership funding is usually required to cover the costs of remediation and assessment work. If all of these issues can be addressed, woodland offers a sustainable, relatively low-cost, reclamation strategy for contaminated land, with the potential to make a positive contribution to ecology and quality of life for local people (Handley and Perry, 1998; Dickinson, 2000).

The main need is to raise awareness among policy makers and planners of the benefits of using woodland for managing and remediating contaminated land. The establishment of regional demonstration sites and provision of appropriate guidance would greatly help in this regard.

Can woodland safely be used for the disposal of waste materials?

Woodlands have been used as a repository for a range of wastes, including abattoir waste, landfill leachates, sugar processing wastes, paper mill sludge and sewage sludge. Some of these in appropriate amounts and on certain site types can act as soil improvers by increasing soil fertility and improving soil structure and drainage (Bayes *et al.,* 1991). They can have a particularly positive role to play in reclaiming ex-mineral and brownfield land, promoting revegetation and the establishment of woodland (Moffat, 2006). However, applications need to be carefully planned and managed as they pose a high risk of soil and water pollution where rates exceed the capacity of the soil and vegetation to utilise and store the nutrients and other chemicals applied. Wastes with potential high levels of toxic compounds present the greatest threat and need to be carefully controlled. This includes sewage sludge, which often contains heavy metals and organic contaminates such as polychlorinated biphenyls.

There is a strict legal framework for the disposal of industrial wastes on land that helps to ensure the risks of pollution are minimised. Disposal of amounts that exceed those

commensurate with improving long-term site productivity are not permitted under the Waste Management Licensing Regulations (2005). Some wastes are exempt from licensing such as waste soil, bark and compost, provided they are applied at no more than prescribed rates and applications will result in ecological improvement. Sewage sludge represents the most common waste applied to forestry and is controlled by The Sludge (Use in agriculture) Regulations 1989. Taylor and Moffat (1991) estimated that about 75,000 ha of forest in Great Britain could benefit from the nutritional effects of sewage sludge, although the area currently treated is a minor fraction of this. Constraints on applications include the remoteness of most forests from sewage sources, limited access to tree stands and public concern over treatments. Application rates are specifically restricted within NVZs and other sensitive areas. The principal risks to water are from nitrate and phosphate leaching and contamination by faecal indicator organisms in run-off. These mainly arise from applications being made under inappropriate conditions or at inappropriate rates (SNIFFER, 2008a). Guidance was published by Wolstenholme *et al. (*1992) to minimise the risk of pollution and this has recently been updated by SNIFFER (2008b). Site studies suggest that the application of good practice is effective at minimising the risk of pollution, leading to the conclusion that sewage sludge application in land reclamation and forestry can be appropriate and beneficial provided appropriate guidelines are followed (SNIFFER, 2008c).

Energy crops are particularly suited to waste applications and can form an effective waste management strategy. For example, applications of sewage sludge and nutrient-rich waste water have been shown to enhance biomass yields of SRC, while the nutrient demand for growth helps to reduce leaching and improve effluent quality (Sims and Riddell-Black, 1998; Britt *et al.,* 2002; Hall 2003; Berndes *et al.,* 2004; Berndes, 2006). SRC has also been shown to be suitable for the application of landfill leachate, with survival rates of 97% or greater for willow, 78% for hazel and 63% for alder (ADAS, 2006). Applications had no effect on the level of six trace metals in the soil or within plant biomass (ADAS, 2006). Daily water balance models such as IRRIGUIDE (Bailey and Spackman, 1996; Silgram *et al.,* 2007) that estimate evapotransipiration and drainage for different land uses can inform site management and provide guidance on the quantity of waste water which may be applied whilst minimising the risk of leaching below the soil root zone.

Woodlands have been successfully used as a repository for a range of wastes, including abattoir waste, landfill leachates, sugar processing wastes, paper mill sludge and sewage sludge. Some of these in appropriate amounts and on certain site types can act as soil improvers by increasing soil fertility and improving soil structure and drainage. They can also have a particularly positive role to play in reclaiming ex-mineral and brownfield land, promoting revegetation and the establishment of woodland. However, applications need to be carefully planned and managed as they pose a high risk of soil and water pollution where rates exceed the capacity of the soil and vegetation to utilise and store

the nutrients and other chemicals applied. Energy crops are particularly suited to waste applications and can form an effective waste management strategy.

If so, how can water quality and WFD objectives be protected?

Adherence to the regulations and implementation of best practice should ensure that water quality and WFD objectives are protected. Good site planning and a site-specific evaluation are essential to determining site suitability, as is early consultation with the appropriate waste regulation body. SNIFFER (2008b) builds on earlier guidance by Wolstenholme *et al. (*1992) and Moffat (2006) and provides a two-stage system for facilitating decision making. The first comprises a site suitability classification based on a standard set of criteria, including site sensitivity, distance from habitation and watercourses, flood risk, slope and topographic complexity. The second stage involves soil sampling to determine soil suitability and a set of recommendations on sludge application method, rate and timing. Key measures to protect surface and groundwater quality include: establishing effective buffer areas along all watercourses; avoiding applications to land that is subject to flooding, where the groundwater table lies within 1 m of the soil surface or is waterlogged; and restricting application rates within NVZs.

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3.8 Land use and spatial planning

Where does new woodland fit in the hierarchy of land use?

Woodland cover in the UK at 13% of land area remains one of the lowest in Europe. National governments acknowledge the need for more woodland for the multiple benefits they provide, including helping to tackle climate change. The multiple values of woodland have been increasingly recognised in recent years and this is helping to push woodland higher up the hierarchy of land use. Although still competing with land use options such as agriculture and urban development, government policy remains focused on supporting the continued expansion of woodland in both urban and rural areas for benefits such as landscape and wildlife conservation, the provision of recreation and access, and the protection of soil and water resources.

Country forestry strategies reflect the potential of woodland to deliver WFD objectives, including highlighting opportunities for woodland to reduce the impact of diffuse pollution from agriculture and urban activities, as well as assist flood risk management. These benefits have also shaped European policy, with a specific Resolution on Forests and Water adopted by the Fifth Ministerial Conference for the Protection of Forestry in Europe (MCPFE, 2007). This recommends action across Europe to better coordinate policies on forests and water, and to incorporate an economic valuation of water-related forest

services. This is in line with the European Union's (EU) rural development regulations, which also call for forest-environment payments to be introduced for voluntary commitments to enhance biodiversity, preserve high-value forest ecosystems and reinforce the protective value of forests and woodlands with respect to soil erosion, maintenance of water resources and water quality, and mitigating natural hazards (EU, 2005).

The implementation of the EU regulations is set out in Defra's UK National Strategy Plan (2006), which recognises that sustainable and competitive agriculture and forestry sectors are a prerequisite for improving the environmental quality of the countryside. The plan identifies common elements that run through the RDP strategies of each country (Scotland, England, Northern Ireland, and Wales), which include the protection and enhancement of natural landscapes in rural areas contributing to three EU level priority areas:

• biodiversity and the preservation and development of high nature value farming and forestry systems and traditional agricultural landscapes;
• water;
• climate change.

Potential means to address these priority areas include:

• improving coverage and/or penetration of agri-environment and woodland creation schemes to increase habitat networks, combat diffuse pollution, and address climate change;
• encouraging energy crops and wood fuel as part of an increasing use of renewable energy.

Since the presentation of the National Plan, these measures have been incorporated into both the RDPE and SRDP (2007-2013), and the Rural Development Plan for Wales (2007-2013). Funding support for woodlands is now provided by the English Woodland Grant Scheme, Rural Development Contracts in Scotland, the Better Woodlands for Wales (BWW) Scheme and Glastir, the Sustainable Land Management Scheme for Wales, due to commence contracts in 2012 (Defra, 2007a; Scottish Government, 2008; WAG, 2008). A summary of these and other funding schemes is given in Table 2 in Appendix 1. The schemes recognise that there is a strong economic rationale for woodland support as purely market forces fail to acknowledge the wide range of public benefits provided by woodland; for recreation, carbon sequestration, watershed regulation, biodiversity conservation, economic security, landscape and amenity, air pollution reduction, employment creation, economic regeneration and the provision of social benefits (Defra, 2007a).

The existing schemes are administered or partly administered by the FC and provide funding for stewardship of existing woodland and the creation of new woodland. For the Woodland Creation Grant in England, the FC uses a regional scoring system to assess individual applications. Each region has set regional priorities some of which award points for water related benefits. For example, the East of England region give 5 points (the highest score is 6) for the establishment of wet woodlands and 2 points for planting within priority catchments under the Catchment Sensitive Farming Delivery Initiative; Yorkshire and The Humber have a regional priority of establishing wet woodland or lowland mixed deciduous woodland for flood risk reduction (3 points); East Midlands' priorities include strategic river corridors of wet woodland comprising locally native species (2 points); and the North-West Region gives 6 points for woodland planting to prevent or reduce soil erosion within the Lake Bassenthwaite catchment in the Lake District. However, while these points help to favour woodland applications to aid water management, they do not provide any additional funding to secure planting schemes. This is a key factor limiting improved integration of agriculture and forestry since land use change remains economically unattractive on better quality agricultural land. A perceived reduction in capital land value, reduction in farm income, including loss of agricultural subsidies, and long-term nature of commitment required, greatly constrain the scope for targeting woodland planting within agricultural landscapes. Additional incentives in the form of locational premiums are likely to be required to achieve significant land use change. A start has recently been made by FC(E) in the Yorkshire and The Humber Region, with the introduction in 2010 of an additional contribution of £2,000/ha under the English Woodland Creation Grant to encourage new planting in areas contributing to flood risk management. Monies are available under the RDPE Energy Crops Scheme to support the establishment of SRC, which could be a more financially attractive option to landowners, but there is no incentive to plant crops where they could benefit water most.

Funding support for woodland creation in Scotland under Rural Development Contracts is administered jointly by FC Scotland, the Scottish Government Rural Payments and Inspections Directorate, and Scottish Natural Heritage. The Rural Priority woodland creation option acknowledges the potential benefits of new woodland for improving water quality but the scheme does not directly target planting to where it can most benefit water or provide any additional funding to promote take-up. A similar situation exists in Wales, where Establishment Grants for new planting are administered by FC Wales.

