A cost-benefit analysis of afforestation as a climate change adaptation measure to reduce flood risk.

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Abstract

Increased river flood frequency is considered a major risk under climate change. Protecting vulnerable communities is, therefore, a key public policy objective. Natural flood management measures (NFM) - notably re-afforestation on hillslope and floodplain - are increasingly discussed as cost-effective means for providing flood regulation, particularly when considering ecosystem services other than flood regulation. However, studies that place flood benefits alongside other benefits are rare, potentially causing uncertainty in policy decision-making.

This paper provides a cost-benefit analysis of the impacts of afforestation on peak river flows under UKCP09 climate change projections, and on additional ecosystem services in a rural catchment in Scotland. We find significant positive net present values (NPV) for all alternatives considered. However, benefits are dominated by ecosystem services other than flood regulation, with values related to climate regulation, aesthetic appeal, recreation and water quality contributing to a high positive NPV. The investment in riparian woodland (under low and central climate change scenarios) delivers a positive NPV alone when considering flood regulation benefits only. The case study suggests that afforestation as a sole NFM measure provides a positive NPV only in some cases but highlights the importance of identifying and quantifying additional ecosystem co-benefits.

Keywords

Climate change, natural flood risk management, afforestation, cost-benefit-analysis

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1 Introduction

The IPCC summary for policy makers (2014) identifies increased harm and economic loss from inland flooding to be among the eight key risks of climate change with potentially severe consequences for humans and socio-ecological systems. Expected Average Annual Damages[1] (AAD) from flooding in Scotland are estimated to increase by 56% (under a 2°C climate change projection) and by 140% (under a 4°C climate change projection) by 2080 from £160 million today (Sayers et al. 2015)

Approaches to flood control across Europe in the past have generally emphasised hard engineering solutions (European Commission, 2011). Such schemes often have significant environmental impacts because they disrupt natural flow and storage processes. It is also likely that land use change in catchments, particularly loss of forest cover, riparian zone embankments and channel straightening have amplified flood extent in addition to the increased runoff predicted by climate change models (Rogger et al. 2017).

The introduction of natural flood management (NFM) may provide support against subsequent flow regime changes due to climate change (Dadson et al. 2017). NFM techniques include the restoration, enhancement and alteration of natural features and characteristics, but exclude traditional flood defence engineering that works against or disrupts these natural processes (SAIFF 2011) .

Afforestation is among the NFM measures that is increasingly applied in the UK (Forest Research 2016) and elsewhere in Europe (European Commission, 2011). Over time trees develop a root system creating preferential pathways for water flow and promoting higher infiltration rates (Schwärzel, Ebermann & Schalling 2012) . Combined with higher rates of interception and evapotranspiration this results in reduced runoff and sediment production(Calder 1990).

The influence of forests in the form of upstream or riparian woodland on flood flows is being investigated either empirically through monitoring of (sub)-catchments or through

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[1] This describes the damage per year that would occur in a specific area from flooding over a very long period of time.

hydrological modelling assessments. Empirical evidence is still limited, however, those studies that are published based on mature forest demonstrate positive effects of coniferous forests on peak flow reduction for smaller events (Swank, Crossley 2012, Kirby, Newson & Gilman 1991, Robinson 1998). Hydrological modelling studies of both coniferous, broadleaf and riparian woodland also suggest a decrease in flood peak or changes in flood risk probability in the catchment (see Iacob et al. (2014) and Stratford et al. (2017) for an overview). Greater afforestation leads to a higher rate of peak flow reduction, but the effectiveness diminishes as storm intensity increases and the effects are greater for small catchments. The performance of NFM and in particular of afforestation will ultimately be dependent on site-specific conditions, including landscape setting, catchment characteristics and the degree of hydromorphological alteration (Dadson et al. 2017, Stratford et al. 2017).

In addition to flood regulation benefits, afforestation can offer other eco-system services, for example recreational, biodiversity and climate regulation. Hence the benefit-to-cost ratio (BCR) of any scheme is potentially more favourable when these are also considered. Indeed, for many small communities, physical engineered measures, whose costs can easily be in the six-digits (Interwies et al. 2015), may never be viable due to too low BCR or limited public budgets. In such circumstances, NFM may provide a valuable contribution to reducing peak flows at a lower cost, in particular for smaller-scale flooding problems, and can be partially complemented by household flood protection measures. With the prospect of increasing flooding impacts from more frequent extreme weather, enhancing resilience is crucial. It is thus not surprising that NFM is attracting more policy interest across Europe (Forest Research 2016, WWF 2017, Forbes, Ball & McLay 2015).

Despite this growing interest in NFM, economic appraisals of the flood regulation benefits of afforestation measures are rare. One detailed case study for the Pickering Beck catchment in North Yorkshire, UK (DEFRA 2011) investigated co-benefits for ecosystem services of afforestation measures beyond flood regulation. They found a cost-benefit ratio of 5.6 driven by habitat creation and carbon sequestration. A related study (DEFRA 2013) evaluated the outcomes under different climate change scenarios, and showed positive net benefits even for the worst case scenarios. Dubgaard et al. (2002) carried out a cost-benefit analysis of the Sjkern River restoration project in Denmark. The benefit-cost ratio is favourable, also as a result of eco-system services other than flood regulation.

Given the limited number of joint biophysical/ economic appraisals of NFM, this paper aims to provide cost-benefit estimates of afforestation as a NFM measure and explore the role of afforestation for climate change adaptation. We specifically quantify the effects on flood regulation and other ecosystem services for riparian, broadleaf woodland. The alternative afforestation configurations are tested under different climate change scenarios.

The remainder of the paper is structured as follows: Section 2 introduces the case study and presents our methodology; subsequently, in section 3 we present and discuss our results. Section 4 provides a short conclusion.

