Evaluating wider benefits of natural flood management strategies: an ecosystem-based adaptation perspective

Oana Iacob, John S. Rowan, Iain Brown and Chris Ellis

ABSTRACT

Climate change is projected to alter river flows and the magnitude/frequency characteristics of floods and droughts. Ecosystem-based adaptation highlights the interdependence of human and natural systems, and the potential to buffer the impacts of climate change by maintaining functioning ecosystems that continue to provide multiple societal benefits. Natural flood management (NFM), emphasising the restoration of innate hydrological pathways, provides important regulating services in relation to both runoff rates and water quality and is heralded as a potentially important climate change adaptation strategy. This paper draws together 25 NFM schemes, providing a meta-analysis of hydrological performance along with a wider consideration of their net (dis) benefits. Increasing woodland coverage, whilst positively linked to peak flow reduction (more pronounced for low magnitude events), biodiversity and carbon storage, can adversely impact other provisioning service – especially food production. Similarly, reversing historical land drainage operations appears to have mixed impacts on flood alleviation, carbon sequestration and water quality depending on landscape setting and local catchment characteristics. Wetlands and floodplain restoration strategies typically have fewer disbenefits and provide improvements for regulating and supporting services. It is concluded that future NFM proposals should be framed as ecosystem-based assessments, with trade-offs considered on a case-by-case basis.

Key words | ecosystem-based adaptation, ecosystem services, natural flood management, trade-offs

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INTRODUCTION

The global climate is expected to change at a rate unprecedented in human history, as exemplified by rising sea levels, glacial retreat, changing precipitation patterns and an increasing frequency of extreme weather events (Kiehl 2011). Evidence for these changes, which include both short-term climatic variability and longer term trends, underpins the need for a twin-track response, involving both mitigation and adaptation strategies (Perez *et al.* 2010). With regard to adaptation, the primary goal is reduced exposure to natural hazards such as flooding whilst increasing human resilience to hazard-related events from the local scale upwards (Tschakert & Dietrich 2010). Evidence increasingly demonstrates that local flood risk must be viewed as non-stationary. Risks vary in direct response to changing hydroclimatic drivers but also to indirect controls on runoff generation and flow routing as a consequence of catchment land use changes and hydromorphological alterations to the channel network (Werritty *et al.* 2006).

Traditional approaches to flood control have emphasised 'hard' engineering 'solutions', mainly centred around protection of high value infrastructure, but also more widely emplaced to defend agricultural production on drained wetlands and floodplains. These schemes often have significant environmental impacts because they disrupt natural flow and storage processes. Moreover, whilst engineered strategies are generally designed to provide protection for specific flood levels (with inferred recurrence intervals), maintaining the same level of cover under changing climatic

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conditions requires upgrading (potentially repeatedly) with attendant economic, social and environmental costs. Thus there is a pressing need to develop improved adaptation strategies centred on sustainable natural resources and for catchment land-based flood management measures promoting greater resilience against the anticipated increased frequency of extreme events (Heller & Zavaleta 2009; Campbell *et al.* 2009).

Ecosystem based Adaptation (EbA) is an emerging paradigm for managing natural resources under increasingly variable and perturbed climatic conditions. As an approach it includes ‘soft’ and ‘hard’ responses in the form of targeted ecosystem conservation, management and restoration actions (Jones *et al.* 2012). EbA therefore aims to enhance the natural dynamic and resilient properties of ecosystems to buffer the adverse impacts of climate change and therefore reduce human vulnerability (Colls *et al.* 2009). The need for interdisciplinary perspectives, including social science, in adaptation planning was emphasised by Heller & Zavaleta (2009). In particular, EbA recognises that future change is intrinsically uncertain due to climate change and associated pressures (e.g. spread of invasive species), and that the most effective strategies to reduce risk therefore include measures to improve system resilience rather than being predicated on a particular outcome.

The focus in this paper is to assess the utility of EbA as a framework for guiding natural flood management (NFM) strategies. NFM is widely recognised as an option to reduce flooding whilst achieving multiple benefits throughout the catchment and is rising rapidly up the policy agenda across Europe because of its potential to buffer the effects of climate change (Wheater *et al.* 2010). Traditional hard (and indeed soft) engineering solutions are generally location specific measures applied to protect social and infrastructural assets at risk of flooding. These measures are designed to provide protection for certain flood events under assumed stationarity in magnitude/frequency relations (Figure 1(a)). Clearly, they become less effective, i.e. risks increase, under non-stationary conditions symptomatic of climate change (Figure 1(b)). By comparison, the introduction of NFM measures potentially provides greater adaptive capacity to negate climate change by re-naturalising flows or at least provides a buffer against subsequent regime changes (Figures 1(c) and (d)). However, the performance of NFM will ultimately be dependent on

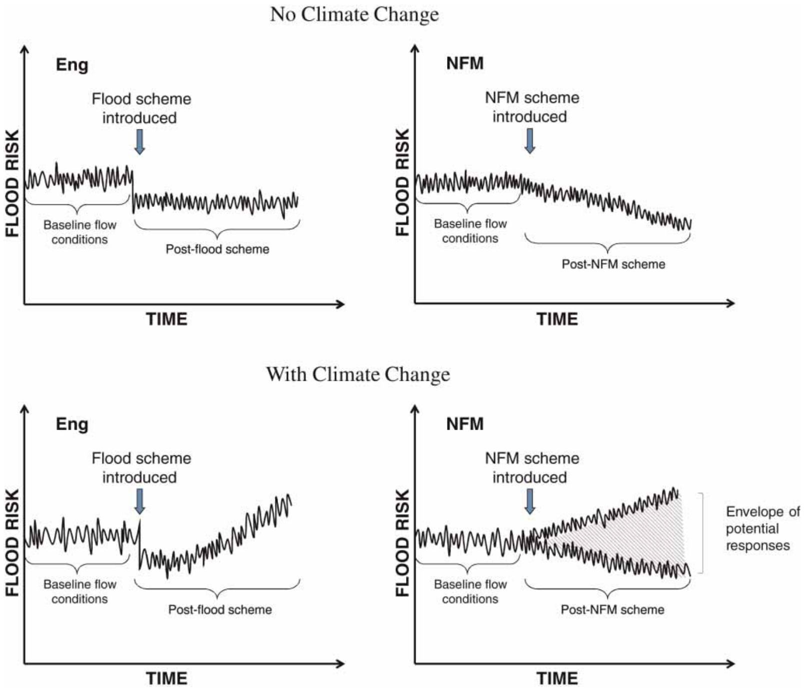


Figure 1 | Representation of expected engineered (Eng) and NFM strategies behaviour in no climate change conditions and with climate change.