The bulk of funding provided by the RDP remains allocated to agri-environment measures, reflecting the large proportion of land (e.g. over 70% in England) used for agriculture, and the potential to transform practices for environmental and economic gain. For example, the ES scheme in England is an agri-environment initiative which is primarily targeted to the protection of landscape features, habitats and species. Some

measures are aimed at providing soil and water benefits, including small-scale woodland creation and improved woodland management. Funding levels are relatively low and the support for woodland cannot be combined with FC England's Woodland Creation Grants. Other notable initiatives include the England Catchment Sensitive Farming Delivery Initiative (ECSFDI). This is designed to promote best practice farming measures to tackle diffuse water pollution within 40 priority catchments but funding is limited to small capital grants for improving farm infrastructure. A priority catchment approach is also being promoted in Scotland by SEPA with funding provided through the SRDP.

Despite strong policy support for woodland expansion for water benefits, the scope for woodland planting remains limited by insufficient financial incentives (as noted above) and wider land use constraints. Nature conservation is a key constraint, with large areas of the country designated for preserving extensive open grassland, heathland and wetland habitats. The potential benefits of expanding woodland areas must also be balanced against the economic, cultural and landscape losses of farmland. The widespread conversion of arable land to woodland is not considered appropriate (SNH, 2009), although targeting conversion in specific vulnerable areas may allow farmers to diversify and so be economically and environmentally beneficial (SNH, 2009; WAG, 2008). There are likely to be greater opportunities for converting grassland to woodland as a result of the decline in the livestock sector.

The landscape constraint reflects national and European policy (e.g. European Landscape Convention (Council of Europe, 2000)) directed at protecting existing landscape features and acting against significant change. Other notable constraints include Common Land and the protection of the historic environment. A study by Nisbet *et al. (*2004) of the scope for using woodland to aid sediment control in the Lake Bassenthwaite catchment in northwest England found that these constraints restricted woodland planting on 66% of the area identified as being at high risk of erosion and sediment delivery to at-risk water bodies. Food security has recently come to the fore as another major constraint and is likely to become an increasingly important limiting factor on future land use change. These limiting factors place emphasis on the need for even greater targeting of woodland planting to where is can generate most benefits.

Assessment of the spatial fulfilment of selected forestry objectives at the national scale in Denmark (Moller-Madsen, 2001) and in Scotland (Gimona and van der Horst, 2007) has indicated that whilst the extent of forestry is expanding in line with Forest Strategy aims, the potential is not being efficiently maximised to fulfil the full range of objectives within the strategies. In a case study of farm woodlands in NE Scotland, Gimona and van der Horst (2007) found that uptake locations were worse than would have been the case had they been randomly selected, i.e. the locations were negatively correlated to where they would provide the greatest benefit in terms of socio-economic benefits (represented by increased biodiversity) and recreation. A similar GIS approach could be used to

identify the successes and limitations associated with spatial targeting of afforestation to fulfil water quality objectives in England and Wales.

Increasing recognition in recent years of the multiple values of woodland has helped to push woodland higher up the hierarchy of land use. Although still competing with land use options such as agriculture and urban development, government policy remains focused on supporting the continued expansion of woodland in both urban and rural areas for benefits such as landscape and wildlife conservation, the provision of recreation and access, and the protection of soil and water resources. Country forestry strategies reflect the potential of woodland to deliver WFD objectives, including highlighting opportunities for woodland to reduce the impact of diffuse pollution from agriculture and urban activities, as well as assist flood risk management. However, despite strong policy support for woodland expansion for water benefits, the scope for woodland planting remains limited by insufficient financial incentives and wider land use constraints, especially nature conservation and landscape protection.

Is there any evidence to support an expansion or contraction of woodland in relation to water or other associated demands on land?

This review provides strong evidence to support an expansion of woodland in appropriate locations/areas for soil and water benefits. Main drivers for woodland expansion include sustainable flood management, water bodies remaining at risk of failing good water status despite improvements in agricultural land practices, and the need to mitigate the effects of climate change. The benefits are potentially greatest for the planting of riparian and floodplain woodland, which can help to reduce diffuse pollution (Hubbard and Lowrance, 1997), protect river morphology (Luke *et al.,* 2007), moderate stream temperature (Malcolm *et al.,* 2008) and aid flood risk management (Thomas and Nisbet, 2006), as well as meet Biodiversity Action Plan targets for the restoration and expansion of wet woodland. The contribution to tackling diffuse pollution includes both a barrier and interception function, where the presence of trees reduces the risk of direct contamination by agricultural activities on the adjacent land, and helps to trap and retain nutrients and sediment in polluted run-off. Riparian and floodplain woodland benefits for protecting river morphology and moderating stream temperatures are well proven, while a good case can also be made for mitigating downstream flooding. Planting SRC or SRW in these locations could help to maximise some benefits but also present some risks.

Similar gains (for managing diffuse pollution and flood risk) can be expected from extending fingers of riparian woodland into upstream source areas and intermittent flow/run-off pathways, although few data are available to quantify impacts at a catchment scale. Targeted planting of woodland buffers along mid-slope or downslope field edges, or on infiltration basins also appear effective for slowing down run-off and intercepting sediment and nutrients but the evidence base is once again limited. Wider woodland planting in the landscape is known to reduce potential pollutant inputs

compared to agriculture in the form of fertiliser and pesticide loadings, as well as protecting the soil from regular disturbance and so reducing sediment delivery to watercourses. The contribution of such planting to managing diffuse pollution and flood risk would depend strongly on the nature of the agricultural activity being replaced and the scale of land use change/proportion of catchment affected.

Aside from woodland clearance for habitat restoration, there is little evidence to support woodland contraction for water. Studies suggest that all water risks associated with woodland can be managed by good woodland design and management practices. The risks are greatest for conifer forests and energy crops, especially involving faster growing, exotic species. The potential reduction in water resources or ecological flows presents the largest threat, which may be accentuated by climate change. However, where there is a significant water shortage, the impact of woodland can be mitigated by a change in woodland type or diversifying the forest structure. Native broadleaved woodland has a much lower water use than conifer woodland and for some species, e.g. ash, could be even lower than that of grass. Such action is only likely to be necessary where there is a relatively high proportion of woodland cover in a given catchment (>20%) or planned large scale new planting. More research is needed to characterise the water use of a greater range of species and woodland systems, such as SRW, as well as to improve our understanding of the effects of climate change.

The main case for woodland contraction is within acid-sensitive upland areas, where the continued scavenging of acid deposition by conifer crops could lead to further acidification. The area at risk though is continuing to shrink in response to emission reductions and forest redesign, including increasing the area of broadleaved woodland and open space.

This review provides strong evidence to support an expansion of woodland in appropriate locations for soil and water benefits. The benefits are potentially greatest for the planting of riparian and floodplain woodland, which can help to reduce diffuse pollution, protect river morphology, moderate stream temperature and aid flood risk management, as well as meet Biodiversity Action Plan targets for the restoration and expansion of wet woodland. Aside from woodland clearance for habitat restoration, there is little evidence to support woodland contraction for water. Studies suggest that all water risks associated with woodland can be managed by good woodland design and management practices.

How can the full range of water-related benefits of woodland creation be factored into discussions over current and future land use?
The first need is to raise awareness amongst policy makers and planners of the benefits of woodland for water. In particular, the potential of woodland to aid water management merits a much greater profile within RBMPs and CFMPs. Currently, woodland solutions

are virtually ignored within these plans, and the few that refer to woodland tend to focus on managing the potential negative impacts of upland conifer forests. The case for woodland solutions also needs to filter down to sub-basin/catchment plans and local farm plans. To achieve this, woodland measures should be considered within relevant land management advice and guidance, WFD Programmes of Measures and agricultural best management practice handbooks, as well as greater acknowledgement in assessment procedures for evaluating applications for woodland planting and management grants. Training of agricultural advisers is also required, as is the provision of better guidance on woodland creation and management to farmers and other landowners. Local demonstration sites would help to communicate how woodlands can contribute to tackling issues such as diffuse pollution and flood risk.

Secondly, there is a need to increase incentives for woodland planting by making these better reflect the full range of water and other benefits. Landowners and farmers will be very resistant to land use change unless it is economically attractive. Planting on better quality land can result in a reduction in land value, a loss of agricultural subsidies and a reduction in income. There will be a need to provide sufficient compensation for these losses to secure change. This is especially the case where the type of woodland and management practices required to promote water benefits represents an added cost or low return. For example, the establishment of woodland riparian buffers or native floodplain woodland may provide little direct income and could lead to increased costs for the construction and maintenance of fencing, removing deposited rubbish, increased soil wetness in adjacent fields etc. A higher incentive is also likely to be required to persuade landowners to plant specific sites to maximise water services. A system is needed for transferring these costs from the service providers to the beneficiaries.

One way of capturing the costs and translating these into appropriate incentives would be to develop a system of payments for water and wider ecosystem services. MCPFE (2007) recommends the development, testing and implementation of such schemes for forestry in order to broaden and diversify the financial basis for maintaining and promoting the protective functions of forests. However, progress is constrained by the difficulty in calculating and placing a value on the different services. There is an urgent need for more research on quantifying woodland services and designing workable schemes. Ideally, these should integrate the full range and economic value of woodland benefits and incorporate any costs.

The first need is to raise awareness amongst policy makers and planners of the benefits of woodland for water. In particular, the potential of woodland to aid water management merits a much greater profile within River Basin Management Plans and Catchment Flood Management Plans. Secondly, there is a need to increase incentives for woodland planting by making these better reflect the full range of water and other benefits. One way of capturing the costs and translating these into appropriate incentives would be to

develop a system of payments for water and wider ecosystem services. There is an urgent need for more research on quantifying woodland services and designing workable schemes.

How can woodland creation be targeted to locations where it contributes most to both water-related issues and wider sustainable development?