2 Case study area and methodology

The Eddleston Water catchment covers 69 km^2 in the Scottish Borders. It is a tributary of the River Tweed, joining it at the little town of Peebles. The Eddleston Water project was established in 2009 to look at the potential contribution that NFM and river restoration techniques could make to address concerns of flooding and habitat degradation (Spray et al. 2016). As is common in the UK, channelisation, land drainage and the creation of flood banks have led to substantial loss of natural habitats, such as wetlands and woodlands (Harrison 2012). These losses may have led to faster runoff generated upstream increasing the risk of riverine flooding in the village of Eddleston (940 inhabitants) and further downstream in the town of Peebles (Spray et al. 2016) (see Figure 1 for the location of the Eddleston Water catchment). Land use is dominated by different types of grasslands predominantly used for grazing (Werritty et al. 2010). Woodland cover amounted to 19% of the catchment in 2009 (Ncube 2016).

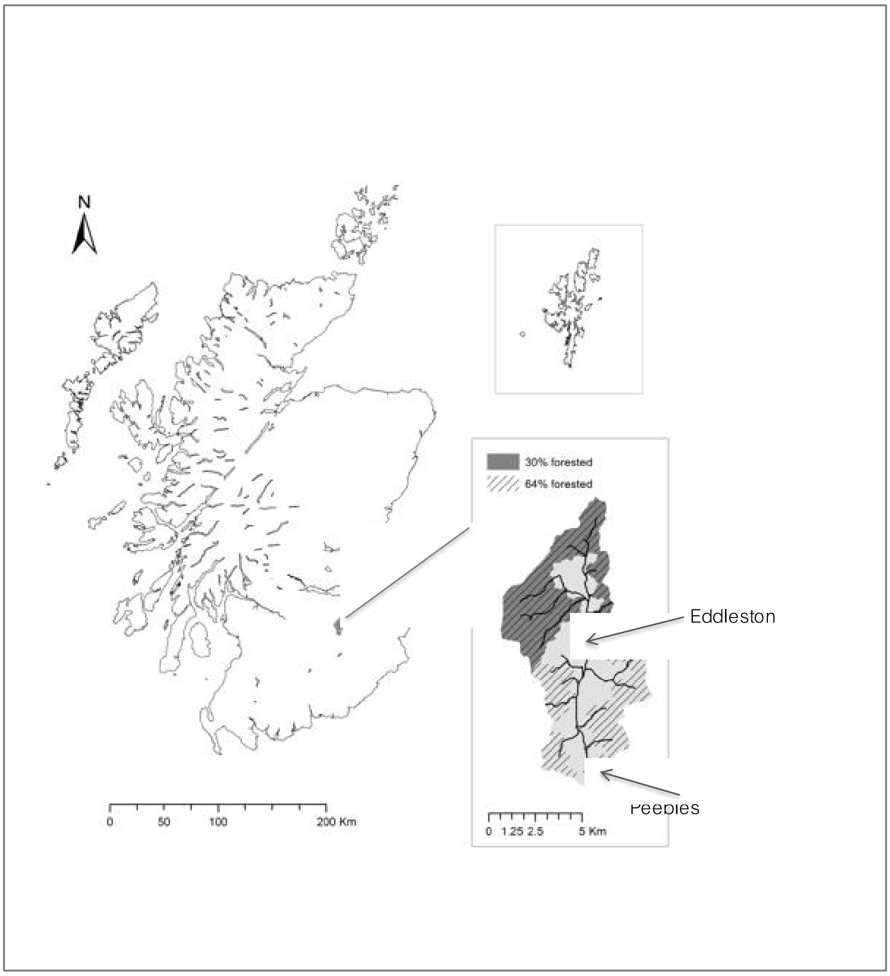

Figure 1 The Eddleston Water Catchment,
Scotland, UK with 30% and 64% broadleaf afforestation of the entire catchment.

A range of NFM have been implemented since 2012, this study focuses on the effects of current and modelled afforestation as a NFM on Eddleston village.

2.1 Climate change scenarios

Climate change scenarios were obtained using the UKCP09 weather generator rainfall data for the relevant area (Jones et al. 2009). The data is conditional on the high, medium and low climate change scenarios. As no information is available on the likelihood associated with the climate change scenarios, we have assumed the medium scenario. However, given the recent evidence on future global emissions (Le Quéré et al. 2015), we may assume that a medium scenario is likely to be a conservative estimate. We downloaded 40 sets of 30-year hourly time series of rainfall with 100 realisations in each set for the baseline, the 2040s and the 2080s resulting in 1200 (years) x 100 (realisations) matrices. The data was analysed using the annual maximum method (Coles 2001) to obtain 100 rainfall intensities for different return periods for all three time periods. The 100 rainfall intensities were grouped in percentile bins (25th, 50th and 75th percentile) to explore lower and higher end climate change outcomes under a medium emission scenario. The rainfall intensities were used as input to the hydrological model.

2.2 Hydrological model and afforestation

The hydrological model – HEC-HMS (US Army Corps of Engineers, 2015) - is open access and has seen widespread use in catchment management around the world, including for flood risk management (Olang, Fürst 2011, Váňova, Langhammer 2011).

The model simulates the transfer of water from rainfall to runoff through various stores. Meteorological sub-models are used to specify the input rainfall, which can be a monitored dataset, design rainfall inputs, or a combination. Initially, interception and canopy storage intercept a proportion of the rainfall, surface storage then intercepts a further proportion, and the residual rain is available for infiltration to soil, which occurs at a rate that relates to the antecedent conditions for each timestep (15 minutes). Evapotranspiration re-transfers some of the moisture to the atmosphere from both soil (non-tension) and canopy, which is a net loss to the system and a component that may be balanced based on known volumes of inflow (rainfall) and outflow (streamflow). Once in the soil, the moisture may percolate down into groundwater stores, again at a specified rate. The computation approach trades-off detailed spatial information with relative simplicity and speed, while preserving the key real-world hydrological stores and transfers. The model was calibrated against baseline data from a distributed network of four tipping bucket rain gauges and 15 stream gauges.

