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Testing the ecosystem service cascade framework for Atlantic salmon

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ABSTRACT

Aligning nature protection with human well-being for the UN Sustainable Development Goals implies that conservation monitoring should indicate the sustainability of ecosystem services (ES). Here we test the value of the ES cascade framework using national, multi-decadal data for an iconic freshwater fish, the Atlantic salmon *Salmo salar*. For the first time, we assemble all long-term monitoring data for England and Wales along the ES cascade for this species from resource to benefit: *juvenile density* to measure the biological resource, *returning adult numbers* to measure potential ES use, and *rod catches* and *angling effort* as measures of actual ES use. We aimed to understand how the ES cascade framework reconciled conservation with ES sustainability targets.

Only some linkages along the ES cascade could be evidenced: in catchments where juveniles declined, rod catches also generally decreased, but angling effort declined everywhere irrespective of the biological resource trends. We suggest that i) programmes focused on juvenile monitoring provide an early-warning system for ES provision as well as nature conservation, ii) the ES cascade framework can reconcile nature conservation and ES sustainability if monitoring efforts link biological resources fully to the ES, and ES monitoring explicitly relates biological resources to human use.

1. Introduction

Over the last decade, the ecosystem services (ES) concept has gained considerable attention as a framework that could reconcile the needs of biodiversity conservation with economic growth and societal benefits derived from natural resources (Fisher et al., 2009; Mekonnen and Hoekstra, 2011). However, despite increasing concerns over the persistent declines in the abundances of many species (WWF, 2018), investigations on the links between biodiversity and ecosystem services (B-ES links) have mostly focused on biodiversity indicators based on 'richness' (Cardinale et al., 2012). While population abundance is a recognised key indicator of biodiversity (Díaz et al., 2006), little attention has been given to the implications of population decline for ES provision (Gaston et al., 2018).

Positive links between biodiverse ecosystems and yields of food or fibre with high market value are documented (Luck et al., 2009), but quantitative evidence linking biodiversity to less tangible ES is still scarce (Durance et al., 2016). This is particularly true for the non-material benefits (e.g. from cultural ecosystem services (CES)) that people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, or aesthetic experiences (Small et al., 2017). And yet people appreciate, benefit and gain wellbeing from CES directly as an implicit link with the natural environment (Daniel et al., 2012; Schaich et al., 2010) which should provide an impetus for greater conservation efforts (Angulo-Valdés and Hatcher, 2010; Plieninger et al., 2013).

While much of the conceptual development about cultural ecosystem services has arisen in terrestrial ecosystems, concerns over the decline of Atlantic salmon (*Salmo salar*) (NASCO, 2016; World Conservation Monitoring Centre, 1996; WWF, 2001) provide a prime example where the ES paradigm might benefit both people and ecosystems – in this case aquatic. Atlantic salmon are an important food source (albeit largely derived from aquaculture (Parrish et al., 1998)), but wild fish also support a recreational angling industry with lucrative economic values (Butler et al., 2009; Kennedy and Crozier, 1997). They also have a range of less tangible benefits to society including raising awareness of environmental issues (Cowx and Portocarrero Aya, 2011) or aesthetic value (Holmlund and Hammer, 2004; O'Reilly and Mawle, 2006). The value of

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Atlantic salmon is particularly pertinent in rural areas where the influx of visitors supports jobs and contributes significantly to local economies (Aprahamian et al., 2010; Peirson et al., 2001). Atlantic salmon are also an exemplar to understand the challenges faced by policy makers and managers reconciling conservation and ES sustainability targets. The high profile of Atlantic salmon means that significant amounts of data have been collected on both their biology and exploitation. The financial and resource costs of acquiring such data has been, and still is, substantial (Hering et al., 2010; Kallis and Butler, 2001), and this gives further impetus to the need to demonstrate clear links between expenditure on monitoring and the social benefits returned.