GIS mapping has a key role to play in identifying the best locations for targeting woodland creation for water benefits. A wide range of models and risk assessments has been developed to locate sources of diffuse pollution, pollutant pathways and soils liable to generate rapid surface run-off. By overlaying these with spatial data on potential constraints to woodland planting such as conservation designations, common land, the built environment, sites of archaeological importance and Grade 1 agricultural land, it is possible to identify the best opportunities for woodland planting to assist water and flood management. This approach has been followed in a number of case studies and shown to be successful in promoting integrated catchment management and delivering new woodlands where it can best benefit society. 'Opportunity mapping' has been used to direct woodland onto preferred sites for protecting sediment sources and intercepting sediment pathways in the Bassenthwaite Lake catchment in the Lake District in northern England (Nisbet *et al.,* 2004), and to reduce rapid run-off, attenuate flood flows and enhance flood storage in the River Parrett catchment in southwest England (Nisbet and Broadmeadow 2003). A recent exercise has extended this approach to map high priority sites for flood attenuation in the Yorkshire and The Humber region in north England (Broadmeadow and Nisbet, 2009). Further model development is required to aid local targeting of measures at the field scale. For example, higher resolution modelling of overland flow pathways is being trialed by SEPA in the Lunan catchment in Scotland to help guide the placement of measures within individual fields.

Financial tools are also important for targeting woodland creation to desired locations. For example, the FC can offer locational premiums on top of the standard Woodland Creation Grant to direct planting to specific areas to deliver a key service. Until recently, these premiums have been restricted to promoting biodiversity or recreation benefits but the introduction in 2010 of an additional contribution of £2,000/ha in the Yorkshire and The Humber Region to encourage new planting in areas contributing to flood risk management is a good example of how this approach can be extended to cover water services. A start has also been made in awarding extra points for planting applications within ECSFDI priority catchments and those subject to flood risk, although these do not bring any added financial incentive.

GIS mapping has a key role to play in identifying the best locations for targeting woodland creation for water benefits. A wide range of models and risk assessments has been developed to locate sources of diffuse pollution, pollutant pathways and soils liable to generate rapid surface run-off. 'Opportunity mapping' has been used in a number of

case studies and shown to be successful in promoting integrated catchment management and delivering new woodlands where they can best benefit society. Financial tools such as awarding locational premiums/incentives are also vital for directing woodland creation to desired locations.

4. Review of cost benefit analyses

Ideally woodlands should be targeted to provide the optimum combination of environmental, social and economic benefits. Understanding the value of woodlands in terms of the various goods and services they provide to people and society will help clarify their role in integrated catchment management. This will enable better decisions to be made about woodland planting and design, and available incentives and regulatory controls used more effectively to deliver the desired result. This review has shown that well designed and managed woodland in the right place can provide a number of water services, including helping to control diffuse water pollution, enhance riparian and aquatic habitats, conserve water resources and reduce downstream flooding. In contrast, poorly designed and managed woodland in the wrong location can increase water costs.

There is a need to know the relative attributes and interdependencies between woodland and water so that new woodland schemes can be targeted to help achieve the objectives of the WFD. Interrelationships with other 'ecosystem services' also need to be investigated, in order to provide an evidence base highlighting the wider advantages or disadvantages of woodland expansion.

Climate change brings a number of new drivers to the potential expansion of woodland. Delivery of some of the carbon services provided by woodland, however, may involve trade-offs for water. These need to be assessed as it is important to understand whether interactions are synergistic or competitive and which processes dominate at different scales. Moreover, trade-offs may be delayed as ecosystem processes occur at a variety of timescales (Brauman *et al.,* 2007).

This section looks at relevant studies that could inform the development of a cost-benefit analysis (CBA) of proposed woodland measures, summarising available valuations of water-based 'ecosystem services'. The CBA provides a way to assess the impacts and effects of woodland planting and monetary valuation, although not an end in itself, can be a powerful tool for decision making because it organises information using a common metric for aiding comparisons (Brauman *et al.,* 2007).

The review focuses on studies related to water but includes wider ecosystem benefits where assessments have been made. Five case studies are highlighted: New York, Aalborg, Thulsfelde, Slea, and a report for the UK FC by Willis *et al. (*2003). The first three involve successful woodland planting schemes; real costs are presented for each, along with an EU Commission funded CBA for the Aalborg study. The two UK studies are

desk based utilising a range of models to perform a CBA. A number of other relevant studies are summarised in Table 1.

Evaluations are converted to Euro's to facilitate comparison, except in studies conducted prior to the introduction of the Euro (pre-1998). Conversion to Euro's is based on the average rate for the year of publication using historical exchange rate data (the original currency evaluations are given in parentheses).

4.1 Ecosystem Service Evaluations

4.1.1 Case Study 1: New York

Scheme: New York – Catskill Watershed Protection Programme[1]
Description Integrated water resource management to protect high quality drinking water supply (from phosphorus and microbial pathogens) and preserve natural catchment filtration, rather than constructing and maintaining expensive new water treatment facilities.
Approach Local public payment scheme administered by non-profit organisation. Scheme initiated with money from the city of New York, the State of New York and the Federal Government. Scheme now financed by a tax included in New York water users' bills. Stakeholders involved in the development and implementation of the program include foresters, landowners, farmers, government officials, technical agencies and business. Protection and remediation programmes include the Watershed Forestry Program – a pollution prevention and educational partnership that supports and maintains well-managed forests as a beneficial land cover for watershed protection (voluntary partnership between the City and the watershed forestry community). Specific projects and programs are implemented by the Watershed Agricultural Council (WAC) and its various partners, with the U.S. Department of Agriculture Forest Service providing a major source of matching grants and project funding. The Department of Environmental Protection has provided funds to the WAC for four major forestry tasks, including implementing a specific forestry basin management plan, including 66 separate riparian buffer plans covering 2,841 acres of riparian land. Model forests have been established in two locations; the Lennox Memorial Forest was opened in 2001 and contains 167 forest inventory plots covering 80 acres; and the Frost Valley Model Forest, which was opened in 2003 and contains 620 forest inventory plots

covering 290 acres. Both model forests cover a range of forestry management practices.

Three types of payment are involved: compensation (subsidies/logging permits/property tax reduction) to landowners for better land management practices; property transfer (land development rights) to farmers and landowners in exchange for agreements to follow good management practices; and development of new markets for non-timber products and timber product certification.

Land acquisition increased New York City ownership from 3.5% of the watershed to 10.9%. The scheme has succeeded in reducing phosphorus loadings, chlorophyll a and water pathogens.

Payment/Cost Benefit Analysis(CBA)
Total of ~ €1.35 billion ($1.5 billion) invested since 1991, equivalent to €3,257/ha (catchment area = 1600 sq. miles).

[1] See Bureau of Water Supply (2006), USEPA (2006), New York City Department of Environmental Protection homepage, and UNECE (2006).

4.1.2 Case Study 2: City of Aalborg, Denmark

Scheme: City of Aalborg, Denmark - Drastrup Pilot Project[2]

Description
Protection of groundwater resource from diffuse pollution (nitrate and pesticides) and provision of recreational facilities close to the city.

Approach
Public funded payment scheme to purchase key land areas for water protection and recreation; farmland bought from farmers, with those who wanted to continue conventional farming offered land outside the drinking water catchment area. The city worked with landowners, farmers and citizens to reduce use of pesticides, nitrogen and other chemicals.

Converting 900 ha of intensive agriculture into 500 ha of forest (natural broadleaved woodland) and 400 ha of pasture. New methods for afforestation and sustainable agriculture have been developed.

Information, campaigns and involvement of local citizens throughout the entire period. GIS developed to aid the process and incorporated into the GIS system of Aalborg Municipality.

Nitrate concentration in groundwater has decreased from >120 mg l^{-1} to <10 mg l^{-1} and pesticide use has ceased on the converted areas.

Payment/CBA
- Government funded: €402,000 per year from city of Aalborg for land purchase plus €805,000 from EU LIFE project between 1991 and 2001. Actual costs: €14,000 – 21,000/ha to purchase land, and €3000 – 6000/ha for cultivation and woodland planting.
- CBA for European Commission:
- Loss of agricultural income = €290/ha/year;
- Leisure/amenity benefit = €750/ha forest/year (for increased house property value and recreational activities [hedonic price method]);
- Carbon benefit = €108/ha forest/year for first 90 years (assuming an absorption capacity of 8 tons C ha^{-1} y^{-1} and a price of €13.5/ton CO_2);
- Drinking water benefit = cost saved estimated at a minimum value of €489/ha/year (€440,000/year) for water treatment (cost of NO_3 removal estimated at €0.2/m^3 for >50 mg l^{-1} NO_3).
- Net social benefit (excluding drinking water cost saving) = €187/ha/year (€168,000/year).

[2] see Aalborg Municipality (2002), Loubier (2002), and Water4all (2005).

4.1.3 Case Study 3: Thülsfelde, Germany

Scheme: Thülsfelde in Lower Saxony, Germany[3]

Description
Afforestation to achieve good water quality by excluding further application of liquid manure and pesticides to the soil, thereby protecting local groundwater resource from diffuse pollution (from rising nitrate and pesticide concentrations).

Approach
Partnership between water board and state forest agency. State administered payment scheme via local cooperatives (115 cooperatives throughout Lower Saxony representing 300,000 ha).

Water companies levy water abstraction charge on consumers (water penny) and money passed to state government who give it to the state forestry agency for afforestation, with conditions that the groundwater level is not lowered and pesticides are not applied. Other measures include provision of advice and compensation to local farmers and private foresters, promotion of best management practice measures, and organic

farming.

The combined measures have led to a reduction in nitrate concentrations from over 100 mg/l to <50 mg l⁻¹ (drinking water decree level).

Payment/CBA
- Local tax: 5 cents/m^3 (water penny) used to finance preventative groundwater protection. Industrial and agricultural use is charged at lower rates, e.g. fishery users pay 0.25 cent/m^3 water, while the nuclear energy industry pay 1 cent/m^3 for cooling water.
- Land purchase for afforestation cost €15,000-40,000/ha, equivalent to €600/ha/year over 25 years (minimum project period).
- Planting cost averaged €5,000-6,000/ha.
- Agri-environment payments also made to farmers.

[3] see Water4all (2005).