Changes of flood peak given the rainfall intensities determined in section 2.1 were analysed under the following alternatives:

1. currently planted riparian woodland in the floodplain (approximately 29 ha measured through detailed aerial photography, checked by ground truthing),
2. three levels of mostly hillslope broadleaf afforestation of the catchment relative to 19% wood cover in 2009 (30%, 64% and 100% of afforestation corresponding to 2070 ha, 4416 ha and 6900 ha respectively) (see Fig. 1); and

3. a combination of the 100 % hillslope broadleaf afforestation variant and the riparian woodland.

Broadleaves were modelled to add to the still limited literature regarding their role for flood regulation (Archer et al. 2016, Bonell et al. 2013). The trees on the hillslopes will reduce the amount of water reaching the channel in a given time. Riparian woodlands affect the routing, which is the travel of a flood wave moving down a floodplain as well as the frictional roughness of the flood plain. The effects of the riparian woodland on flood regulation are likely to be slightly over-estimated due to the model requiring a minimum area to be specified, which is in some places greater than the actual planted areas.
NFM measures are dynamic in nature and the lag times in relation to consequent effects on runoff response are debated (Hümann et al. 2011). In our model, we assume that 15% of the flood benefits shown by the model are realised in year 1, benefits then increase in equal steps until they are fully realised from year 15 onwards. The peak flow results of the hydrological analysis were used to determine the economic flood regulation benefits. The baseline river stage record in Eddleston village was obtained by 2.5 years of pre-intervention monitoring using a gauge whose height was related to LIDAR data[2] using a ground survey. The stage data were related for flow outputs using a rating curve based on field measurement. For each of the properties at risk, heights were measured with LIDAR data and we calculated inundation depth relative to the riverbank for different flood events.

2.3 Cost-benefit analysis

The timeframe for the cost-benefit analysis is 75 years. Costs and benefits are in 2012 prices when most riparian woodland was planted and the main cost incurred. The discount rate applied up to year 30 is 3.5%, after that 3% as recommended by the UK Green Book (HM Treasury 2003)

2.3.1 Flood regulation benefits

The flood regulation monetary benefits were obtained using the multi-coloured handbook (MCH) commonly used in the UK for flood risk management scheme appraisal (Penning-

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[2] Light Detection and Ranging—is a remote sensing method used to examine the surface of the Earth.

Rowsell et al. 2010). This required classifying all buildings at flood risk by type through a local survey. Based on inundation depth and type of building, the MCH then provides damage estimates. To calculate the benefits, the calculations are carried out with and without the implementation of a flood risk management scheme to obtain a comparison: the damage avoided under the scheme is equal to the benefits of the scheme.

2.3.2 Ecosystem services co-benefits

The UK National Ecosystem Assessment (UK NEA 2011)provides a framework for the consideration of ecosystem services for the current study. The NEA distinguishes between provisioning, regulating, cultural and supporting services. Supporting services such as soil formation and water recycling are not included in the analysis to avoid double counting, as they are intermediate to other final services (Haines-Young, Potschin & Somper 2007).

This study uses a benefit transfer approach for ecosystem valuation, deriving values from previous studies. There are numerous valuation estimates for woodlands, but values are sometimes difficult to compare and standardise to common units (Bockstael et al. 2000). To simplify this potential complexity, we chose studies from the UK with a similar context. Second, the marginal recreational values of a tiny woodland may be trivial and can initially increase with size, but eventually exhibit declining marginal values. We attempt to reflect these potentially decreasing marginal values by choosing very low values in categories at risk to avoid over-estimation of these benefits. Additionally, the analysed areas are sufficiently small for constant marginal values to be a reasonable approximation. Third, the value of ecosystem services are likely to change with climate change (Pedrono et al. 2016). We include these changes specifically for flood risk management. However, it was beyond the scope of the study to investigate the changes in other co-benefits.

Various ecosystem services are affected by afforestation. We explicitly monetized climate regulation, recreational and aesthetic values, water quality, as well as educational and biodiversity benefits. It was not feasible to obtain monetary estimates for air quality effects, which is partly due to their limited impact as well as lack of data.

2.3.2.1 REGULATING SERVICES

The climate change mitigation benefit corresponds to the value of the carbon sequestered by the broadleaf woodland. The total number of hectares of all woodland was multiplied with the relevant carbon prices set out in UK Department of Energy and Climate Change guidance (DECC 2009) and by per hectare carbon sequestration rates in tons (based on the Woodland Carbon Code developed by the Forestry Commission as a guidance to calculate carbon sequestration rates[3]). The relevant prices for the forestry sector are 'non-traded'. We allow for uncertainty in the amount of carbon sequestered by applying the low and high values for the social cost of carbon. Forestry Commission pays farmers substantially less than proposed by DECC, however, the benefits to society may be better reflected by the DECC values which are closer to other studies (Ackerman, Stanton 2012, Brainard, Bateman & Lovett 2009).

Riparian woodland can affect water quality positively in a number of ways. First, it may lower the water temperature of the adjacent water course through appropriate shading (Weatherley, Ormerod 1990). This may have a positive influence on fish stocks by lowering the metabolism of fish and reducing their oxygen use. Second, riparian woodland can significantly reduce the amount of sediment washed into the river (Broadmeadow, Nisbet 2004) which can reduce channel flood capacity and disrupt breeding grounds for fish. Finally, riparian woodland can reduce diffuse pollution from fertilisers on adjacent fields by means of their root system (Leveque 2003). Quantifying these benefits related to water quality is challenging, as there are few relevant studies in the UK. Instead, we apply the National Water Benefit Values (Metcalfe et al. 2012) determined by the willingness-to-pay (WTP) of households for non-market benefits under the Water Framework Directive (WFD – Directive 2000/60 EC) in England and Wales to the riparian woodland. The riparian woodland in the catchment was also planted to achieve habitat restoration along the river, with the aim of changing its ecological status under the WFD from 'bad' to 'good'**.** We thus consider the set of measures as an indicator for the combined potential benefits to water quality from riparian woodland and the supporting services described above. We applied Metcalfe's et al. (2012) water body valuation function, which takes into account the surface of the water body and population numbers. The values in this study represent total WTP for 1km^2 of water area for the effect of riparian woodland (which corresponds to 36% of all

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[3] https://www.forestry.gov.uk/forestry/infd-8hut6v

implemented water quality improving measures), relative to a low-quality base, for each year at which the water body is at moderate quality (the current status of Eddleston Water).