specific site conditions, inclusive of landscape setting, catchment characteristics, the degree of hydromorphological alteration and the extent and appropriateness of the different measures adopted. Performance will also evolve or mature over time, meaning that flood risk should be constrained within an envelope of possible outcomes (Figure 1(d)) rather than based upon a specific deterministic outcome.

NFM involves the utilisation or restoration of 'natural' land cover and channel-floodplain features within catchments in order to increase the time to peak and reduce the height of the flood wave downstream (Environment Agency 2010). This may involve altering multiple elements of a catchment water balance by promoting interception, infiltration and groundwater storage, enhancing water losses through evapotranspiration, lengthening hydrological pathways and increasing flow resistance. In terms of scale, NFM measures are typically evaluated at the catchment scale, consistent with concepts of whole-system planning (Figure 2(a)), though specific actions may be more local, depending on catchment size, levels of stakeholder acceptance and governance arrangements. Figure 2(b) seeks to show, at least in a qualitative way, the relative differences in the invested capital and net benefits of different flood control strategies, illustrating that costs are typically highest in relation to hard-engineering infrastructure protection. NFM schemes, and more systemically EbA, capitalise on the regulating services of natural systems in terms of flow regulation and flood control but can also realise significantly greater co-benefits. Hence the benefit-to-cost ratio is potentially much more favourable for these schemes, as would be represented in a total economic evaluation, although rarely accounted for in conventional assessments. On the other hand, while engineering schemes provide increased flood protection from the day of completion, NFM schemes generally involve a lag time to establish. NFM performance also tends to be less certain because comparable interventions on different hillslope, channel, wetland or floodplain features can produce complex and dynamic response and divergent outcomes at the catchment scale in relation to runoff and sediment production (Schumm 1979; Chorley *et al.* 1984; Scottish Environment Protection Agency (SEPA) 2012).

This paper aims to provide a better understanding of NFM approaches and their potential role as a climate change adaptation strategy using the ecosystem services (ESS) framework (UK National Ecosystem Assessment (NEA) 2011). The meta-analysis, drawing on monitoring and modelling data from 25 (mainly) European studies, was used to explore the links between afforestation extent and flood risk downstream. A comparative analysis of different NFM strategies was also undertaken using an ESS framework revealing positive and negative impacts on goods and services and providing the basis to consider options and trade-offs in terms of decision-making by catchment managers and wider stakeholder groups. The study does not include the full range of NFM options but provides a foundation for further investigation.

METHODS

The evaluation framework for the current study was drawn from the UK National Ecosystem Assessment (NEA). This is

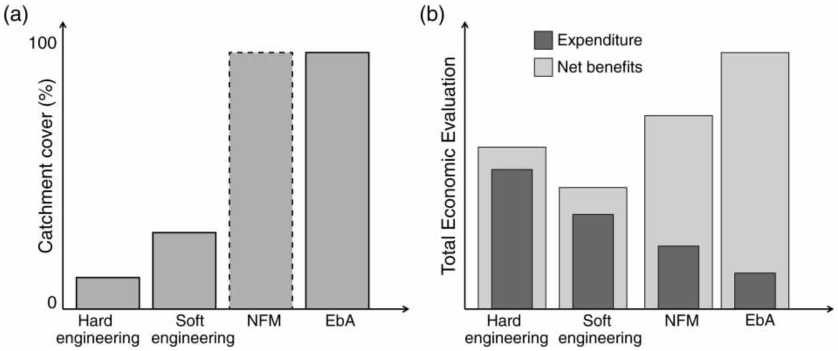


Figure 2 | The relationship between different approaches for flood risk management: (a) size on which they are being implemented, (b) the financial means engaged in the implementation of these approaches including potential benefits.

the first systematic assessment of goods and services provided by the natural resources underpinning the UK economy (UK NEA 2011). Building on the global Millennium Ecosystem Assessment (MA), the NEA distinguishes between provisioning, regulating, cultural and supporting services. These services are further divided into 'final ESS' (e.g. water purification) that directly contribute to the tangible goods that are valued by people and 'intermediate ESS' (e.g. nutrient cycling) that underpin these final ESS, but not directly linked to goods. For the present purposes only final and intermediate ESS were considered, and not the goods or beneficiaries which are often associated through complex human systems.

The significant adverse impacts were noted with a '- -', whilst the less significant ones with a '−'. Similarly a '+ +' was assigned for significant positive impacts and '+' for less significant improvements. If there were no changes in the initial state of the ESS a '0' value was assigned and a 'NA' (Non-Applicable) was assigned if certain ESS were not represented in a particular catchment. The scoring process was informed by evidence from the literature and expert-judgement tested between the authors. The high level of internal agreement suggests that the direction and scale of impacts is a sound first approximation.

STUDY CASES

Twenty-five study catchments were compiled for this project drawn from the review in Scotland of Price *et al.* (2011) and other examples from the wider academic literature. Most of the study cases are based in the UK, other studies being located in mainland Europe and New Zealand (Figure 3). Consistent with Price *et al.* (2011) four categories of NFM schemes were recognised: (a) (re)establishment of forests and woodland; (b) drainage and drain blocking; (c) wetlands and floodplains restoration; (d) combined measures.