4.1.4 Case Study 4: Slea catchment, UK

Scheme: Slea Catchment Study, E. England, UK[4]

Description
Assessing land use scenarios to improve groundwater quality (reduce nitrate concentration).

Approach
Model simulations to assess effects of land use change scenarios on nitrate concentrations.

Evaluation of costs associated with land use change scenarios including:

Land use protection zones – e.g. low input grassland and/or woodland in targeted areas (such as well capture zones and in upper River Slea catchment). Conversion of arable to grassland and woodland within water protection zones (total area of 3,200 ha), moving from 2003 baseline of 14% grass and 3% woodland to 30% grass (960 ha) and 20% woodland (640 ha); simulating the Danish Drastrup type scheme.

Protection zone scenario simulations suggest a reduction in nitrate concentrations from >100 mg l⁻¹ to below the regulatory 50 mg l⁻¹ drinking water limit.

Payment/CBA (conversion using average exchange rate for 2006, £1 = €1.47)

- Cost of land use change estimated at €1.96 million (£1.33 million)/year, equivalent to 0.068 cents (0.046 p)/litre of water (based on an output of 8 Ml d^{-1}) or 12 cents (8 p) /person/day (based on average per person use of 180 l d^{-1}) or approximately €44 (£30) /person/year.

- Nitrate water treatment costs in the Sleaford WSZ are approximately €12 (£8) /person/year so the additional cost would be €44 - €12 = €32 (£30 - £8 = £22).

- Biodiversity and amenity benefits provided by conversion to grassland and woodland need to be considered.

- Land use changes could produce substantial reductions in nitrate levels on a timescale of 10 to 20 years

[4] Lovett *et al. (*2006) and Water4all (2005).

4.1.5 Case Study 5: Assessment of Social and Environmental benefits of forests in GB

Scheme: Social and Environmental Benefits of Forests in Great Britain.

Description
The impact of forests and woodland on water supply, recreation, landscape, biodiversity, carbon sequestration and pollution.

Approach
The impact of woodland and forests on water supply was assessed from hydrological and ecological models of the effect of woodland on rainfall inception and transpiration rates compared to grassland. The cost of woodland on water supply can be estimated from marginal costs faced by different water companies for abstracting potable water supplies. Information from existing literature and discussions with water companies were used to assess the impact of forests on water quality.

Payment/CBA (conversion using average exchange rate for 2003, £1 = €1.45)
The marginal benefits of woodland were estimated to be:
- €2.41 - €3.99 (£1.66 - £2.75) for each recreational visit.
- £269 /household/year, for those households with a woodland landscape view on the urban fringe.

- 51 cents (35p) /household/year for enhanced biodiversity in each 12,000 ha (1%) of commercial Sitka spruce forest; €1.22 (84p) /household/year for a 12,000 ha increase in lowland new native broadleaved woodland, and €1.64 (£1.13) /household/year for a similar increase in ancient and semi-natural woodland.
- €9.67 (£6.67)/tonne of carbon sequestrated.
- €181,247 (£124,998) for each death avoided by 1 year due to PM10 and SO_2 absorbed by trees, and €873 (£602) for an 11 day hospital stay avoided due to reduced respiratory illness.
- And a cost of 19 cents to €1.80 (3p to £1.24) per m^3 where water is lost to abstraction for potable uses, although for most areas the marginal cost is zero (whilst hydrologists point to the potentially large impact of forestry on water availability, British water companies perceive little impact, in general, of existing forests on water supply costs (Willis, 2002)). However, there is no database on the opportunity cost of water supply and water quality improvements on a spatial unit basis. Hence the costs and benefits of forestry on water supply and water quality cannot at present be mapped in any accurate, robust and reliable manner

The externality cost of woodland on water quality has been internalised within forestry through the application of guidelines ('Forests and Water') on woodland planting and conditions attached to forest certification.

The value of all the benefits at a Great Britain level is approximately €2.2bn (£1.5bn) /year or, as a capitalised value (at a 3.5% per annum discount rate) of approximately €62bn (£43bn). The single largest value is for biodiversity (49%) and then recreation (39%). Approximately 75% of the total benefits in Great Britain accrue in England.

[5]Willis *et al. (*2003)

Table 1 Summary of cost benefit analysis studies related to woodland planting and/or protection of water resources.

Scheme	Description	Approach	Payment (CBA)
Public/private payments for ecosystem services (PES) scheme to protect groundwater well-fields near Copenhagen (Denmark) See IUCN report (2009)	Protecting the Solhøj and Vigersted groundwater well-field by afforestation, and restrictions on the use of fertilisers and pesticides.	Land use change from agriculture to forests through afforestation with mainly broadleaf species. Restrictions on the use of fertilisers and pesticides in existing forest areas, and in some cases underplanting of conifer stands with broadleaf tree species to increase groundwater recharge.	Fund set up by water company (Copenhagen Energy) to finance the provision of environmental services. The consumer pays about €10 (75 kroner)/year to the fund which is paid to the forest owners and farmers. To set aside 95 hectares of private forest, the water company has calculated payment to be around €1.5 million (~10 million kroner) in total. The forest owner is paid on a yearly basis for reducing the use of pesticides and fined for non-compliance with contract obligations.
Public PES scheme to protect groundwater near Odense (Denmark) See IUCN report (2009)	Afforestation to protect the drinking water resource and increase recreational possibilities.	The Danish Forest and Nature Agency cooperated with Odense municipality and the local waterworks to establish more than 2000 hectares of new forest close to Odense.	€2 million per year paid to buy agricultural land and start afforestation. The farmland can be bought at around €10-15,000/ha and afforestation costs may be another €5000/ha. Up to €100/ha is paid to forest owners for changing forest management practices to favour water. To fund the scheme a levy is charged to the water consumers (based on the Water Supply Act). The money raised is dedicated to, and invested in, afforestation projects in public forests by the state and municipalities.

Scheme	Description	Approach	Payment (CBA)
Voluntary agreement to recharge overexploited aquifers, and for additional social and environmental benefits (Spain). See IUCN report (2009)	Afforestation scheme to recharge aquifers by 2027. River Basin Authority working with private (agricultural) landowners. Other aims include: restoration of aquatic flora and fauna, and biodiversity; reduction of climate change effects; developing and stabilising the forest sector as an alternative to traditional agriculture; enhancing conditions to increase tourism in the mid- to long term; and enhancing the creation of new industries linked to the forestry sector.	Payments for reforestation of agricultural lands will be made: - for reforestation/planting - to maintain the planted forest - to compensate for lost income	Payments for the 2008-2027 period are estimated at €1.2 bn, to cover costs of reforestation/planting over 1 year, maintenance of planted forest over 5 years, and compensation for lost income over 20 years.
Mandatory PES scheme to protect drinking water in the Salzburg basin (Austria) See IUCN report (2009)	Restriction on pesticide use to protect drinking water resource.	The state designated a water sanctuary around the groundwater resource thereby restricting pesticide use in farming and forestry. The Water Association of the Salzburg Basin (WSB) act as intermediaries paying the farm and forest owners money collected from the water consumer.	From 1999 until 2006, the WSB paid a total amount of €1.5m (average €190k/year) to compensate the landowners. The money spent by WSB is collected from its members (the local water suppliers) who charge their customers.

Scheme	Description	Approach	Payment (CBA)
Voluntary agreement where Bionade (soft drinks company) pays to protect water resource in the Rhoen region of Bavaria (Germany). See IUCN report (2009)	Protection and enhancement of water quality through afforestation, forestry and organic farming.	Aiming to create 130 hectares of drinking water protection forests by conversion of conifer monoculture forest to deciduous broadleaves. Estimated that this will provide on average 800,000 litres of additional available groundwater per hectare per year. Scheme operates with the Trinkwasserwald e.V. (Drinking Water Forest Association), an NGO, as the intermediary between Bionade, and the public and private forest owners.	Conversion of one hectare of conifer monoculture into drinking water forest has a cost of €6,800/ha, including possible re-plantings, maintenance of the cultures etc. The payments by Trinkwasserwald e.V. to the forest landowners are made as the actual costs occur.
Voluntary agreement between the municipality and forest owners to protect water quality in Kaufering (Germany). See IUCN report (2009)	Protection and purification of water resources within water protection area by converting from coniferous to deciduous forests.	Forest owners within water protection area are paid to change from coniferous forests to deciduous. The higher costs of forest management spanning from the prescriptions of the agreement are based on the higher percentage of deciduous species, continuous forest cover structures, the ban on creating larger felling areas, and the limitation of the mode of utilization, such as operating without pesticides and fertilisers in the case of energy forests. Incentive is paid to the forest owners by the waterworks who charge the water users by increasing the water bill accordingly.	Forest owners receive a yearly payment of €200-300/ha for the transformation from coniferous to deciduous forests. Details of the payment are as follows: At the planting of a water protection forest a one-off payment of €250 is made. In addition, yearly payments are made of up to €230/ha for a forest consisting of 95% of broadleaf species and 5% spruce (Picea abies), or up to €275/ha for 100% broadleaf forest. For an energy forest (afforested agricultural area) a single payment of €650 is made for its planting, with additional yearly payments of €230/ha.

Scheme	Description	Approach	Payment (CBA)
Vittel S.A.'s payments for water quality. (France) See UNECE (2006) and Perrot-Maître, D. (2006)	Protection of high quality mineral water by reducing nutrient and pesticide run-off from farmland.	Private (self-organised) deal. Compensatory measures developed and agreed upon by Vittell and farmers for reduced agricultural profitability. Property acquisition and change of agricultural management practice through compensation, including planting woodland within filtration zones.	Vittell paid farmers subsidies of, on average, about €200/ha/year over five years. The exact amount negotiated for each farm. Long term security through 18 or 30 year contracts. Up to €150,000 per farm to cover the cost of all new farm equipment and building modernisation. Abolition of debt linked to land acquisition by Vittel. Long term security through 18-y or 30-y contracts.
Forests for water protection. Neidling and Walser (2005) cited in European Union (2008).	The value of forested land for water protection in Baden Württemberg (Germany).	N/A	Value of forested land for water protection is estimated at €35/ha The authors estimated the total recreational value of forest cover at €3 billion. Taking the total forested area of Germany to be 11.1 million ha (Bundeswaldinventur, 2007), this would correspond to an average value of €270/ha.