2.3.2.2 CULTURAL SERVICES

Use values in the cultural component include recreation, aesthetic appeal and education. Use values accrue from direct contact with natural resources. Here, this is non-consumptive use where the resource does not have to be consumed or affected to derive value from it (Pearce, Moran 2013). Important non-use values include heritage and biodiversity conservation (EFTEC 2010). Non-use value is the value people assign to goods without (ever) using them. It is challenging to separate use and non-use values as neither people nor survey instruments may be able to distinguish clearly between values for viewing a landscape and non-use values associated with the same features. This again raises the issue of double counting. We thus use separate values for recreation, aesthetic and educational values, and consider any additional non-use values under the heading biodiversity.

26 ha of riparian woodland have been judged by the Tweed Forum (H. Chalmers, personal communication, February 2015) as accessible and likely to be used for walking. The calculation is based on travel cost (the cost of time and travel to the woodland expresses WTP) which have been turned into per hectare values by EFTEC (2010). We apply the category rural wood with low (£190 ha/year) and high values (£2500 ha/year) and their central value which is represented by the mean of the two values (£1300 ha/year) in order to reflect uncertainty.

Woods and forests are often considered attractive landscape features, though some forest types can also be thought to detract from natural beauty. We use the values developed by Entec and Hanley (1997) and EFTEC (2010) to estimate the aesthetic benefit, which suggest £42/ha/yr for rural woodlands. We add upper and lower bounds (+/-20 %) for sensitivity analysis.

The Eddleston Water Project has also created opportunities for educational visits by student groups and professionals. We use a 'cost of investment' approach, which estimates the outlay for making the trip as a proxy of its worth; in this case based on travel cost relative to the cost of providing knowledge in a normal classroom environment. UK NEA (Bateman et al. 2011) estimates the costs to be £16 to £26 per pupil visit for outdoor learning visits. We assume that the number of visits of currently 15 groups each year with approximately 20 people per group will decrease over time as more projects may evolve and curricula change. The last visits are calculated to occur in 2026.

Finally, woodland has positive effects on biodiversity. Broadleaf forest provides some habitat and there is strong evidence that riparian woodland is particularly important for landscape biodiversity (Gundersen et al. 2010). The total value of biodiversity in forests comprises both use and non-use values. Use values are measured through recreational and aesthetic values. Non-use values are existence value (the benefit people receive from just knowing that wildlife exists even though they never see it) and bequest value (the benefit people derive from knowing that wildlife will be protected and preserved for the benefit of future generations).

Based on the work of Hanley et al. (2002), EFTEC (2010) estimate that the range of non-use values of woodland biodiversity is from £30-£300/ha/yr. Riparian woodland is considered a high priority, coniferous woodland is low priority woodland under the UK Post-2012 Biodiversity Framework (JNCC and Defra 2012) and we assume that broadleaves would have medium priority. For the value of riparian woodland, we therefore use low (£180/ha/yr), central (£240/ha/yr) and high (£300/ha/yr) estimates. For the value of the broadleaves, we use £135/ha/yr as the central value (the central value of the EFTEC range and +/- 20 % as lower and upper boundary). We assume that the biodiversity values increase linearly and reach a constant value either once trees reach the age of 55 (low estimate), 20 (central estimate), or 10 years (high estimate) following the approach of Nisbet et al. (2015) .

2.3.3 Cost of afforestation measures

The costs for implementing the afforestation measures can be divided into investment and maintenance costs. Maintenance is calculated at £282/ha per year based on the payments farmers currently receive for this work. Investment costs include planting costs and putting fences in place as well as labour cost. For the riparian woodland, we have actual figures for most areas with lower and upper boundaries. Fixed costs constitute various fees (low, central and high values are respectively, £1,504, £1,712, £1,920). We apply the same estimates to the broadleaf variants.

Beyond the implementation cost, we need to consider the opportunity cost of agricultural land related to forgone use of land for sheep grazing, which is and was the land use of the (modelled) afforested areas. Quality Meat Scotland (QMS 2014) figures on sheep profitability for 2012/2013 suggest a net margin of £26 per ewe for improved pasture. We further assume that 1.5 ewes can be fed on one hectare in the case study area based on land use data (Scottish Government, 2015) and foregone farm income due to the implementation of NFM measures in Scotland (Spray et al. 2015) .

3 Results and Discussion

3.1 Hydrology

The results of the hydrological analysis in Figure 2 for a 5% and 1% annual exceedance probability (AEP)[4] demonstrate that the peak flows of return periods of floods increase over time across all modelled precipitation scenarios (without afforestation) which confirms the increasing severity of flood events under climate change as observed in the literature (Wilby, Keenan 2012). For example, under the 25th percentile, peak flow for the 5% AEP increases by 9% in the 2040s and by 14% in the 2080s. Under the more extreme 75th percentile, peak flow for the 5% AEP goes up by 24% and 30% for 2040 and 2080 respectively. Consequently, flooding may cause more damage in the case study area in the future.

Figure 2 also demonstrates the decreases in peak flow (for 2016, 2040 and 2080) and therefore in flood risk due to forest variants. Generally, a greater relative reduction of peak flow is obtained for a 5% AEP event than for a 1% AEP event, confirming what other studies have found, that afforestation is more effective as a flood management measure for smaller events. Note that the reduced effect for the 1% AEP event is less pronounced for the riparian woodland, which suggests a greater effect on resulting peak flow through floodplain afforestation, on average, than through upstream afforestation.