The case-study catchments differed greatly in size, spanning four orders of magnitude from 10,000 km^2 to under 1 km^2 (see Table 1). Two alternative methods were used to assess the effectiveness of different NFM proposals: (i) hydrologic and hydraulic modelling exercises to assess flood attenuation potential and (ii) direct monitoring. The variation in scale and lack of consistency in assessment

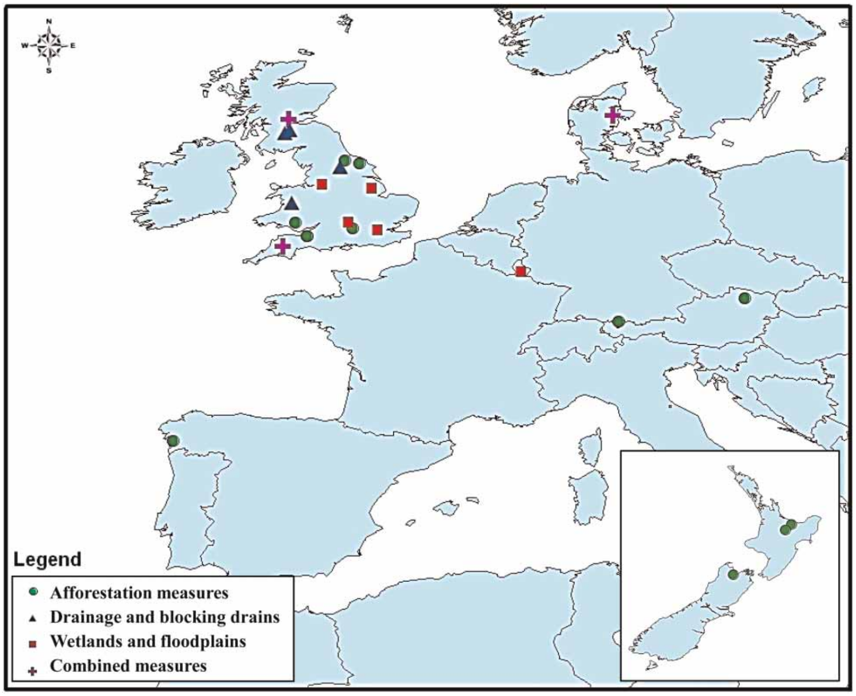


Figure 3 | The locations where the selected projects have been implemented, by NFM categories.

Table 1 | General information for the selected studies

No	Catchment name and type of NFM scheme	Country	Area (km^2)	Approach	Reference
Forests and woodland					
1	Trent, Severn, Thames	England	10,000	Modelling	Naden *et al.* (1996)
2	Parrett	England	1,675	Modelling	Park *et al.* (2006)
3	Iller	Germany	954	Modelling	Francés *et al.* (2008)
4	Tarawera	New Zealand	906	Monitoring	Dons (1986)
5	Kamp	Austria	622	Modelling	Francés *et al.* (2008)
6	Poyo	Spain	380	Modelling	Francés *et al.* (2008)
7	Laver	England	79	Modelling	Nisbet & Thomas (2008)
8	Cary	England	77	Modelling	Thomas & Nisbet (2006)
9	Pickering Beck	England	66	Modelling	Odoni *et al.* (2010)
10	Pontbren a,b	Wales	4	Modelling	Wheater *et al.* (2010)
11	Parukohukohu	New Zealand	~0.29	Monitoring	Dons (1981)
12	Moutere	New Zealand	~0.06	Monitoring	Duncan (1995)
Drainage and drain blocking					
13	Llanbrynmair	Wales	3	Monitoring	Leeks & Roberts (1987)
14	Coalburn	England	1.5	Monitoring	Robinson *et al.* (1998)
15	Blacklaw Moss	Scotland	0.07	Monitoring	Robertson *et al.* (1968)
16	Ripon	England	120	Modelling	JBA (2007)
17	Ballard study	England	0.2	Modelling	Ballard *et al.* (2010)
Wetlands and floodplains					
18	Steinsel	Luxembourg and France	2	Monitoring	Liu *et al.* (2004)
19	Sinderland Brook	England	2	Monitoring	Environment Agency (2010)
20	Quaggy	England	–	Monitoring	Potter (2006)
21	Cherwell	England	–	Modelling	Acreman (1985)
22	Long Eau	England	–	Monitoring	Moss (2007)
Combined measures					
23	Lilea	Denmark	–	Monitoring	Hansen (1996)
24	Glendey	Scotland	2	Modelling	Johnson (2007)
25	Tillicoultry River	Scotland	–	Modelling	Johnson (2007)

methods present challenges when evaluating the performance of different NFM measures, but these differences do not substantially affect the qualitative ESS analysis undertaken here.

PERFORMANCE OF NFM MEASURES

The performance of the NFM measures was presented in the original studies in different ways: (i) as flood peak reduction for different flood event return periods (e.g. 1, 2, 25, 50, 100 years), (ii) as increase in time to peak or (iii) as a decrease in annual probability of flood risk for the area (see Table 2). Baseline and catchment data were also presented in a wide variety of styles and completeness presenting further uncertainties in comparing the relative performance of different NFM schemes (cf. Naden *et al.* 1996; Wheater *et al.* 2010). Consequently, the analysis mainly explores the relationships between afforestation projects and their impact on floods of different recurrence interval, for example, distinguishing between small and frequent floods (<2 years) versus much larger and rarer floods (50–200 years). For studies reporting

Table 2 | Indicators of NFM actions in reducing the flood risk in the selected study cases

Categories	Type of measurement
Forest and woodland	Peak flow reduction Time to peak
Drainage and drain blocking	Time to peak Factor of unit hydrograph Percentage of runoff
Wetlands and floodplains	Peak flow reduction Time to peak Annual probability of flooding Water volume
Combined measures	Peak flow reduction Water volume Water velocity

flood peak reduction in terms of envelope ranges we have used the mean or mid-range value for reduction performance. The role of catchment size was also investigated.