The ES cascade framework, which depicts how biological resources drive the availability of ES and their benefits to society (Haines-Young and Potschin, 2010; Small et al., 2017), is a widely recognised approach to explore these linkages. It is particularly well suited to reconcile conservation goals with ES sustainability agendas for human wellbeing because it highlights that to be meaningful, assessments of ES and their benefits need to reflect not just the immediate and proximal quality (e.g. rod catches in the case of Atlantic salmon), but also the resilience of services in the short term (e.g. adult Atlantic salmon) and, as importantly, in the long term (e.g. juvenile Atlantic salmon).

One of the main challenges in implementing the framework is that data to inform the ES cascade steps is often constrained to the most commonly used measures from existing monitoring schemes, this is particularly true for cultural ecosystem services (CES). Since most conservation efforts for Atlantic Salmon have focused on monitoring juveniles as a cost-effective measure of the population, juvenile density is by far the most commonly available measure of the *biological resource* (Fig. 1). Adult numbers are a clear measure of ES *potential use*, since this is the life stage at which they can be exploited, but these data are only sporadically monitored at single points in the catchment (CEFAS et al., 2016; Cowx and Fraser, 2003). The social dimensions of ES are notoriously difficult and resource intensive to account for (Chan et al., 2012a; Small et al., 2017). As a result, ES assessments are often limited to the use of economically relevant proxy data (Eigenbrod et al., 2010; Naidoo et al., 2008); however, in the case of Atlantic salmon, adult rod catches, angling effort and license sales provide measures to estimate the *actual use* and *benefits* derived by this species (Fig. 1).

Here we analyse and compare four national scale and multi-decadal Atlantic salmon datasets from across the ES cascade framework: *juvenile density* as a measure of the of the *biological resource*, *returning adult numbers* as a measure of *potential use*, and *rod catches* and *angling effort* as measures of *actual use* (Fig. 1), with the overall aims to understand i) the extent to which current monitoring programmes inform ES sustainability, and ii) the practical value of the ES cascade framework to reconcile conservation and ES sustainability targets.

2. Materials and methods

2.1. Study area

To provide a framework for the analysis, we identified catchments (n = 141, split into eight regions; Fig. 2) that support populations of Atlantic salmon from the UK National Fish Population Database (NFPD). These catchments covered most of England and Wales and ranged in size from Black Beck (12.5 km^2) to the River Severn (10082.5 km^2, median = 150.0 km^2).

2.2. Juvenile density - a traditional 'biodiversity' measure for population monitoring

Juvenile density data were available for England and Wales between 1975 and 2018, with 21,660 individual surveys spanning more than four decades. We retained Atlantic salmon data that were collected using electric fishing with semi-quantitative or quantitative methods, with the number of juveniles recorded during the first run converted to a density by dividing by the area surveyed. Within each salmon catchment, sites which had 10 or more years of data, with at least 6 years where salmon were recorded, were identified. This resulted in a final dataset of 7526 surveys at 501 locations used for the analysis. To examine temporal trends in juvenile Atlantic salmon density, we fitted a generalized additive mixed model (GAMM) to each of the eight regions, regressing density upon sampling year. For each region (except those regions containing a single salmon catchment) a model that allowed the non-linear relationship between density and time to take a different shape across individual salmon catchments was used (Supporting Information Table S1). Each model included a random effect for sampling site. The structure of the models allowed trends in juvenile salmon to be assessed at the catchment level. These trends were constructed using a variable number of sites (range 1–38 sites per catchment), with sampling at each site not consistent across years.