The changes of peak flow under climate change have important implications for flood regulation through the afforestation measures, in particular for the 5% AEP event. Figure 3 relates the results of the hydrological analysis to the corresponding decrease in damage cost. Every afforestation alternative leads to the prevention of damage of a 5% AEP event for all baseline scenarios (for the riparian woodland, this is only true for the 25th and 50th percentile), which equals a median value of £585,000 worth of benefits (if the event occurs) and therefore implicitly also avoids flooding less severe than associated with 5% AEP. While the currently implemented riparian woodland seems to be sufficient in preventing flooding from a 5% AEP event at least under the flow of the 25th and 50th percentile, this is not the case under any climate change scenario for 2040 or 2080. For instance, if the objective was to

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[4] The annual exceedance probability (AEP) indicates the probability of occurrence of a flood in any given year.

maintain a flood protection standard of a 5% AEP event in the future, further afforestation measures as modelled in this study would need to be implemented. This has also financial implications: the current median of £585 000 for 5% AEP would increase by 37% in 2040 and by 38% in 2080 relative to 2016, leading to higher damage cost of a 5% AEP in the future. The increase of peak flows for the 1% AEP event under climate change is less pronounced (an increase of 10% and 14% for 2040 and 2080 relative to 2016), however it is only with 100% afforestation (and riparian woodland) that we can observe substantial decreases in flood peak (between 10% to 41% per cent depending on the climate change scenario). These results emphasize the complementary role of NFM alongside hard engineered, household flood protection or other measures as part of a flood management strategy under climate change: while afforestation variants provide some flood regulation benefits, none would significantly reduce the effects of a major flood such as a 1 % AEP event. In addition, the full flood regulation benefits are only realised about 15 years after implementation. This is important, particularly in catchments where communities are currently at risk of flooding.

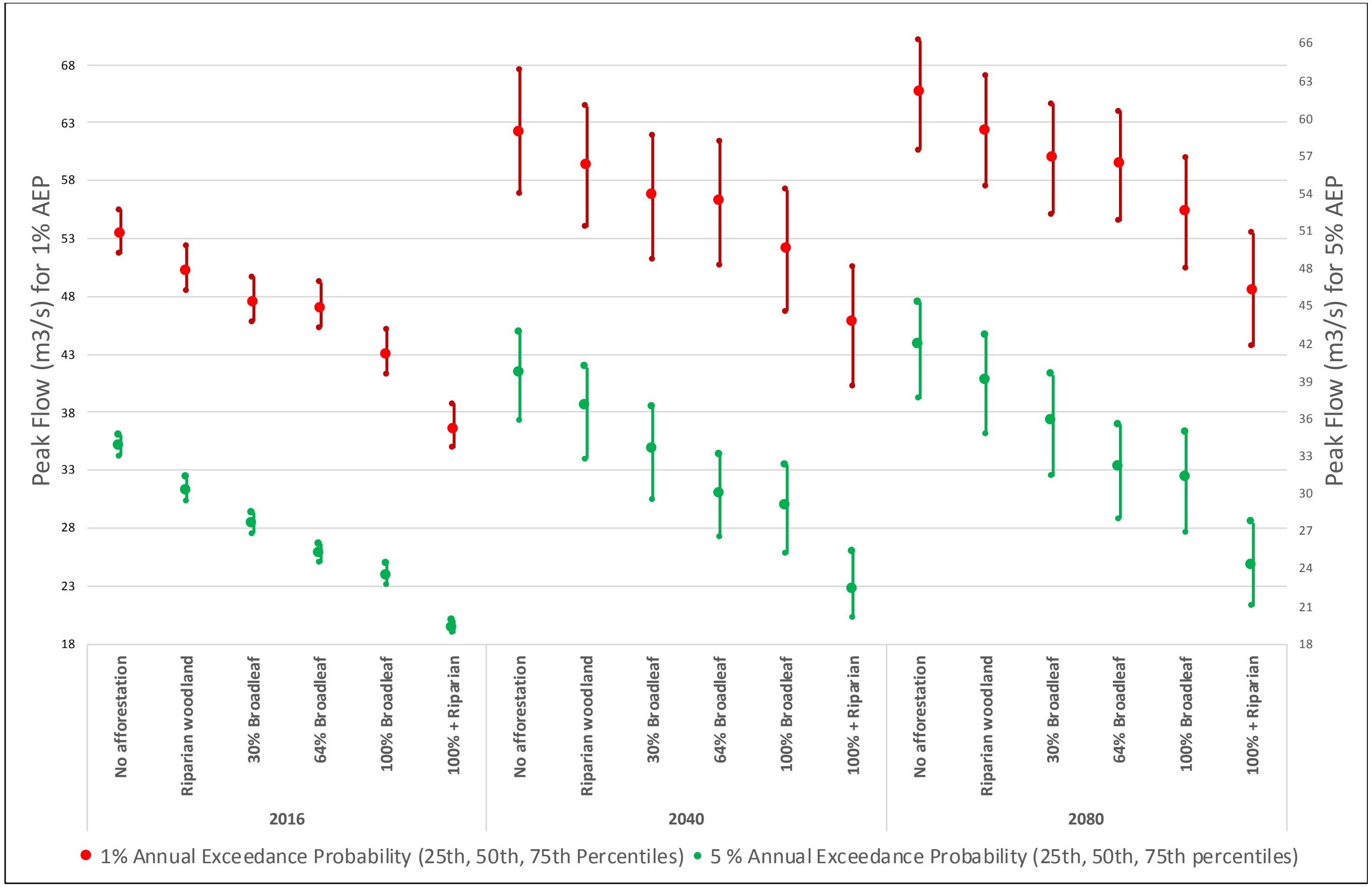

Figure 2 25th, 50th, 75th percentiles of peak flow (m^3/s) for 5% and 1% AEP (annual exceedance probability) without afforestation, with riparian woodland, 30%, 64%, 100% broadleaf woodland and riparian woodland & 100 % broadleaf hillslope woodland for 2016, 2040 and 2080.