The relationships between afforestation extent and flood peak attenuation for two return period groups is shown in Figure 4. The baseline vegetation varies among the studies, some documenting an increase of tree cover replacing grassland, pasture, arable land, mixture of scrub and non-irrigated trees whilst for others it is not stated. These relations are clearly non-linear and statistically significant ($r^2 = 0.52$, $p < 0.001$) for small magnitude events but also for larger events ($r^2 = 0.61$, $p < 0.05$). The higher exponent for the <2 year floods means that the greatest attenuation potential occurs for the smaller events achieving predicted flood peak reductions approaching 60–70% as complete forest coverage is attained. The effects are less pronounced in the case of the larger events, where woodland coverage of c. 80% was reported to effect a 30% reduction in peak flow values.

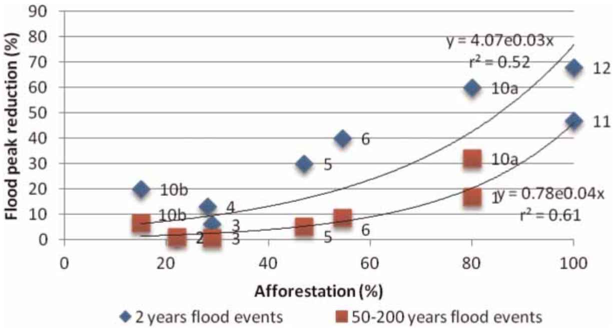


Figure 4 | The relationship between the percentage of several afforestation strategies and their performance for small and large events (labels refer to catchments in Table 1).

Across the magnitude-frequency range shown in Figure 4 afforestation is shown to deliver 'benefits' in terms of flood attenuation, especially in those catchments where woodland cover was initially low. However, the results also clearly point to threshold conditions in the full continuum of events beyond which NFM and ultimately hard engineered solutions will be overwhelmed and extensive flood damage is inevitable.

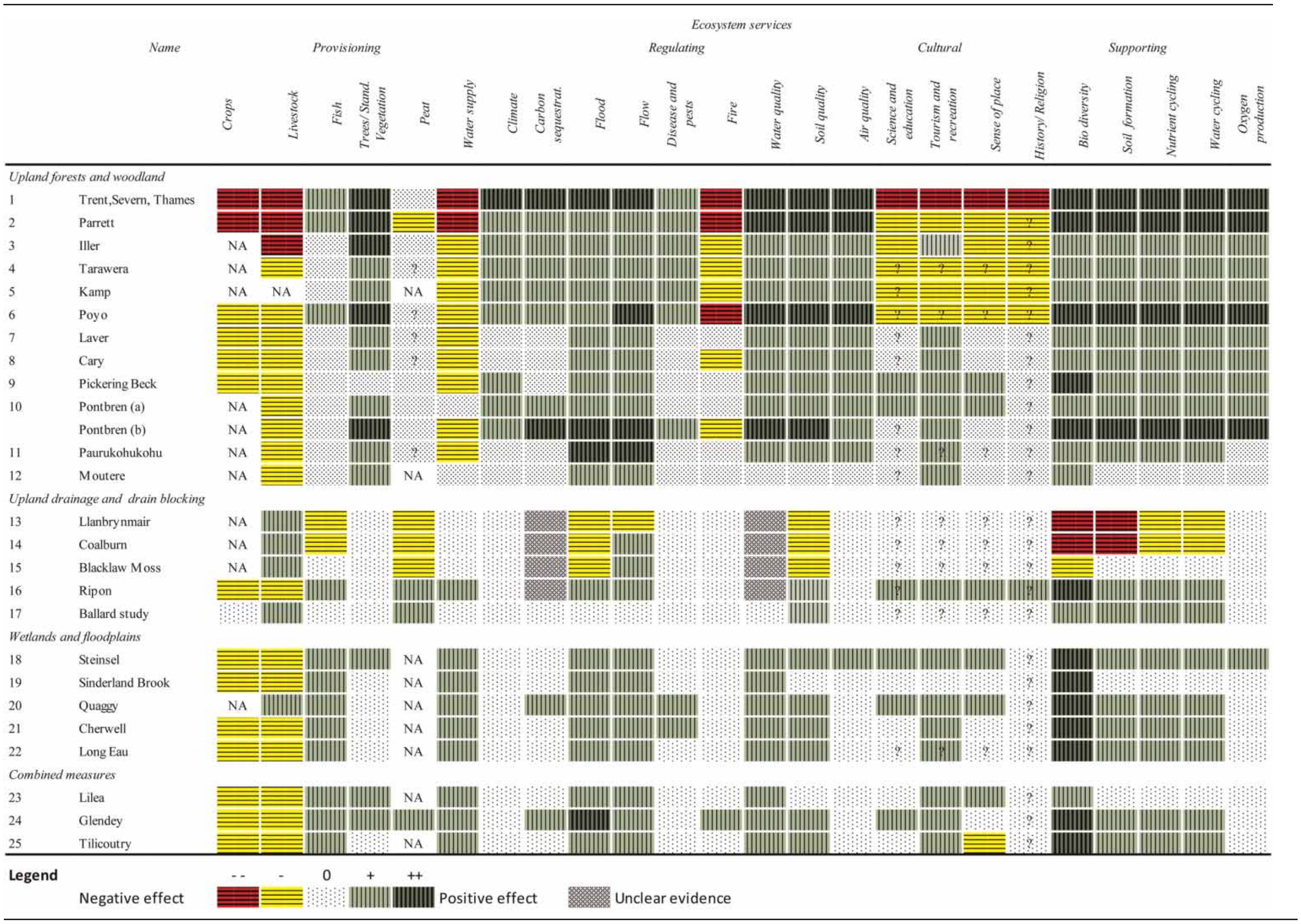
Recent analysis has also established that NFM cannot be universally considered as a 'no regret' measure (i.e. benefits will exceed costs in all circumstances) in adaptation terms. Odoni & Lane (2010) demonstrated that NFM can in certain circumstances synchronise previously de-coupled sub-basin flood peaks and consequently aggravate downstream flooding problems. This further highlights that NFM measures are more effective in some locations than others. Deciding the best location for NFM measure implementation can be rather complex and will generally require detailed modelling and good calibration data similar to hard engineering schemes.