2.3. Returning adult numbers – a measure of potential ES use

Locations with ≥10 years of data on the number of returning adult Atlantic salmon collected using electronic fish counters or traps (CEFAS et al., 2018; CEFAS, Environment Agency, Natural Resources Wales, 2015; CEFAS and Environment Agency, 2005; CEFAS, Environment Agency, 2002, 2000), were only available from 14 out of the 141 salmon catchments. Temporal coverage at these locations ranged between 12 and 30 years. We analysed trends in returning adult fish with two generalized additive models (GAMs), with one GAM for those rivers where mean annual number of returning adults was <2500 and the other for rivers where mean annual number of returning adults was >2500 (Supporting Information Table S1). The analysis was split to ensure it met the statistical assumptions of the model, with the threshold for splitting the models determined by examining plots of the Pearson

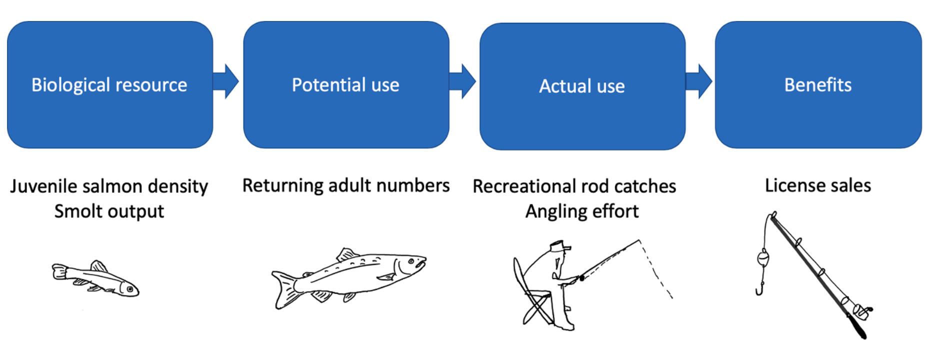

Fig. 1. Measures of Atlantic salmon populations and benefits from conservation monitoring schemes and ecosystem service assessments, and how they are linked across the ES cascade framework.