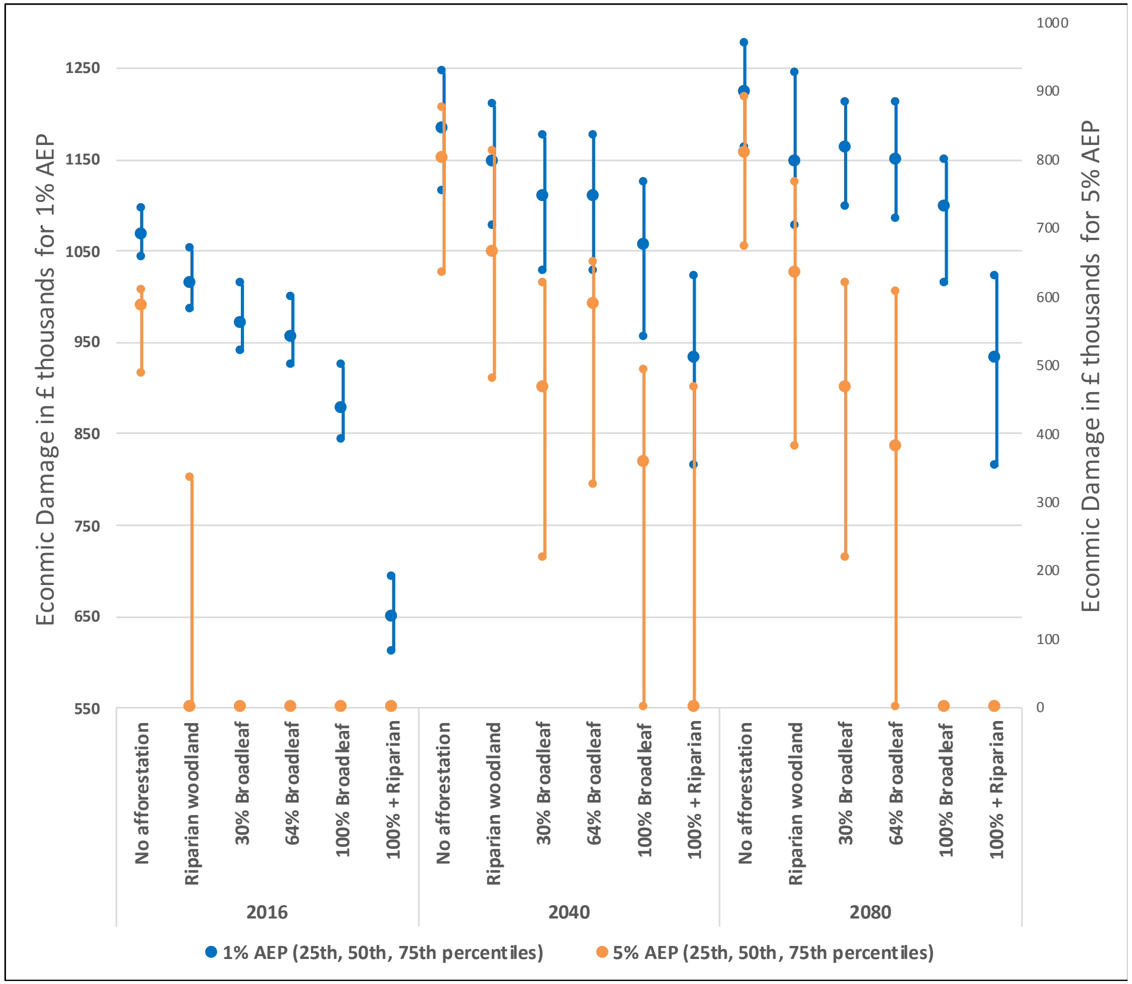

Figure 3 25th, 50th and 75th percentiles of economic damage from flooding in £ thousands 5% and 1% Annual Exceedance Probability (AED) without afforestation, riparian woodland, 30%, 64%, 100% broadleaf afforestation, riparian woodland & 100 % broadleaf afforestation for 2016, 2040 and 2080.

3.2 Cost-Benefit Analysis

Figure 4a presents the net benefits for all alternatives per year for 2016. The 25th, 50th and 75th percentiles of the flood regulation analysis based on annual average damages (AAD) were combined with the low, central and high scenarios respectively from the further ecosystem services analysis to provide a simple sensitivity analysis. The NPVs across climate change scenarios are very similar. This is to be expected, since flood risk management is the only element that changes with the climate change scenarios. At the same time, flood risk constitutes a very low percentage of the overall benefits (around 1 % across the scenarios). We therefore only present the results for the year 2016 in Figure 5.

All alternatives show a positive NPV ranging from £20,000 per year (central scenario) for the riparian woodland only, to £1,3 million per year (central scenario) for 100% afforestation combined with riparian woodland. This suggests that all alternatives would be worthwhile implementing from an economic point of view when including flood regulation and other ecosystem services. Overall the highest total NPV is observed for the combination of 100 % afforestation and riparian woodland, however the highest benefit-cost ratio for the central scenario can be observed for the riparian woodland with the central estimate being 2.8, slightly higher than 2.3 for 100 % afforestation and riparian woodland (see Figure 4b).