ECOSYSTEM SERVICE ASSESSMENT

The ecosystem approach provides a framework for evaluating NFM options both in terms of their primary goal of catchment runoff control, but also more systemically in relation to ecosystem function and the delivery of wider goods and services. NFM targets, such as reducing flood peak height and extending time to peak, are examples of response metrics resulting from specific land management interventions. Here the related (direct and indirect) consequences are assessed for different groups of ESS using scores ranging from 'significantly adverse' to 'significantly positive' impacts (Table 3). Some services, such as biodiversity, arguably span several columns but for clarity we here attribute positive/negative impacts to the single most important category for each NFM project considered. Within the table, question marks accompany those scores where the case-study background information was restricted and so acknowledges a greater level of uncertainty.

Increasing the coverage of 'forests and woodland' in upstream areas was convincingly shown to reduce downstream flood peaks and base-flows in the Polo, Iller and

Table 3 | ESS assessment



		Ecosystem services																							
	Name	*Provisioning*						*Regulating*									*Cultural*				*Supporting*				
		Crops	*Livestock*	*Fish*	*Trees/ Stand. Vegetation*	*Peat*	*Water supply*	*Climate*	*Carbon sequestrat.*	*Flood*	*Flow*	*Disease and pests*	*Fire*	*Water quality*	*Soil quality*	*Air quality*	*Science and education*	*Tourism and recreation*	*Sense of place*	*History/ Religion*	*Bio diversity*	*Soil formation*	*Nutrient cycling*	*Water cycling*	*Oxygen production*
Upland forests and woodland																									
1	Trent,Severn, Thames	--	--	+	++	0	--	++	++	++	++	+	--	++	++	++	--	--	--	--	++	++	++	++	++
2	Parrett	--	--	+	++	-	--	+	+	+	+	+	--	++	++	++	-	-	-	- ?	++	++	++	++	++
3	Iller	NA	--	0	++	0	-	+	+	+	+	+	-	+	+	+	-	+	-	- ?	+	+	+	+	+
4	Tarawera	NA	-	0	+	0 ?	-	+	+	+	+	+	-	+	+	+	- ?	- ?	- ?	- ?	+	+	+	+	+
5	Kamp	NA	NA	0	+	NA	-	+	+	+	+	+	-	+	+	+	- ?	-	-	- ?	+	+	+	+	+
6	Poyo	-	-	+	++	0 ?	-	+	+	+	++	+	--	++	++	++	- ?	- ?	- ?	- ?	++	++	++	++	++
7	Laver	-	-	0	+	0 ?	-	0	0	+	+	0	0	+	+	+	0 ?	+	0	0 ?	+	+	+	+	+
8	Cary	-	-	0	+	0 ?	-	0	0	+	+	0	-	+	+	+	0 ?	+	0	0 ?	+	+	+	+	+
9	Pickering Beck	-	-	0	0	0	-	+	0	+	+	0	0	+	+	+	+	+	+	0 ?	++	+	+	+	+
10	Pontbren (a)	NA	-	0	+	0	0	+	+	+	+	0	0	+	+	+	+	+	+	0 ?	+	+	+	+	+
	Pontbren (b)	NA	-	0	++	0	-	+	++	++	++	+	-	++	++	+	0 ?	+	0	0 ?	++	++	++	++	++
11	Paurukohukohu	NA	-	0	+	0 ?	-	0	0	++	++	0	0	+	+	+	0 ?	+ ?	0 ?	0 ?	+	+	+	+	0
12	Moutere	NA	-	0	+	NA	0	0	0	+	+	0	0	0	0	0	0 ?	+	0	0 ?	+	0	0	0	0
Upland drainage and drain blocking																									
13	Llanbrynmair	NA	+	-	0	-	0	0	▩	-	-	0	0	▩	-	0	0 ?	0 ?	0 ?	0 ?	--	--	-	-	0
14	Coalburn	NA	+	-	0	-	0	0	▩	-	+	0	0	▩	-	0	0 ?	0 ?	0 ?	0 ?	--	--	-	-	0
15	Blacklaw Moss	NA	+	0	0	-	0	0	▩	-	+	0	0	▩	-	0	0 ?	0 ?	0 ?	0 ?	-	0	0	0	0
16	Ripon	-	-	+	0	+	+	0	▩	+	+	0	0	▩	+	0	+ ?	+	+	+ ?	++	+	+	+	0
17	Ballard study	0	+	0	0	+	0	0	0	0	0	0	0	0	+	0	0 ?	0 ?	0 ?	0 ?	+	+	+	+	0
Wetlands and floodplains																									
18	Steinsel	-	-	+	+	NA	+	0	0	+	+	0	0	+	+	+	+	+	+	0 ?	++	+	+	+	+
19	Sinderland Brook	-	-	+	0	NA	+	0	0	+	+	0	0	+	0	0	0	0	0	0 ?	++	0	0	0	0
20	Quaggy	NA	+	+	0	NA	+	0	+	+	+	+	0	+	+	0	+	+	+	0 ?	++	+	+	+	0
21	Cherwell	-	-	+	0	NA	+	0	0	+	+	+	0	+	+	0	0	+	0	0 ?	++	+	+	+	0
22	Long Eau	-	-	+	0	NA	+	0	0	+	+	0	0	+	+	0	0 ?	+ ?	0 ?	0 ?	++	+	+	+	0
Combined measures																									
23	Lilea	-	-	+	+	NA	+	0	0	+	+	0	0	+	0	0	0	+	+	0 ?	+	0	0	0	0
24	Glendey	-	-	+	+	+	+	0	+	++	+	0	+	+	+	0	+	+	0	0 ?	++	+	+	+	0
25	Tilicoutry	-	-	+	0	NA	+	0	0	+	+	0	0	+	+	0	0	+	-	0 ?	++	+	+	+	0