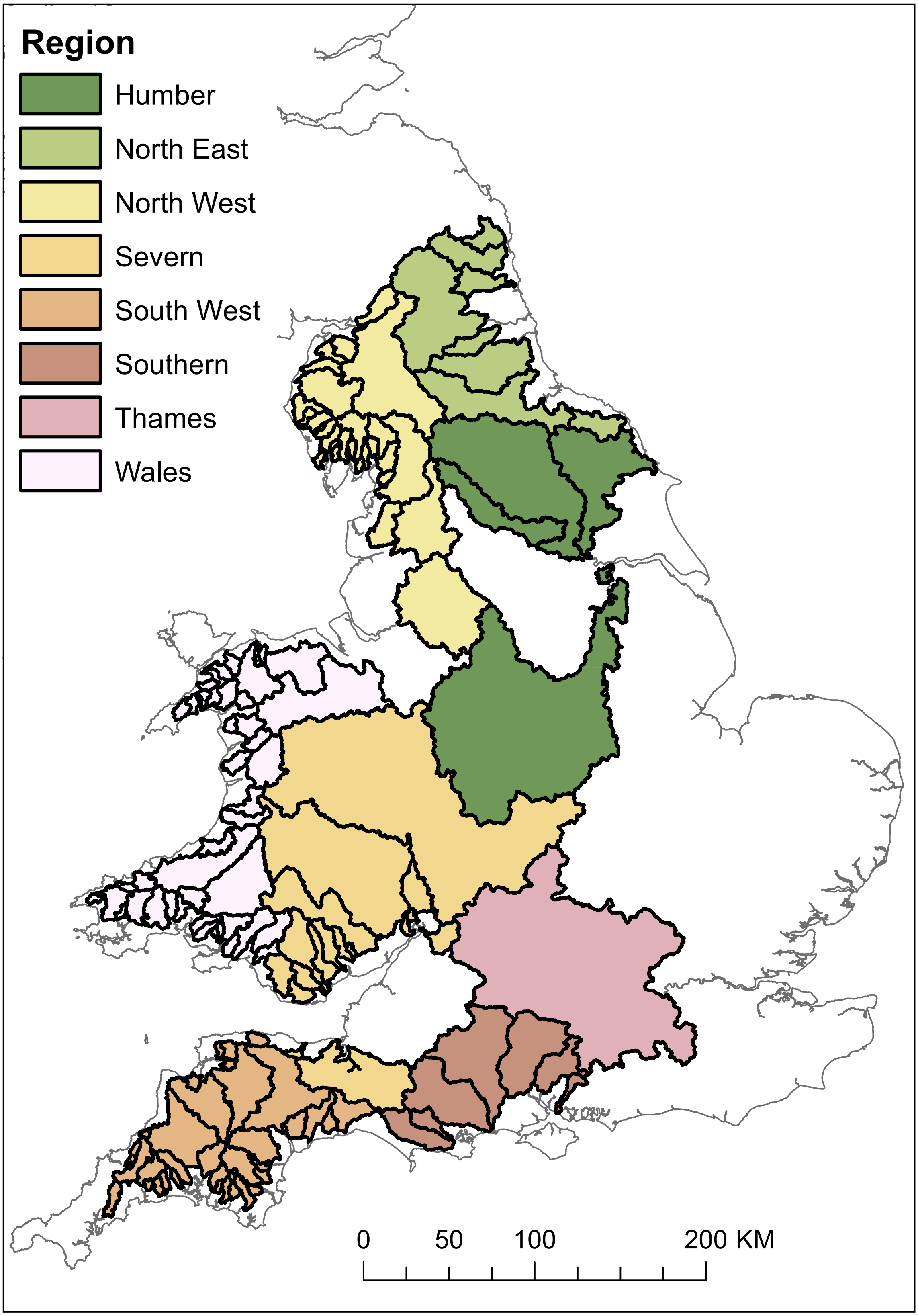

Fig. 2. Location of the 141 salmon catchments and the eight English and Welsh regions where Atlantic Salmon are monitored.

residuals against the fitted values and the covariates, year and catchment (Zuur, 2012; Zuur et al., 2010). The model allowed the shape of the relationship between total catch and year to vary between salmon catchments.

2.4. Rod catches and angling effort – measures of actual ES use

To examine trends in actual Atlantic salmon ES use, we assessed variation in recreational angling, both in terms of the number of fish caught (adult rod catches) and amount of time spent angling (angling effort). We collated data on the numbers of rod-caught Atlantic salmon