Scheme	Description	Approach	Payment (CBA)
Forests and water. Japan Forest Conservation Association (2003)	Report on the economic and environmental value of Japan's forests, particularly in relation to water.	Evaluated by the Alternative Method. Forests cover 25.2 million ha in Japan. This figure used for per ha calculation. See report for Yen values.	Forest value in Japan = € 530 billion (€21,100/ha) including: Headwater conservation function ~ €230 billion (€9,150/ha); Flood mitigation = €50 billion (€2,000/ha); water resource reserve = €70 billion (€2,800/ha); and water flow control = €110 billion (€4,400/ha)]. Land slide prevention = €65 billion (€2,600/ha) and soil erosion prevention = €215 billion (€8,550/ha) CO_2 absorption = €9.5 billion (€400/ha). Rest (Health and recreation) = €17 billion (€700/ha).

Scheme	Description	Approach	Payment (CBA)
Climate change impacts on water resources. Bateman and Georgiou (2006).	Cost benefit analysis for mitigation of eutrophication and a change in water supply colour.	Willingness to Pay (WTP) for prevention of climate change impacts on open-access water bodies and the costs of ensuring high quality domestic supplies. WTP per household to prevent eutrophication of rivers and lakes in East Anglia associated with increased climate change Estimates of households' (in East Anglia) mean WTP for the avoidance of the tap water problems associated with increased climate change.	WTP per household (excluding non-response) to prevent eutrophication of rivers and lakes: £75.41/year; aggregate benefit - £169.89 million. Mean WTP for the avoidance of the tap water problems per household (including non-response): £38.48/year; aggregate benefit - £86.70 million. Mean WTP (£) per household to avoid one day of colour problems: £5.40 Mean WTP (£) per household to avoid one day of smell and taste problems per household: £3.96 Conclusions: impacts of climate change on lakes and freshwater systems can impose significant loss of benefits and hence measures to reduce these impacts are likely to provide worthwhile investments.
Linking nutrient retention function of mangrove forests to enhanced agro-ecosystem function (India). Hussain and Badola (2008).	The role of mangrove forests in biogeochemical cycling of coastal environment.	Soil samples from both mangrove and non-mangrove areas were analysed and the quantities of organic carbon, total nitrogen, available phosphorus and potassium were derived. The replacement cost method was used to derive the value of nutrient removal by mangrove soils.	Mangrove forest contains additional nutrients (organic carbon, total nitrogen, available phosphorus and potassium) worth €158.09/ha (US$232.49/ha) in comparison to non-mangrove areas. The difference in nutrient content in mangrove versus non-mangrove areas gave the value of €2.29 million (US$3.37 million) for the nutrients in 145 km^2 of mangrove forests.

Scheme	Description	Approach	Payment (CBA)
Ethnobiology, socio-economics and management of mangrove forests: A review. Walters *et al.,* (2008)	Review of studies on mangrove forests.	Factors considered included: Water quality maintenance of mangroves. Environmental disturbance prevention (storm, flood and erosion control) of mangroves. Mangroves as carbon sink.	Water quality maintenance: US$5,820/ha/year (Lal, 1990); €811.24/ha/year (US$1,193/ha/year) (Cabrera *et al.,* 1998). Value dependent on extent and types of mangroves. Environmental disturbance prevention: US$4,700/ha (Costanza *et al.,* 1989); €4120/ha (US$3,679/ha) (Sathirathai and Barbier, 2001). Mangroves as Carbon sink: 155 kg C ha^{-1} day^{-1} (Clough *et al.,* 1997); 1500 kg C ha^{-1} (Ong, 1993)
AMBER: Ammonia Mitigation by Enhanced Recapture. Theobald *et al.,*(2004)	The profitability of tree belts for capturing ammonia emissions from livestock farming to prevent ecosystem eutrophication and soil acidification.	The Silsoe Whole Farm Model was used to calculate the financial impact of giving up the land and preparing the ground for the tree belt. Discounted cash flow techniques with sensitivity analysis were used to calculate the net present value of investing in a tree belt.	Average net annual cost to establish and manage a tree belt specifically for NH$_3$ recapture is approx. €588 (£400)/ha. Case study of a tree belt downwind of a broiler unit: tree belts represent an abatement cost of ~€1.84-€3.68 (~£1.25-£2.50) per kg of nitrogen abated, or €0.54-€1.10 (~£0.37-£0.75) per kg of nitrogen abated if the opportunity cost of the land used can be excluded (cost of losing one hectare of productive agricultural land to trees; 1995 prices, ranging from €923-€1250 (£628-850) per ha, depending on soil type and rainfall). There may be potential to establish profitable use of the tree belt such as game cover, agro-forestry or short-rotation wood products.

Scheme	Description	Approach	Payment (CBA)
Economic accounting of carbon sequestration by forests. Thoroe *et al.,* (2005).	Analysis of the production process, and the entrepreneurial income in the forestry sector (Germany).	European System of Integrated Economic Accounts (ESA) and the Economic Accounts for Forestry (EAF) used to analyse the production process, and the entrepreneurial income in the forestry sector. The EAF does not take into account activities such as forest management services, hunting, recreation services etc. The value of timber growth and harvested volume are not included. Per ha calculation based on total forest area in Germany of 11.1 million ha (Bundeswaldinventur, 2007).	The monetary value of carbon sequestration by forests in Germany is estimated to be between €50 and €500 million/year. €4.5 – €45/ha

Scheme	Description	Approach	Payment (CBA)
Cost benefit analysis of establishing new forest land in Ghent (Belgium). Moons, E. (2002). Cost-benefit analysis of the location of new forest land.	Afforestation of agricultural land with oak and ash trees over a 200-year time period.	Highlighting importance of recreation and non-use values: Bequest value - benefit accruing to any individual from the knowledge that others might benefit from the forest in the future, and Existence value - the benefit accruing to any individual from the knowledge of that forest area. Non-use values estimated by Contingent Evaluation Method (CVM)	Costs: Planting and management = €38.6/ha/year Loss of agricultural production = between €714 and €362/ha/year Loss of manure deposition = €457 – €490/ha/year Benefits: Timber = €28.5/ha/year Hunting = €15/ha/year Carbon Fixation = €25/ha/year Non-use (e.g. Existence/Bequest values) = €3,680/ha/year Recreation (Average) = €1440/ha/year
Household Willingness To Pay (WTP) analysis for the establishment of 100 ha of recreational woodland. Bateman *et al.,* (1996)	Establishment of recreational woodland (100 ha) on farmland.	Householders make payments; calculated on a per annum basis and per visit basis. Contingent Valuation method.	In the vicinity of local woodland, households WTP was £9.94/year as tax (aggregate £44,500 per annum for the woodland); while visitors WTP for visits based on entrance fees was £12.29/adult/year (total £141,252 per annum). £445/ha/year for tax £1413/ha/year for visits based on entrance fees.

Scheme	Description	Approach	Payment (CBA)
The amenity value of woodland in Great Britain: A comparison of economic estimates. Garrod and Willis (1992).	Estimating the amenity value of woodland using economic evaluation methods.	Hedonic price method.	1% increase in the relative proportion of FC forested area in a given 1 km^2 into broadleaved woodland increased the selling price of an individual property by £42.81
Recreational Benefits of Forests in Germany. Elsasser (1999)	WTP analysis for forests in Hamburg and Pfaelzerwald nature park. Study carried out within existing forests.	Contingent Valuation method. Per ha calculation based on total forest area in Germany of 11.1 million ha (Bundeswaldinventur, 2007).	Max. WTP = €51.02 (100 DM) /person/year on average for Hamburg, and €15.3 (30 DM) /person for the nature park. Total forest recreation benefits in Germany can approximately be put at €2.4 billion (4.8 billion DM)/year for day users, and €0.26 billion (0.5 billion DM)/year for holiday makers, equating to €216/year/ha and €23/year/ha, respectively.
Monetary benefits of forestry. Meyerhoff *et al.,* (2006) cited in European Union (2008).	Estimate of the monetary benefits of forests with improved biodiversity. (Germany)	WTP analysis.	The mean willingness to pay of residents ranged between €6.60 and €13.28/household for forests in the Lüneburger Heide and between €6.23 and €6.64 for forests in the Sollingen area, depending on elicitation procedure.

Scheme	Description	Approach	Payment (CBA)
WTP for afforestation in Denmark. Anthon *et al.,* (2005)	Case studies of afforestation at two sites: True Forest = 101 ha Bakkely Forest = 60 ha	Residents' WTP for urban-fringe afforestation with hardwoods (beech and oak).	Aggregate increase in house prices near True Forest estimated at €4,662,000 (€46,158/ha of forest), and near Bakkely Forest, €1,243,000 (€20,717/ha of forest). Differences due to various factors, e.g. number of houses close to the forest, the area of forest, and house prices (affluence of residents). Conclusions: 15% increase in house prices close to the forest at one site, 10% increase at the other.

4.2 Summary

A total of 25 CBA studies are presented, of which 18 considered the direct benefits of woodland planting for water protection. Land acquisition was a component of five schemes and most involved public funding, but there are also examples of private funding (e.g. Vittel) and voluntary agreements (Kaufering). Key needs are to identify who pays, how much, to whom, for what, and for how long (Brauman *et al.,* 2007).

The cited case studies at New York, Aalborg, and Thülsfelde provide very good examples of successful woodland planting schemes with beneficial effects for water quality and resource protection. Common features include:

- Identified woodland planting as the favoured land use measure (e.g. in terms of cost effectiveness and security of change) to reduce diffuse pollution and protect water resources (Figure 20).
- Cooperation between all main stakeholders: the state, landowners and public.
- Raised environmental awareness amongst children and adults through environmental education ('teaching trails'), including where water comes from and why we need to protect the resource and use water wisely.
- Generated multiple benefits (e.g. in terms of biodiversity, carbon sequestration, recreation, landscape, public health, local house values and wood products), both in the short and longer-term.
- Resulted in major improvements in water quality, with nitrate concentrations falling considerably in Aalborg and Thülsfelde, while there has been a significant reduction in phosphorus loading and pollution by water pathogens in New York scheme.