Legend -- - 0 + ++

Negative effect 🟥 🟨 ░ ▥ ■ Positive effect ▩ Unclear evidence

Parrett catchments. Some projects focussed specifically on establishing riparian or floodplain woodland, for example, Pickering Beck, Cary, Laver but for both groups as tree cover increases, the negative consequences on 'Crops' and 'Livestock' services rise as a result of less land being available for those services. Those catchments, such as Tarawera, Kamp, Pontbren, with a proportionately small arable footprint limited the loss of food production to 'Livestock' service. By contrast the 'Trent, Severn and Thames' and Pontbren case-studies had the most significant negative effects on these agrarian ESS, as both proposed complete coverage of woodland. These comparisons highlight that both the scale of the measure and the size of the area on which the measure is being implemented play a key role when assessing system responses.

Increasing tree cover in the Pontbren, Poyo and Kamp studies had multiple hydrological consequences as quantified through the catchment water balance. Over time trees develop a complex root system (growing and dying) creating preferential pathways for water flow and promoting higher infiltration rates (Archer *et al.* 2002; Schwärzel *et al.* 2012). Combined with higher rates of interception and evapotranspiration it results in reduced runoff and sediment production, the effectiveness of which diminishes as storm intensity increases (Calder 1990). Over time biogeochemical cycling dynamics changed, promoting greater carbon sequestration and reduced nutrient efflux (subject to woodland species composition), with the potential to significantly augment biodiversity and soil and water quality

(Hastie 2003). The largest gains in ESS were reported for those studies involving a significant increase of tree cover with a diverse forest structure.

If trees are planted on organic-rich and peat soils deeper than 20–40 cm, there can be a negative impact on 'carbon sequestration' services as a result of elevated mineralisation rates (Cannell 1999). Most of the studies did not give a full characterisation of soil properties and this impact was therefore hard to quantify. Increasing the tree cover percentage will have mixed impacts on 'Tourism and recreation' services. Whilst for relatively small increases it would likely have a positive impact, for significant afforestation increases a negative impact may result from limited and restrictive access (assuming that the afforestation is fast-growing coniferous plantations). The Parrett catchment has important cultural assets (Postchin *et al.* 2008) thus a 22% afforestation as proposed in the study would be likely to have negative impacts on key features of the cultural landscape such as 'History', 'Education' and 'Sense of place'.

Studies which addressed actions in the 'Upland drainage and drain blocking' category were based both on monitoring and modelling approaches (e.g. Robertson *et al.* 1968). Upland drainage options were historically implemented to improve land quality for enhanced agricultural, forestry or game bird productivity (Burt 1995). The method is documented as having significant adverse impacts in terms of runoff response. In the three studies included herein, although the evidence is variously reported (e.g. time to peak, runoff response) they all point to a flashier response and higher flood peaks. Robertson *et al.* (1968) and Robinson *et al.* (1998) documented reductions in 'time to flood peak' parameter for the Blacklaw Moss and Coalburn studies, while Leeks & Roberts (1987) recorded a much peakier runoff response for the Llanbrynmair following land drainage. Therefore, although lowering local water tables on the land can improve grazing potential and stocking capacity, reference to the ESS framework suggests that these benefits may come at the expense of increased erosion and carbon loss in organic-rich upland soils. Water quality also typically declines due to increased colour and higher sediment-associated nutrient fluxes (Table 4).

Drain blocking strategies are generally considered to have positive effects on ESS, inclusive of flood peak reduction (JBA 2007; Ballard *et al.* 2010). Whilst Ballard *et al.* (2010) assumed no vegetation change after drain blocking in their model, the present analysis explicitly considered this effect. As the ecosystem integrity of soil and vegetation recovered, its physical cohesion increased and erosion rates declined (Holden *et al.* 2007). The effects in relation to carbon storage and water quality were however more mixed (Table 4). Whilst some studies showed a significant reduction in pore water dissolved organic carbon (DOC) and the level of discolouration (Armstrong *et al.* 2010), others have suggested the method is inefficient (Glatzel *et al.* 2003; Wallage *et al.* 2006). The norm linking drain-blocking to decreased peak runoff rates has exceptions, for example, vegetation-filled drains in peat-rich soils if this blocking results in faster overland flow rates over less vegetated surfaces (Ballard *et al.* 2012). Overall, evidence for the efficacy of upland drain blocking remains equivocal, varying with local conditions, drain spacing, and the availability of unsaturated water storage capacity (Robinson 1990). The time lag may explain some of these contradictory findings however they are not explicitly described in the original studies thus these differences could not be fully explained.

The restoration of wetlands and floodplains was assessed for five studies. In all cases the focus was on the operational phase and thus discounted the initial restorative-engineering phase. The Cherwell and Sinderland Brook studies both aimed to re-connect the channels to their floodplains, resulting in minimal land use change, but important gains in connectivity, water storage and runoff response. The Quaggy River project proposed floodplain restoration through culvert removal, whilst the Steinsel study aimed to rehabilitate the river basin by planting, changing riparian and in-stream vegetation and by re-meandering the channelised reaches. Negative impacts in relation to crop and livestock production were minor, whereas significant positive benefits were registered for biodiversity, fisheries and wider amenity value. Reinstating the overbank flow storage capacity of the floodplain will yield a positive effect for 'Water supply' and 'Flood regulation' due to enhanced buffering of the response of low and high flows to precipitation variability.