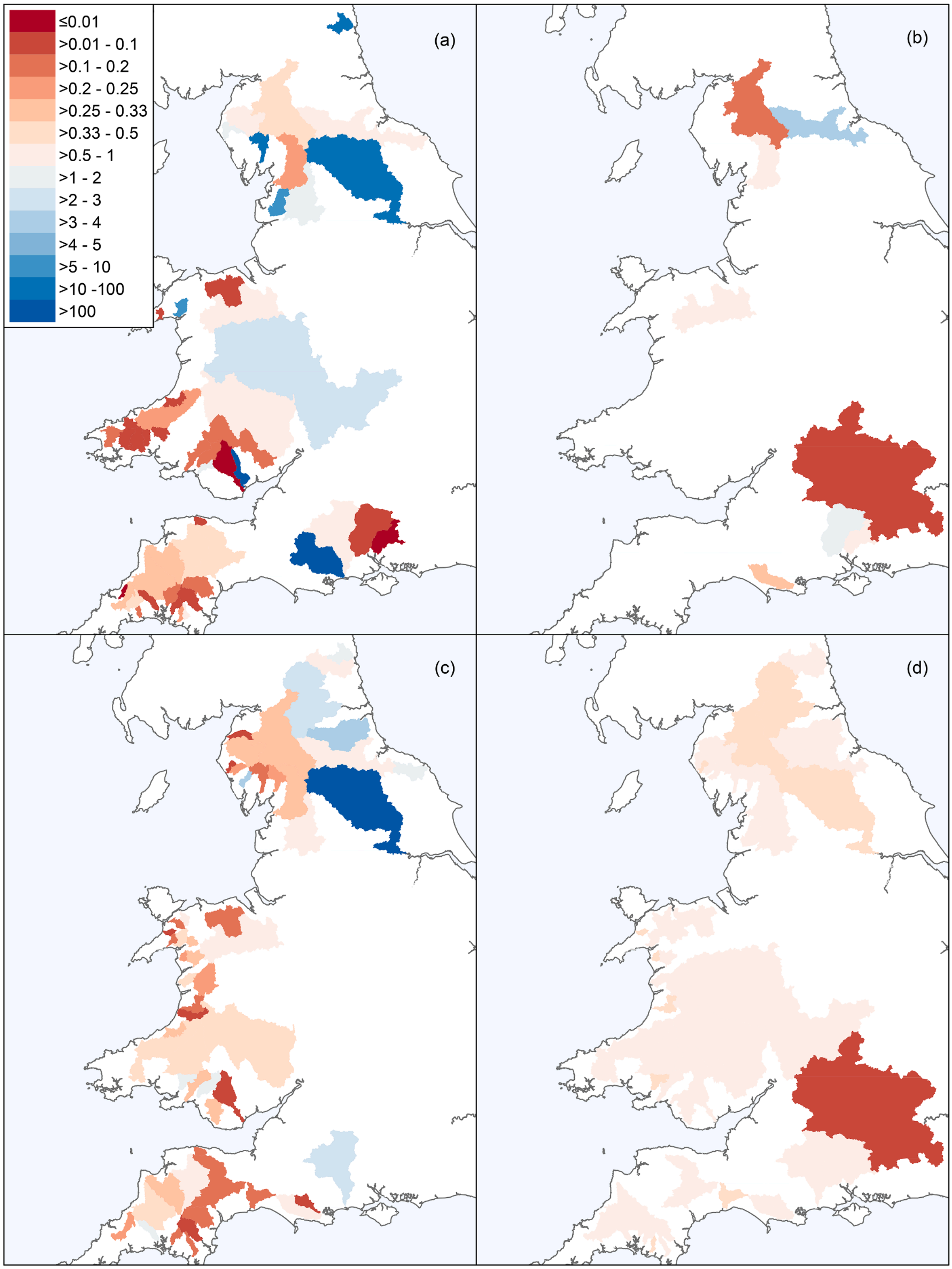

Fig. 3. Monitoring data changes over time in a) juvenile density, b) returning adult numbers, c) total rod catch and d) angling effort, for salmon catchments across England and Wales. Declines are in red and increases are in blue. Only catchments with a significant model relationship plotted. Change is calculated as the ratio of the model mean value for the last year of data, divided by the model mean value of the first year of the dataset. For catchments where mean juvenile density for the latest year was predicted as less than zero, the prediction for the previous year was used to calculate change.

recorded from angling licence returns for the ‘principal’ salmon rivers across England and Wales, and angling effort in terms of the reported number of days fished for salmon and sea trout (*Salmo trutta*) per license return (for a subset of the licence returns) from the Environment Agency’s Salmonid and Freshwater Fisheries Statistics for England and Wales (1994–2017) reports. Data on rod catches were available for 74 catchments and covered the period 1994–2017 for all but four catchments. Data on angling effort was available for 73 catchments, all covering the period 1994–2017. It should be noted that angling effort data recorded for the licence returns was for both salmon and sea trout and therefore only provides an indication of changes in angling behaviour.

We analysed trends in adult rod catches using generalized additive models (GAMs). A separate negative binomial GAM was fitted to the total rod catch for each region. As before the model allowed the non-linear relationship between total catch and time to take a different shape across individual salmon catchments. The final set of models assessed trend in angling effort, measured as catch per licence day. As previously, an individual Gaussian GAM was fitted to each region, with the model structure allowing a different non-linear trend in each catchment.