The review provides a good knowledge base to inform the future development and implementation of payments for water-related forest services in the UK. Where there are water trade-offs in terms of the potential for woodland to reduce water yield, these can be managed by attention to woodland type, design and scale. Targeted woodland planting within appropriate catchments offers an effective measure for controlling diffuse pollution from more intensive agricultural and urban activities, as well as helping to alleviate downstream flooding in towns and cities. However, securing these opportunities will require a higher level of financial incentive to persuade landowners to plant woodland on higher value farmland, or to provide funding provided for land purchase. A start has been made by using locational premiums to raise the value of woodland grants to encourage land use change where water benefits are potentially greatest but it remains to be seen whether this will have the desired outcome. More work is required on assessing the economic value of water and other forest services and incorporating the resulting evaluations into relevant policies and strategies to promote forests for water.
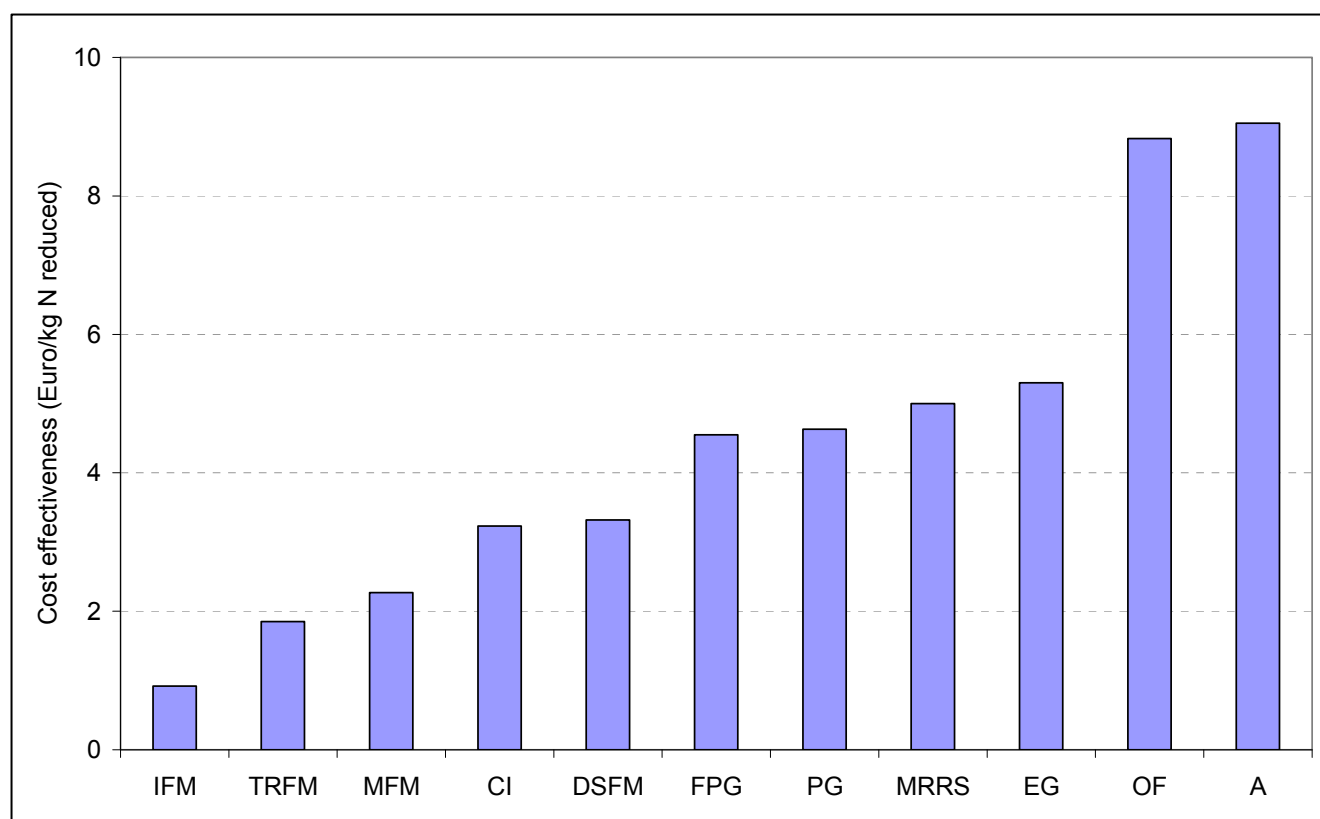
Figure 20. A number of payment schemes for water-related forest services have been developed in Europe. The plot compares the cost effectiveness of different groundwater protection measures for reducing nitrate pollution in Denmark (from: http://www.watercost.org/download/research/watercost_booklet.pdf). IFM = Integrated fertiliser and manure application; TRFM = Temporal restrictions on fertiliser and manure application; MFM = Maize with limited fertiliser and manure application; CI = Cereals with intercropping; DSFM = Direct soil fertiliser and manure methods; FPG = Active fallow plot greening; PG = Permanent grassland; MRRS = Maize with reduced row spacing; EG = Extensive grassland; OF = Organic farming; A = Afforestation.

5. Opportunity mapping

Opportunity mapping offers considerable potential for identifying where woodland creation should be targeted in the landscape to help meet the objectives of the WFD. A GIS based mapping methodology has been developed and applied to a case study involving the Bassenthwaite Lake catchment on the River Derwent in Northwest England to show how this approach could work. The method is reported in Appendix 2 and can be applied across a range of scales from assessing opportunities for planting at a strategic regional or river basin level down to the practical farm/field scale. The key features of the methodology are:

•   It utilises existing and widely available data sets to characterise the opportunities and constraints to woodland planting.
•   The procedure is easy to follow and adaptable by local staff to meet the particular needs and circumstances of their region.
•   Individual components of the method can be updated to incorporate revised model outputs, as new information becomes available.

The main steps involved are to:

•   Identify water bodies currently failing to meet 'good' ecological or chemical status based on RBMP, or at risk of flooding in CFMP.
•   Identify the probable cause(s) of a water body failing to meet the required status, using risk maps and pressures identified in the RBMP, or catchment factors contributing to flood risk in CFMP.
•   Depending on risk factor, identify potential pollutant sources and run-off pathways within the catchment using best available data.
•   Assess connectivity to watercourses or groundwater.
•   Identify constraints and sensitivities to woodland creation.
•   Check opportunities for woodland creation to deliver other benefits, such as expanding or restoring woodland habitat networks.
•   Identify priority areas for woodland creation.

An example 'Farm Estate' has been created to illustrate how the catchment mapping can be translated to the field scale in terms of identifying precise locations where tree planting could be targeted for water quality improvement. An assessment of the farm reveals a number of opportunities for woodland creation to help reduce diffuse pollution, enhance stream morphology and slow down flood flows.

The main output is a set of maps describing catchment sensitivity, constraints and opportunities for woodland planting. The approach is already being applied to the catchment of Bassenthwaite Lake, where it is successfully directing woodland planting

onto preferred sites to protect sediment sources and intercept sediment delivery pathways.

6. Conclusions

This review provides strong evidence to support new proposals to expand woodland in appropriate locations for soil and water benefits. Main drivers for woodland expansion include sustainable flood management, water bodies remaining at risk of failing its objective despite improvements in agricultural land practices, and the need to mitigate the effects of climate change.

The benefits are potentially greatest for the planting of riparian and floodplain woodland, which can help to reduce diffuse pollution, protect river morphology, moderate stream temperature and aid flood risk management, as well as meet Biodiversity Action Plan targets for the restoration and expansion of wet woodland.

The contribution to tackling diffuse pollution includes both a barrier and interception function, where the presence of trees reduces the risk of direct contamination by agricultural activities on the adjacent land, and helps to trap and retain nutrients and sediment in polluted run-off. Riparian and floodplain woodland benefits for protecting river morphology and moderating stream temperatures are well proven, while a good case can also be made for mitigating downstream flooding. Planting SRC or SRW in these locations could help to maximise some benefits but also present some risks.

Similar gains for managing diffuse pollution and flood risk can be expected from extending fingers of riparian woodland into upstream source areas and intermittent run-off pathways, although few data are available to quantify impacts at a catchment scale. Targeted planting of woodland buffers along mid-slope or downslope field edges, or on infiltration basins also appear effective for slowing down run-off and intercepting sediment and nutrients, but the evidence base is once again limited. Wider woodland planting in the landscape is known to reduce potential pollutant inputs compared to agriculture in the form of fertiliser and pesticide loadings, as well as protecting the soil from regular disturbance and so reducing sediment delivery to watercourses. The contribution of such planting to managing diffuse pollution and flood risk would depend strongly on the nature of the agricultural activity being replaced and the scale of land use change/proportion of catchment affected.

Aside from woodland clearance for habitat restoration, there is little evidence to support woodland contraction for water. Studies suggest that all water risks associated with woodland can be managed by good woodland design and management practices. The risks are greatest for conifer forests and energy crops, especially involving faster growing, exotic species. The potential reduction in water resources or ecological flows

presents the largest threat, which may be accentuated by climate change. However, where there is a significant water shortage, the impact of woodland can be mitigated by a change in woodland type or diversifying the forest structure. Native broadleaved woodland has a much lower water use than conifer woodland and for some species, e.g. ash, could be even lower than that of grass. Such action is only likely to be necessary where there is a relatively high proportion of woodland cover in a given catchment (>20%) or planned large scale new planting. More research is needed to characterise the water use of a greater range of species and woodland systems, such as SRW, as well as to improve our understanding of the effects of climate change. The main case for woodland contraction is within acid sensitive upland areas, where the continued scavenging of acid deposition by conifer crops could lead to further acidification. The area at risk though is continuing to shrink in response to emission reductions and forest redesign, including increasing the area of broadleaved woodland and open space.