The last category under consideration examined combined NFM measures and their cumulative effects. As this involves a wider range of strategies, including the

Table 4 | Changes in stream chemistry following the drainage and drain blocking

Action taken	Water quality parameter	Direction of change	Author	Location	Soil type
Drainage	DOC	Increase	Freeman *et al.* (1993)	Laboratory	Peat rich soils
		Increase	Glatzel *et al.* (2003)	Quebec, Canada	Bog
		Increase	Wallage *et al.* (2006)	River Wharfe, UK	Blanket peat
		Decrease	Moore (1987)	Sept Iller, Canada	Bog
		Decrease	Chapman *et al.* (1999)	Rivers Wye and Severn, UK	Mixed upland of peat, stagnopodzols and stagnogleys
		Decrease	Chapman *et al.* (2005)	Upper Teesdale, UK	Deep peat
	Organic carbon	Increase	Lundin & Bergquist (1990)	Torvbraten, Sweden	Peatland
		Increase	Wallage *et al.* (2006)	River Wharfe, UK	Blanket peat
		Decrease	Nilsson & Lundin (1996)	SW Sweeden	Dissected peatland area
Blocking drain	DOC and Water discoloration	Increase	Glatzel *et al.* (2003)	Riviére du Loup, Canada	Peatland
		Increase	Worrall *et al.* (2007)	Whitendale, UK	Blanket peat
		Decrease	Wallage *et al.* (2006)	River Wharfe, UK	Blanket peat
		Decrease	Armstrong *et al.* (2010)	Catchments across UK	Peat soils

interactions between them, the co-benefits were expected to be high. The Lilea study (Hansen 1996) sought to control discharge whilst re-establishing flow continuum thereby ensuring free passage to fish (e.g. introducing a two-stage channel section and planting riparian trees). Although these actions involved small land use changes, the enhanced environmental quality provided important 'Biodiversity' and 'Recreational' benefits. The Glendey study (Johnson 2007) investigated the realignment of an artificial water course into a meandering channel and the restoration of the wetland (drain blocking and the planting of tree barriers across the wetland). The scale of the interventions at this site (c. 2 ha) are small in relation to the whole catchment (2 km^2), but yield disproportionally positive benefits because of their functional significance (e.g. water quality and biodiversity gains within small but important wetland patches). The only adverse effects were expected to be on 'Crops' and 'Livestock' due to land use change. In the Tillicoultry system (Environment Agency 2010) multiple measures were introduced including meander restoration to improve habitat quality, reducing the need for channel bank maintenance. This had also increased cultural value through aesthetic improvements and angling potential. The threshold of significance when multiple small localised interventions express themselves cumulatively at the catchment scale, particularly in consideration of complex response, is a key issue in hydromorphological research (Fullerton *et al.* 2010). Cumulative benefits or multiple actions are likely to outweigh disbenefits and hence coordinated action-packages are recommended rather than individual or localised actions to realise the full potential of integrated catchment management.

DISCUSSION

In a stationary climate, NFM measures are generally ascribed more uncertainty as compared with traditional engineering approaches to flood control. Under changing climate conditions such distinctions become blurred. Traditional measures typically focus on water level control in relation to the protection of specific assets but less attention has been given to flow generation and downstream routing dynamics. The few reliable instrumented catchment studies available span a range of hydroclimatic, landscape and local geomorphological controls, which makes up-scaling from the specific to the general highly challenging. Consequently extrapolating to new situations is a major source of uncertainty in applying NFM.

In addition the impact of an increased percentage of tree cover is not limited just to the afforested zone. Particularly for riparian woodland the interactions between terrestrial and aquatic ecosystems will lead to alterations of nutrient inputs, changes in micro-climate and contribution of organic matter to the stream and floodplain, and retention of inputs (Gregory *et al.* 1991). The change may therefore provide benefits such as 'Climate regulation' and 'Biodiversity' outside the afforested area.

To date the ESS assessment has not explicitly considered the significance of a non-stationary climate. However, it is acknowledged that climate changes, expressed in terms of systemic trends (e.g. warmer/wetter winters, hotter/drier summers, increased variability and changing magnitude/frequency of events) will also play out in relation to runoff and water quality effects (reflecting altered biogeochemical processes) and land management choices driven by dynamic policy influences.

Moving forward the selection of NFM strategies should consider both local catchment and wider exposure to climate changes, situating NFM as a central component of EbA (Colls *et al.* 2009; Perez *et al.* 2010; Jones *et al.* 2012). For example afforestation measures are not recommended in areas where drier summers are projected to occur, as trees directly impact on the water yield and may exacerbate existing drought problems (cf. Ray 2008). Ensuring the climate-readiness of NFM options requires context specific information taking into account climate change predictions and further acknowledging how different choices will play out under alternative socio-economic scenarios (cf. Brown *et al.* 2008; Dunn *et al.* 2012).

The performance of afforestation measures in reducing the flood peak depends on several factors, notably the previous land use. Runoff reductions are likely to be larger and more sustained for afforestation from grassland compared with afforested shrubland (Farley *et al.* 2005). Other studies report a higher infiltration rate (up to 60 times more) for young native woodland shelter-belts compared to grazed pasture (Bird *et al.* 2003; Eldridge & Freudenberger 2005). The performance is also dependent on the tree species selection (Farley *et al.* 2005). Species composition and planting style also influence biodiversity gains with the greatest benefits associated with diverse land use schemes that provide mixed habitats (depending on patch sizes, composition and connectivity). Scale is another fundamental challenge to the assessment process and the examples here span four orders of magnitude within the same NFM category. Theoretically a larger catchment area has the potential to achieve greater benefits in relation to nationally significant issues such as biodiversity and food production (Hein *et al.* 2006).