2.5. Linking biodiversity to benefit along the ES cascade

The trends in the four core datasets (juvenile density, returning adults numbers, rod catches and angling effort) were visually compared for each catchment. Extended methods that detail data selection procedures and analyses are available in the Supporting Information Appendix S1.

3. Results

Our results present for the first time an overview at a national scale, and over four decades, of trends in Atlantic salmon densities across the England and Wales, and provide evidence whether current monitoring of these populations through *juvenile density* can be linked across the ES cascade framework to *returning adult numbers* as a measure of *potential use*, and *rod catches* and *angling effort* as measures of *actual use*.

3.1. Juvenile Atlantic salmon densities present non-uniform trends through time

Of the potential 141 salmon catchments across the eight regions of England and Wales (Fig. 2), 83 had sufficiently long data runs (>10 years) to model juvenile density and there were significant trends in just over half, but trajectories varied (Supporting Information Table S2 and Figs. S1–S80). Data spatial and temporal coverage was most extensive in Wales and the south west, with model explanatory power good ($R^2 \geq$ 30%) only in the north east, Wales and the north west. Few catchments ($n = 11$) saw an increase in juvenile density, with the north west region having the largest number (Fig. 3a). In the Thames region, the raw data showed a population crash after 2005 with no salmon recorded in subsequent surveys, but no model could be fitted to capture these patterns. Trends in the south west were consistently negative, with only sporadic examples of increasing populations across the southern, Severn, and Welsh regions. Generally, trends in juvenile density were variable, and adjacent catchments had divergent trajectories (Fig. 3a).

3.2. Trends in returning adult numbers, and their relationship to juvenile density

The two models of returning adult numbers had strong model fit (mean annual number of returning adults <2500, $n = 225$, $R^2 = 0.79$ and mean annual number of returning adults >2500, $n = 89$, $R^2 = 0.75$). The fourteen catchments produced eight significant trends, with increases over time in returning adult numbers only observed in two (Fig. 3b): the River Tees and to a lesser extent the River Test, and an indication of potential recovery in the River Itchen (Supporting Information Table S2, Figs. S9B, S10B). However, these increases in returning adult numbers were not matched by the trends in juvenile density. There was some evidence of analogous declining trends of juveniles and returning adults. Numbers of returning adults also exhibited a crash in the River Thames (Supporting Information Fig. S8B), with the declines in the River Lune and River Eden (Supporting Information Figs. S70B, S80B) operating on similar time scales.

3.3. Rod catches tracked juvenile density only in catchments with negative trends

Actual ES use data in terms of total rod catch were available for over half the salmon catchments and produced 56 significant trends. Across the regions, model fit was generally high (Supporting Information Table S2). Increases in rod catches were most prevalent in the northeast catchments (Fig. 3c), although more recent reductions in catch were also observed (e.g., Supporting Information Figs. S2–4C). In the Thames region the raw data revealed a clear decline in adult rod catches that corresponded with the juvenile and adult data.

Despite some exceptions, the overall trend for southern, south west and Welsh regions was a decline in rod catches over the study period. In these regions only four catchments had mean modelled values higher in 2017 than in 1994 (Fig. 3c). In the northwest catchments the generally positive trends observed in the late 1990s and early 2000s have been negated by declines at the end of the timeseries (Supporting Information Fig. S68C & S70C). Increased mean modelled juvenile density was only translated to increased mean modelled rod catches for two catchments, one of which has seen rod catches decline for 2010 onwards (Supporting Information Fig. S1C). Conversely, declines in juveniles and returning adults were much more frequently translated to trends in rod catches (Fig. 3c).