Indeed, the cost-benefit analysis indicates that the marginal benefit of flood management (excluding other eco-system services) does not exceed the marginal cost of planting further forest beyond the currently planted riparian woodland under current flow. For 2040 and 2080 flows, the net benefits from flood regulation become negative as the riparian woodland becomes less effective under higher flows. Still, the riparian woodland that was implemented in the catchment is the only alternative under which the flood regulation benefits make the investment worthwhile given the cost under the low and central scenario 2016: the yearly cost of the central riparian alternative equals £9,000 and the yearly flood regulation benefit adds up to £13,000. This suggests that afforestation as a climate change adaptation measure for flooding only in the case study area can only play a limited role when viewed from an economic perspective. This does not consider, however, two important other benefits which were beyond the scope of this study. First, if the damage reduction for the town of Peebles further downstream were considered, this would add significant benefits as a number of as many as 520 properties are at risk of flooding as opposed to 61 in Eddleston, with only the later included in the study. Second, woodland planting also brings benefits from delays in time for a flood to peak – as much as an hour under the currently planted riparian woodland and up to two hours for 100 %

afforestation in addition to the riparian woodland. This buys additional time for residents to prepare for the arrival of flood waters.

With respect to other ecosystem services, the values for the different alternatives show a great disparity which reflects the uncertainty of the underlying data for ecosystem services (see Fig. 4). For example, the low and high NPV for the 30 % afforestation variant are £135,000 and £670,000 respectively. For the broadleaf variants the net benefits increase considerably with the amount of afforestation as the costs do not increase proportionately with the benefits. 50 % of benefits for the riparian woodland come from flood regulation in 2016. By 2080, under climate change, this number decreases to about 25% as the effect decreases with increasing flows. Other important benefits for riparian woodland recreational values, climate regulation and water quality under the WFD as illustrated in Figure 5 for 2016, central scenario. The climate regulation values are driven by the prices of carbon assumed by DECC. While the water quality values take account of the population – which is assumed to benefit from the higher water quality - within a 30-mile radius of the water body, the small surface area of Eddleston water limits the benefits measured in monetary terms.

Given that a range of ecosystem services could not be monetised, we can be confident that the riparian woodland exhibits a strong positive NPV under all scenarios. As can be seen in Figure 5, for the broadleaves, the positive net benefits are driven by climate regulation, recreation and aesthetic values. The per hectare estimates do not reflect decreasing marginal values which may apply, in particular with respect to the 64 % and 100 % afforestation. Nevertheless, even a 100% afforestation refers only to a relatively small area (the catchment is about 16 kilometres long and on average 4 km wide), and while it is unlikely that the estimates for the high scenario are appropriate, we would not expect negative values due to the afforestation.

Afforestation delivers highly significant positive NPVs for all alternatives if all monetised ecosystem services are considered, in particular recreational values and climate services. For all hillslope broadleaf afforestation alternatives, flood regulation benefits amount to less than 1% of total benefits in comparison with 25-50%, depending on the climate change scenario, for riparian woodland. Thus, for hillslope afforestation, it is those co-benefits that drive our cost-benefit analysis similar to the Pickering study described in the literature review (DEFRA 2011). For riparian woodland, the co-benefits are less significant but result in positive net benefits under all climate change scenarios. Flood regulation benefits are greater for the riparian woodland alternative as the other ecosystem services depend strongly on area afforested which is much greater for the broadleaf hillslopes than for riparian woodland. While benefit estimates are inherently uncertain, even the alternatives which use conservative values deliver significant positive NPVs. This indicates a strong case for implementing measures such as afforestation when the project objectives include multiple ecosystem benefits in addition to climate change adaptation benefits from flood risk reduction. Economic appraisals aim to include all accrued costs and benefits to reflect the true NPV of a policy to the public. We therefore suggest considering further ecosystem services beyond flood regulation for the appraisal of NFM to enable policy-makers to make informed decisions with regard to investment in NFM.