Despite strong policy support for woodland expansion for water benefits, the scope for woodland planting remains limited by insufficient financial incentives and wider land use constraints. There is a need to increase incentives for woodland planting by making these better reflect the full range of water and other benefits. Landowners and farmers are likely to be resistant to land use change unless it is economically attractive. Planting on better quality land can result in a reduction in land value, a loss of agricultural subsidies and a reduction in income. There will be a need to provide sufficient compensation for these losses or funding provided for land purchase to secure change. This is especially the case where the type of woodland and management practices required to promote water benefits represents an added cost or low return. Experience from the rest of Europe and further afield provides a range of examples of effective payment schemes for water-related forest services, which have succeeded in achieving woodland creation for water protection.

There is also a need to raise awareness amongst policy makers and planners of the benefits of woodland for water. In particular, the potential of woodland to aid water management merits a much greater profile within RBMPs and CFMPs. Currently, woodland solutions are largely absent within these plans. In the future, woodland creation may have an important role to play in mitigating more intractable water pollution problems within Water Protection Zones.

The case for woodland solutions also needs to filter down to sub-basin/catchment plans and local farm plans. To achieve this, woodland measures should be considered within relevant land management advice and guidance, WFD Programmes of Measures and agricultural best management practice handbooks, as well as greater acknowledgement in assessment procedures for evaluating applications for woodland planting and management grants.

Training of agricultural advisers is also required, as is the provision of better guidance on woodland creation and management to farmers and other landowners. Local demonstration sites could help to communicate how woodland can contribute to tackling issues such as diffuse pollution and flood risk.

The report calls for closer integration of forestry and water policy to enable better decisions to be made and available incentives and regulatory controls used more effectively to secure woodland opportunities for water. It also highlights the need for more research to quantify water benefits and evaluate how woodland can be best integrated with agriculture and urban activities for water and wider environmental benefits, while minimising any water trade-offs.

Spatial mapping offers significant potential for promoting integrated catchment management and delivering new woodlands where they can best benefit society. 'Opportunity mapping' has been developed to help direct woodland onto preferred sites for protecting sediment sources, intercepting the pathways of diffuse pollutants, reducing rapid run-off, enhancing flood storage and to attenuate flood flows.

7. Recommendations

7.1 Evidence into practice:

- It is important to be aware of all the additional services and benefits woodland can bring to water. There is potential for woodland to benefit water management through River Basin and Catchment Flood Management Plans.

- There is a strong case for woodland solutions to be delivered through catchment level planning and then to local farm and field planning. To achieve this, woodland measures should be considered within relevant land management advice and guidance, WFD Programmes of Measures and agricultural best management practice handbooks.

- A re-evaluation of the advice and guidance on woodland creation and management for farmers, landowners and land management advisers could, potentially, encourage appropriate woodland creation. Local demonstration sites could help to communicate how woodland can contribute to tackling issues such as diffuse pollution and flood risk.

- The scope for woodland planting remains limited by constraints on land use and financial viability of schemes for land managers. Solutions to these barriers should be explored in view of the additional services woodland can provide besides the value of timber.

- Evidence gaps, relating to how woodland can be best integrated with agriculture and urban activities to deliver benefits to water resources and the wider environment, need to be addressed.

- Additional financial opportunities could be explored to complement existing grant payments to reflect the value of the ecosystem services provided by riparian and floodplain woodland, further incentivising their establishment.

7.2 Evidence gaps:

There are remaining gaps in the evidence base for the use of woodlands for delivering water benefits. River Basin Planning requires effective and beneficial measures to help reduce pollution, and any potential for land use change would need to be supported by sound science. The following five research recommendations would help to secure a better understanding of woodland benefits at a catchment scale.

1. Establish case studies to evaluate through measurement and modelling the costs and effectiveness of different woodland measures for water protection, including planting riparian buffer areas, mid-slope shelterbelts, infiltration basins and Sustainable Drainage Systems (SuDS). Also to assess the practicability of integrating their use into the UK farming environment.

2. Evaluate the effect of woodland design (e.g. width, structure and species choice) and management factors (e.g. thinning, coppicing and felling) on the efficacy of woodland measures for diffuse pollution control and flood alleviation. This will help to improve advice and guidance to maximise woodland benefits.

3. Continue long-term monitoring of streams draining acid sensitive forested catchments to establish whether existing measures remain fit for purpose and guide the need for future revisions to best practice guidance.

4. Extend measurements and model testing of the impact of woodland creation on flood generation, including floodplain and riparian woodland, SRC and SRW, and assess the effectiveness of measures designed to trap large woody debris.

5. Further develop the opportunity mapping approach and support model development to aid local targeting of measures at the field and catchment scale.

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List of abbreviations

AFFOREST	EC Framework 5 Programme: Afforestation management in north-western Europe - influence on nitrogen leaching, groundwater recharge, and carbon sequestration. EVK1-CT-1999-00020, Completed 2004.
ANC	Acid Neutralising Capacity
AP	Action Plans
ArtWET	EU LIFE Environment Project: Mitigation of agricultural nonpoint-source pesticide pollution and phytoremediation in artificial wetland ecosystems, LIFE 06 ENV/F/000133, http://ec.europa.eu/environment/life/project/Projects/index.cfm
BOD	Biological Oxygen Demand
BMP	Best Management Practice
BWW	Better Woodlands for Wales
CAP	Common Agricultural Policy
CBA	Cost Benefit Analysis
CFMP	Catchment Flood Management Plan
C:N	Soil carbon:nitrogen ratio
Defra	Department for environment, food and rural affairs
EA	Environment Agency
EC	European Community
EAF	Economic Accounts for Forestry
ECSFDI	England Catchment Sensitive Farming Delivery Initiative
ES	Environmental Stewardship scheme
ESA	European System of integrated economic Accounts
ETWF	Defra's strategy for England's Trees, Woods and Forests
EU	European Union
EUROHARP	EC Framework 5 Programme: European harmonised procedures for quantification of nutrient losses from diffuse sources. EVK1-CT-2001-00096. Final report submitted 2007.
EveNFlow	Computer model which estimates inorganic nitrogen fluxes and concentrations in rivers. (see Anthony *et al. (*2009))
FAO	United Nations Food and Agricultural Organisation
FC	Forestry Commission
FIO	Faecal Indicator Organisms
GAEC	Good Agricultural and Environmental Condition
GIS	Geographic Information System
HYLUC	HYdrological rainfall-run-off model for Land Use Change.
IEEP	Institute for European Environmental Policy
IUCN	International Union for Conservation of Nature
LWD	Large Woody Debris

MAGIC
Model of Acidification of Groundwaters In Catchments. Computer model simulating soil and surface water acidification at the catchment scale. http://www.freshwaters.org.uk/air_pollution/magic_model.php

MAGPIE
Modelling Agricultural Pollution In the Environment - ADAS modelling framework for evaluating diffuse pollutant losses from the landscape at catchment and national scales; developed for policy support to Defra and the Environment Agency

MCPFE
Ministerial Conference on the Protection of Forests in Europe

MimAS
Morphological impact Assessment System – General risk assessment tool for classifying river morphology and assessing impact of morphological pressures.

MORECS
Meteorological Office Rainfall and Evaporation Calculation System

MOSES
Meteorological Office Surface Energy Scheme

NAO
North Atlantic Oscillation

NEAP-N
ADAS model developed for modelling N losses from agricultural soils based on soil type, land use and rainfall

NITEX
http://www.macaulay.ac.uk/dynamo/nitrex.htm

NSA
Nitrate Sensitive Areas

NVZ
Nitrate Vulnerable Zones

OECD
The Organisation for Economic Cooperation and Development

PAMUCEAF
EC project: Poplars: A multiple-use crop for European arable farmers (PAMUCEAF). EC FAIR6 CT98-4193, Completed 2001

PES
Payments for ecosystem services

PM10
Particulate Matter <10 µm

PnET
US computer model which provides a modular approach to simulating the carbon, water and nitrogen dynamics of forest ecosystems. http://www.pnet.sr.unh.edu/

RBMP
River Basin Management Plan

RDP
Rural Development Plan

RDPE
Rural Development Programme for England

RWBS
Riparian Woodland Buffer Strips

SEPA
Scottish Environment Protection Agency

SHETRAN
Computer model for water flow, solute and sediment transport in river catchments

SMART
Computer model, which simulates soil response to acid deposition scenarios in Europe. http://www.macaulay.ac.uk/dynamo/contres.htm

SNH
Scottish Natural Heritage

SNIFFER
Scotland and Northern Ireland Forum For Environmental Research

SRC
Short Rotation coppice

SRDP
Scottish Rural Development Programme

SRW
Short Rotation Woodland

SPS
Single Payment Scheme

SUDS	Sustainable Urban Drainage Systems
UKAWMN	UK Acid Waters Monitoring Network
UKCIP	United Kingdom Climate Impacts Programme
UNECE	United Nations Economic Commission for Europe
USEPA	United States Environmental Protection Agency
VFS	Vegetated Filter Strips
VSD	Very Simple Dynamic soil acidification model
WAG	Welsh Assembly Government
Water4all	EU Interreg IIIB North Sea Region Programme completed 2005. Aimed to integrate spatial and land use planning with groundwater management by matching land use to soil and groundwater vulnerability
Water Renew - EU LIFE Environment Project: Wastewater Polishing Using Renewable Energy Crops	
Wilwater	EU LIFE Environment Project: The aim of the WILWATER LIFE Environment programme is to demonstrate the purification properties of Short Rotation Coppice of Willow (SRWC) and the economic and environmental advantages of this purification method.
WFD	Water Framework Directive
WTP	Willingness to Pay

Appendix 1

UK Incentive Schemes relating to woodland creation, management and maintenance.