3.4. Angling effort declined and was unrelated to trends in juvenile density or adult rod catches

Across England and Wales actual ES use expressed as angling effort declined in every catchment (Fig. 3d). Declines in the number of days fished per licence return were apparent even in catchments that saw large increases in rod catches over time (e.g. Supporting Information Fig. S3). Despite these overall declines, several catchments saw a stabilisation or increase in angling effort post 2005 (Supporting Information Figs. S25D, S34D, S51D).

4. Discussion

Overall, this analysis of over four decades of data available in England and Wales to monitor Atlantic salmon and their derived benefits has revealed: i) non-uniform trends across Atlantic salmon populations measured as juvenile density, or as returning adult numbers, ii) a lack of data to comprehensively link juveniles and returning adults (potential use) beyond select catchments, iii) that rod catches (a measure of actual use) tracked juvenile density (biological resource) only in catchments with negative trends, and that iv) angling effort (another measure of actual use) declined and was unrelated to trends in juvenile density or returning adult numbers.

4.1. Trends in salmon populations

Our results reveal variable trends in salmon populations across England and Wales, highlighting a clear need to understand the proximate drivers. Local studies corroborate our findings and reveal multiple potential mechanisms. For example, the increases in juvenile salmon density, returning adult numbers or rod catches in some northern catchments correspond with similar results for the Tyne, Wear, Tees and the Yorkshire Ouse rivers, which have been attributed to the regulation of industrial and urban pollution that had previously reduced salmon populations (CEFAS et al., 2016; Mawle and Milner, 2003).

In contrast, the discernible decline in juvenile salmon density observed in the River Thames is thought to be a result of low flows and poor water quality in the lower river acting as a migratory barrier (Griffiths et al., 2011). Declines in the chalk stream rivers of southern England (WWF, 2001), mainly manifested in our study at the juvenile density stage, have been attributed to several factors in both the freshwater and marine environments (Hilton et al., 2001). Our own studies in the Wye, point to the role of climatic changes (Clews et al., 2010) and agricultural pollution as potential drivers of change.

An intriguing result in these patterns is the apparent increase in returning adult numbers in the River Tees, and to a certain extent the River Test, that are not matched by similar trends in juvenile density. The exact mechanism behind this divergence is unknown but may highlight a potential bottleneck in the freshwater environment that affects juvenile survival. In addition, data coverage is also likely to be an issue: for example, monitoring data for returning adults was only available for the Tees until 2010 with subsequent declines in juvenile density (and rod catches) apparent after that point.

4.2. The extent to which current monitoring programmes inform ES sustainability

A central result of this large-scale, multidecadal investigation lies in the demonstration that declines of juvenile Atlantic salmon populations coincide with a significant decline in the utilisation of recreational fishing, a key source of social and economic benefit in the UK. However, a corresponding increase in angling effort in those catchments that witnessed increases in juvenile Atlantic salmon was not observed. Declines in juvenile Atlantic salmon populations also coincide with a significant decline in potential ES provision (returning adult numbers) in certain catchments, and thus also potential reductions in other less tangible ES provided by Atlantic salmon such as awareness of environmental issues (Cowx and Portocarrero Aya, 2011) or aesthetic value (Holmlund and Hammer, 2004; O'Reilly and Mawle, 2006).

Further research is required to determine the causal mechanisms of the declines identified at the different levels of the ES cascade. However, management interventions at the actual use level have been identified. This is critical as angling can result in the exploitation of a significant proportion of a river's Atlantic salmon stock (between 5% and 35% in UK rivers, as reviewed in Thorley et al. (2007)). As part of their 2008–2021 strategy to increase the abundance and distribution of Atlantic salmon and sea trout in England and Wales while maximising the economic and social benefits from their fisheries, the Environment Agency highlighted several actions. These include reducing exploitation pressure on at risk populations through voluntary or mandatory controls on angling, including a ban on the sale of rod-caught fish (Environment Agency, 2008). Overall these findings suggest that current monitoring schemes, largely guided by the Water Framework Directive, offer a key early-warning system for the provision of ES provision by Atlantic salmon. This, to our knowledge, is the first assessment showing that population decline in the freshwater domain has significant implications for ES provision, and corroborates findings from terrestrial systems (e.g. Gaston et al., 2018).