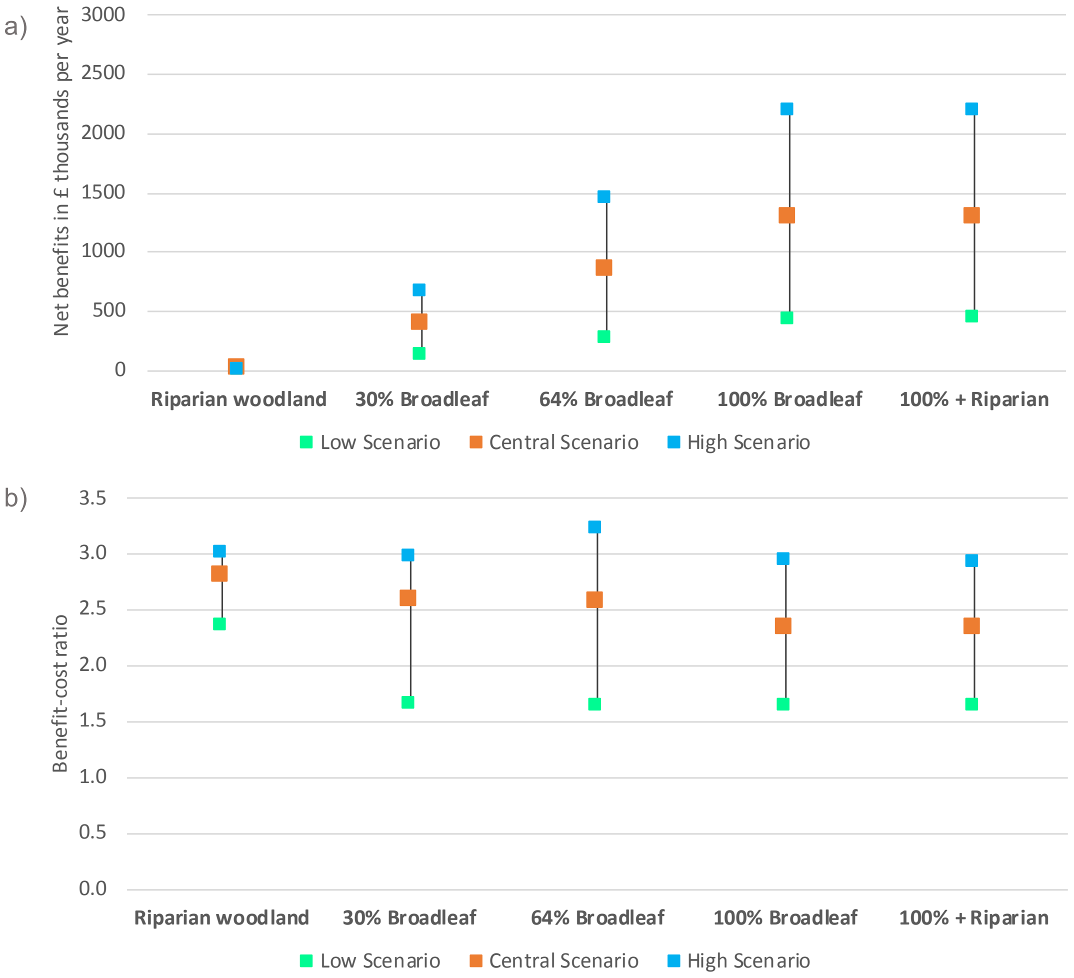

Figure 4 a) Range of net benefits under low, central and high scenarios for riparian woodland, 30%, 64%, 100% broadleaf afforestation and 100% & riparian woodland in 2016. b) Benefit-cost ratios under low, central and high scenarios for riparian woodland, 30%, 64%, 100% broadleaf afforestation and 100% & riparian woodland in 2016.

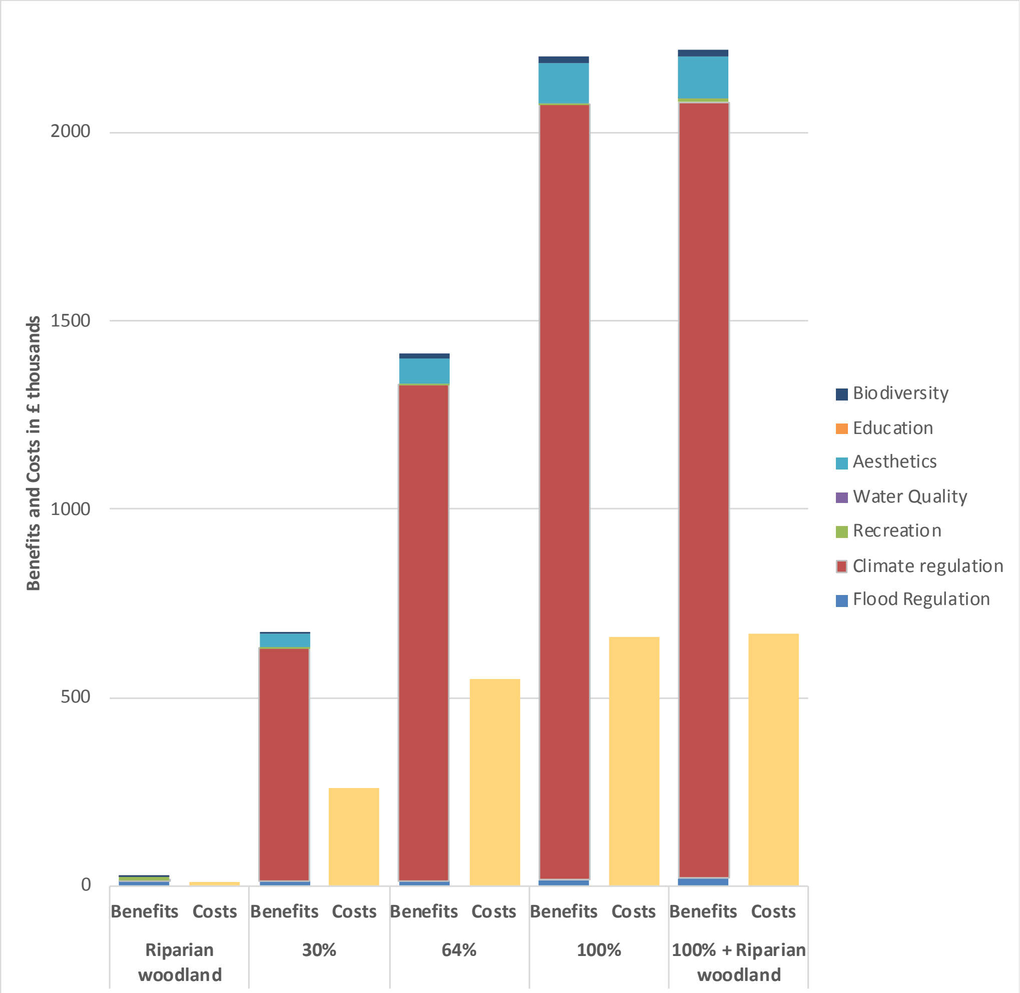

Figure 5 Benefits and Costs in £thousands per year for riparian woodland, 30%, 64% and 100% broadleaf afforestation & 100% and riparian woodland afforestation by benefit category for the central scenario in 2016.

4 Conclusion

This study set out to provide a better understanding of the costs and benefits of afforestation as a climate change adaptation measure for flooding. We provided a cost-benefit analysis of the impacts of the NFM measure afforestation on peak flows under climate change and on further ecosystem services in a small rural catchment in Scotland. We found significant positive NPVs for all alternatives considered, with the largest NPV provided by a combination of 100 % afforestation of the catchment and riparian woodland in the floodplain. The benefits for the hillslope afforestation are driven mainly by ecosystem services other than flood regulation, the latter accounting for approximately only 1% of total benefits. All afforestation variants provide some flood regulation benefits, which increase with the degree of afforestation and are greater for higher frequency flood events. Only riparian woodlands provide greater benefits than costs under the current climate if only flood risk management is included. For riparian woodland, flood regulation amounted to 50% of total benefits. We conclude for our case study that afforestation, when considered exclusively as a NFM measure and a climate change adaptation measure, provides a positive NPV only in some cases, but delivers positive NPVs for all afforestation alternatives if further ecosystem services are considered.

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