Scheme	Country	Eligible woodland type	Notes:
Single Payment Scheme	UK - Defra, WAG and S	All woodland established under a grant scheme where the land was eligible for SPS in 2008. Short Rotation Coppice with aid for energy crops. Low-intensity orchards Agroforestry	All agricultural land must be managed in accordance with cross compliance good agricultural and environmental condition (GAEC) rules. These include controls on establishment of green cover, timing and frequency of cutting, prohibition of inorganic fertiliser use and manure/slurry application (except where being used in the preparation of seedbeds). Exemptions from GAEC rulings may apply in SSSI's and special circumstances where permission has been granted from the Rural Payments Agency. Orchards that have less than 150 trees per hectare or are jointly supported by an orchard maintenance or regeneration option of an agri-environment scheme. • Grazed woodland with <50 trees per hectare • Grazed woodland with >50 trees per hectare where woodland grazing has already been shown to be non-damaging to the ecological value of the site. • Scrub/bracken sparse enough to allow grazing
Entry Level Stewardship	England, NE	Hedgerows (with/without trees) Broadleaf ("Traditional")	• Management of existing hedgerows • Maintenance of stock-proof woodland boundary to prevent livestock damage to woodland. An alternative option is available under the EWGS. • Woodland margin (2 m wide buffer) on agricultural land adjacent to woodland.

Scheme	Country	Eligible woodland type	Notes:
Higher Level Stewardship	England - subject to regional / local priorities, NE	Broadleaf ("Traditional") Wood pasture, scrub and orchards Ancient Trees	• Maintenance of small woodlands (<1 ha) within the farmed landscape (<3ha in total)[2] • Restoration of native woodland in poor condition • Woodland management where application to multiple grant schemes would cause excessive administration. • Creation, restoration and maintenance of wood pasture, scrub and orchards • Woodland management integrated into holding management plans (e.g. grazed woodland) • Restoration and maintenance of historic parklands • In-field and boundary tree management (including the protection of ancient trees in arable fields and intensively managed grass fields) • Heathland restoration from forestry plantations
Energy Crops Scheme	England, NE	Short Rotation Coppice	Grants to establish energy crops (>3 ha in blocks of >0.5 ha). Planting may be phased over three years. Minimum of 5 y agreement. Higher payments available for willow/poplar SRC than Miscanthus. An enhanced rate for SRC on ex-livestock land is under review following CAP reform (DEFRA, 2007c). Funding available to set-up producer groups.
Tir Cynnal – closed to new applicantions	Wales, WAG	Streamside/small-scale tree planting (up to 5% of the farm area)	Entry level agri-environment scheme including grants to retain woodland habitats on the farm or create woodland habitats to achieve the minimum 5% habitat threshold to be eligible for the scheme, for example, small-scale tree planting and establishment of streamside corridors.
Tir Gofal – closed to new applications	Wales -subject to regional / local priorities, WAG	Streamside/small-scale tree planting (<0.25ha)	Higher level agri-environment scheme included grants for the establishment and management of small woodlands (up to 0.25ha) and streamside corridors (minimum 7m width from water's edge). New planting grants (BWW) are part funded by the WAG's Rural Development Plan for Wales. The existing Welsh agri-environment schemes are now closed to new applicants and will be replaced by a single new scheme 'Glastir' from 2012.
Rural Development Contracts – Rural Priorities	Scotland	Broadleaf/coniferous woodland, SRC, SRW.	Integrated funding mechanism to deliver environmental, social and economic benefits. Grant support for forests and woodlands is delivered through a number of forestry-specific and non-specific options. Forestry specific options are linked to Regional Priorities and include grants for SRC crops of willow or poplar, improving the economic value of forestry, woodland creation (min 0.25 ha, 15 m wide), sustainable

Scheme	Country	Eligible woodland type	Notes:
			management of forests, and woodland improvement. Non-specific options include support for renewable energy, key species conservation, processing and marketing, and enhancing rural landscapes.
Rural Development Contracts – Land Managers Options	Scotland	Broadleaf/coniferous woodland.	Provides support for the provision of economic, social and environmental improvements across Scotland. Funding support is available for a number of forestry options: small-scale (<1 ha) woodland creation, management of small woodlands, and support for key species conservation, including juniper.
England Woodland Grant Scheme	England, FC subject to regional / local priorities	Broadleaf/coniferous woodland[3]	An amalgamation of six grant schemes for the creation and stewardship of woodland; Woodland Planning Grant; Woodland Assessment Grant; Woodland Regeneration Grant; Woodland Management Grant; Woodland Improvement Grant and Woodland Creation Grant. Also includes annual Farm Woodland Payments for woodland creation, covering the first 15 years after planting on farmland. Additional contributions are available in some regions to increase the value of the Woodland Creation Grant to help promote new planting for specific benefits, including for water.
Better Woodlands for Wales – closed to new applications from 2010	Wales, FC	Broadleaf/coniferous woodland	Support provided via Management Plan Preparation Grants; Woodland Establishment Grants; Replanting Grants and various social and environmental Woodland Improvement Grants The level of Establishment Grant payment varied by woodland type (e.g. new native woodlands), type and diversity of species planted and crop type. Additional capital grants were available for management costs including fencing, pest control and opening up new woodland to the public.

Scheme	Country	Eligible woodland type	Notes:
Glastir Woodland Creation	Wales	Native woodland for carbon or biodiversity; enhanced or basic mixed and 'small, simple' woodland	Offers planning, planting and establishment support for multiple benefits, including water quality, available to all landowners with more than 0.25 hectares of land which has been assessed by FCW and conservation bodies in Wales as suitable for new planting. Native woodland and mixed woodland receive the highest payments with specifications designed to encourage greater tree species diversity, better woodland structure and appropriate management regimes. WAG (run by FC to 1st Jan 2013) thereafter woodland grants will be integrated into Glastir, the new Sustainable Land Management Scheme for Wales managed by WAG's Department for Rural Affairs.
Glastir 'All-Wales' Element (AWE)	Wales	Broadleaf / coniferous woodland	Entry level scheme, paying average flat rate area payment per ha, having achieved a threshold score over the area of the farm. There are no woodland management or creation grants (woodland defined as 0.5ha, according to EC Regs). Applicants may decide to omit woodlands from their AWE application, because options for woodland are so limited in AWE (the option to 'maintain fence around existing woodland as stockproof' was developed after this rule was allowed). - Streamside corridors – with and without tree planting - Maintain stock proof fence around existing woodland - Move existing fence around existing woodland into improved fields to allow natural regeneration - Creation of new 'traditional' orchards - Parkland and individual in-field trees - Allow field corners to 'scrub over' - Hedgerow creation and maintenance - Create woodland connectivity feature From January 2012 the new Sustainable Land Management Scheme for Wales managed by WAG's Department for Rural Affairs.

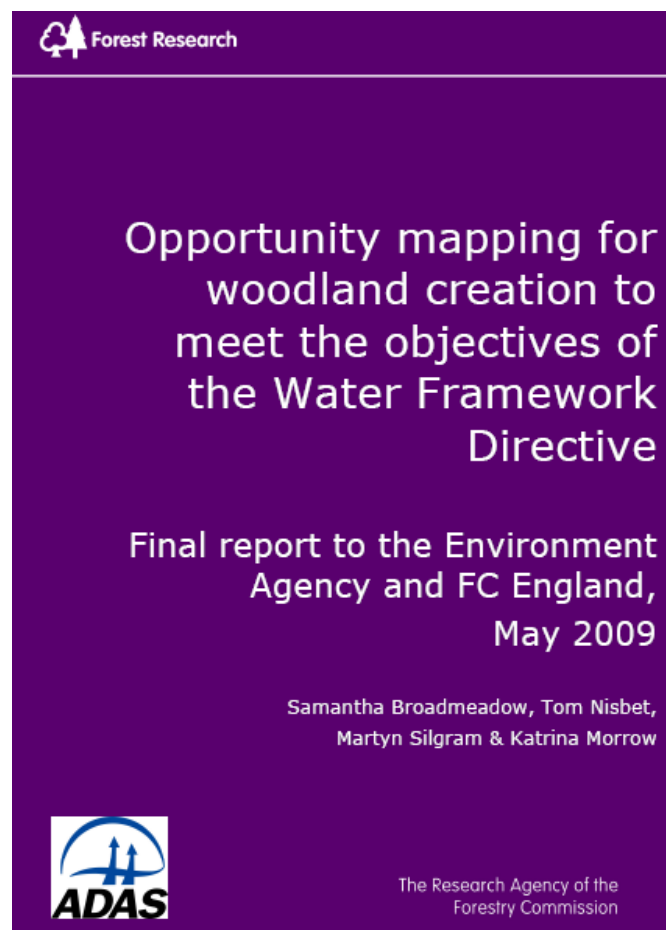| Scheme	Country	Eligible woodland type	Notes:
Glastir 'Targeted Element' (TE) - Woodland Management	Wales - (under development)	Broadleaf / coniferous woodland	Supports the compulsory management of existing woodland over 0.5ha for land managers that apply and qualify for the Targeted Element of Glastir, having first entered Glastir AWE. For land managers who wish to manage their woodland including those in the All Wales Element and those who are not, capital grants are available to support the management of woodland over 0.5ha. The scheme will 'target' woodland management to deliver beneficial outcomes for bio-diversity, carbon, water quality and quantity and access. There will be management planner and capital grant support for these environmental and access objectives, including the restoration of PAWS, management by LISS, increasing the diversity of species in woodlands to improve resilience and improvement of riparian habitat. Land managers in AWE, who apply for TE on all the land in their AWE contract, will have to include woodland that they excluded from their AWE application if their woodland is in one of the targeted areas. From 1st January 2013 the new Sustainable Land Management Scheme for Wales will be managed by WAG's Department for Rural Affairs.
Glastir 'Targeted Element' (TE)	Wales	Tree planting and small-scale woodland on farm holdings in the Targeted Element.	Supports the creation of water interception strips (shelter belts), streamside planting and management and hedgerow creation and management. There are currently no plans to target woodland creation at a strategic scale but the most effective tree planting actions will be incorporated into individual scheme design. From 1st January 2013 Glastir, the new Sustainable Land Management Scheme for Wales will be managed by WAG's Department for Rural Affairs.

[1]Decreasing relevance with changes to the rules for set-aside.

[2]Since qualification is area-weighted, it is uneconomical to include large portions of land as woodland under this scheme – Woodland Grant Schemes are more appropriate.

[3]Usually applies to larger areas (not suitable for support under the agri-environment or Farm Wood Payment schemes)

Appendix 2

[Opportunity mapping for woodland creation to meet the objectives of the Water Framework Directive](#)

Forest Research

The Research Agency of the
Forestry Commission