A key point to be emphasised is the evolutionary nature of NFM measures and the lag times in relation to consequent effects on runoff response, which should therefore be considered in NFM planning. This relationship is dynamic and susceptible to change over time. Similarly, the relationship between the NFM measure and the co-benefits for ESS is dynamic, and there are often significant time lags to be considered particularly for the other regulating services in addition to flow regulation (e.g. C sequestration, water quality). For example as forest systems mature they have an increasingly strong effect on the environment around them, and their benefit for some of the ESS will increase with time, for example, carbon storage (Andréassian 2004). Farley *et al.* (2005) noted that streamflow response to afforestation is anticipated to be very rapid (within 5 years of planting) with maximum runoff reductions achieved between 15 and 20 years after planting. This was investigated across a wide range of climatic conditions mostly for pine and eucalyptus afforestation. A similar response was recorded by Scott & Lesch (1997) for South Africa's Mokobulaan catchment. Completely afforesting the catchment with eucalypts was noted to decrease significantly the stream flow after three years of planting, stopping it all together after nine years. The same afforestation with pine trees produced a significant decrease in the fourth year and dried up the stream completely after 12 years.

CHALLENGES OF AN ESS ASSESSMENT

Examining the relative merits of different NFM schemes from an ESS perspective presents many challenges. The impact on 'Cultural Services' was particularly difficult to assess as limited information was typically provided in this regard and the implications for cultural services are often strongly dependent on the current context (e.g. past and present land use patterns). In some cases (e.g. Thames, Trent, Severn, Parrett) finding alternative sources of information was relatively easy, but for the smaller catchments this was rarely the case. Afforestation measures will impact the

'Tourism and recreation' service differently depending on the type of forest (i.e. commercial forest or natural woodland restoration). Natural woodland restoration will enhance the 'Sense of place' and bring benefits for 'Tourism and recreation' whilst commercial forest is expected (depending on local conditions) to have no impact or an adverse impact. Moreover the percentage of afforestation cover plays an important role in the assessment for 'Cultural Services'. Whilst the strategy proposed in the Pontbren study is considered to bring benefits for 'Tourism', the full afforestation cover that was postulated for the Trent, Severn, Thames study would likely have a negative impact because of the extent of landscape change. The limit between benefit and disbenefit as a result of different percentages of afforestation will depend on catchment specific characteristics, such as size, presence of cultural edifices and social aspects, for example, community attitude and priorities (cf. Rounsevell *et al.* 2010).

Subjectivity in the assessment is another important challenge in an ESS analysis. Different investigators may have different views assigning impacts or prioritising the benefits provided by NFM strategies and identifying the thresholds depending on their level of expertise, area of research and interests. Whilst important research is currently being undertaken in establishing a method for evaluating ESS (Liu *et al.* 2010; Fisher *et al.* 2011; Rutgers *et al.* 2012), a standardised practice is not yet available. For some services it is possible to model changes due to NFM in a similar quantitative framework as is the case for hydrological modelling for flood/flow levels (e.g. carbon sequestration, water quality, crop production), whereas other types of services (notably cultural) necessitate a different approach including the use of qualitative surveys to elicit responses from local stakeholders. The simple scoring method used in this review has its subjective limitations but represents a transparent and equitable approach to assess trade-offs between different types of service, without a bias towards those for which more quantitative data is available. Questions remain however about the most appropriate or comprehensive approaches to evaluate different options and trade-offs in terms of decision making locally and at the catchment scale because of scale and data availability issues (Postchin *et al.* 2008).

The complexity that lies within every category of ESS is different. Whilst the recognition of changes to provisioning service is easily assessed, the losses and indeed gains of regulating and supporting services have a higher level of complexity, with interactions and feedbacks occurring over a range of spatial and temporal scales (Hein *et al.* 2006; Brown *et al.* 2008; Colls *et al.* 2009). Moreover 'Cultural Services' are highly dependent on the local social and environmental context meaning the assessment can only draw tentative conclusions in the absence of detailed information and local surveys.

Comparing between various NFM strategies is very challenging as these measures are aimed to increase water storage, reduce the flood peak or increase the time to peak parameter. In the absence of common indicators that measure their performance, representing them on the same matrix is not possible. More research is needed to develop such indicators and develop a common matrix that will help stakeholders, such as insurance companies, make socially-significant decisions in a transparent and consistent manner (Feld *et al.* 2010).

CONCLUSIONS

A review of recent NFM studies, evaluated in terms of both flood risk reduction and wider ecosystem service benefits, highlighted the importance of geographical setting along with the nature, scale and location of different NFM options. Time lags before the maximum NFM benefits are realised are especially important in those catchments with flood-vulnerable communities for which there is already stakeholder demand for risk reduction, even at current levels of exposure (Harries & Penning-Rowsell 2011). This situation is of course amplified where climate predictions indicate flood risk is likely to increase either directly from altered magnitude-frequency relations of precipitation (hydroclimatic), or indirectly mediated through changes in land management practices.

The study highlights the challenges of mapping ESS and establishing a conceptual framework within which different NFM options can be evaluated because catchments are intrinsically dynamic and complex adaptive ecosystems (cf. Dawson *et al.* 2010). The case-studies reviewed evidenced overwhelmingly net positive benefits, subject to the caveat of unintended consequences (cf. Odoni & Lane 2010).

Whilst fully quantitative and economic valuation of different options remains beyond the scope of this study, the analysis highlights that NFM measure provides at the very least 'low regret' options in relation to climate change adaptation especially in the long term.

The study of ESS is increasingly promoted as a cornerstone of effective environmental management, but there remain many methodological challenges to operationalise the approach and fully integrate options analysis into decision-making at both the policy level and at the local level by catchment managers. A systems-based approach, incorporating alternative land management scenarios, offers a framework to explicitly include flow and flood regulation as one of multiple ESS and thus better situate NFM within the wider context of climate change adaptation in the UK.

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