Linking measures of biological resources to ES provision remains a key challenge (Balvanera et al., 2014; Cardinale et al., 2012; Tolonen et al., 2014). For the Atlantic salmon, the difficulty lies not only in finding biological measures that can be related effectively through the ES cascade to the recreational services and benefits (e.g. Fig. 1), but also in finding measures that account for their complex life history spent over large geographical ranges (Chaput, 2012; Hendry et al., 2007). While there is extensive monitoring of juvenile populations, the relatively high capital costs of operating smolt and adult Atlantic salmon monitoring facilities, have significantly limited monitoring of these life stages in the UK (Cowx and Fraser, 2003; Youngson et al., 2007) and across the species' distribution generally (ICES, 2018). Consequently, despite the extensive datasets curated in England and Wales, information on Atlantic salmon across the ES cascade is limited to a few catchments. This means that, currently, efforts to link Atlantic salmon resources to ES provision can only realistically rely on measures of juvenile populations.

As for other species, assessments of the ES delivered by the Atlantic salmon are often limited to the use of economically relevant proxy data, such as rod catches or angling effort, despite increasing evidence that these fish provide a far broader range of social benefits. Anglers display individual behaviours and abilities (Youngson et al., 2002) so that rod catches and effort may not in fact reflect population trends (Hendry et al., 2007). Numbers of adults alone is unlikely to be the sole factor affecting angling effort, as participation is affected by a range of socio-economic elements (Aprahamian et al., 2010; Potter et al., 2003) and satisfaction influenced by a variety of factors outside actually catching a fish (Arlinghaus, 2006). On the River Lune for example, increased adult salmon numbers resulted in significant increases in the proportion of anglers catching salmon and increases in the number of salmon caught per angler; however, a significant decline in the number of anglers was still observed (Aprahamian et al., 2010). Generally, the National Angling Survey (Brown, 2019) suggests that these declines are mostly linked to lack of time, convenience and an aging demography. The complexity in linking ES with a biological resource is also confounded by the fact that anglers obtain a variety of other benefits from their angling such as relaxation or a "break from everyday life" (Lawrence and Spurgeon, 2007). This suggests there are a range of well-being benefits associated with angling, which provide value outside economic benefits.

4.3. Reconciling Atlantic salmon conservation and ES sustainability goals

To efficiently monitor changes in Atlantic salmon populations, while also better capturing the services or benefits they provide to people, we propose several strategies.

4.3.1. Monitoring across the whole life cycle from juveniles to adult returning fish:

While long-term data sites are central to detecting shifts in abundance, and considerable amounts of data have been collected, just over half of the catchments identified as supporting salmon populations had monitoring sites with more than 10 years of data. It should be noted that for a proportion of these 141 catchments salmon population are historically small and therefore recorded captures are sporadic. However, most catchments with suitable data had fewer than five sites with which to build a model. While juvenile monitoring is clearly valuable in appraising local effects on production, recruitment and inter-site variations, for example as a result of habitat quality, pollution and catchment land use, it is unlikely to be a good estimator of production at scales above the site level (Hendry et al., 2007). Greater spatial coverage in the monitoring of downstream migrating smolts and returning adults, based on existing and new techniques (e.g., eDNA, Levi et al., 2019) applied alongside traditional juvenile monitoring, would allow early detection of population bottlenecks (e.g., freshwater vs. marine stressors). At the moment, such a joined up approach is limited to a few 'index' rivers (CEFAS et al., 2016), which cover a small proportion of the species' global distribution (Prévost, 2015).

4.3.2. Broader capture of the benefits derived from Atlantic salmon populations:

Given the wider societal benefits of Atlantic salmon, particularly non-use values, their quantification would ideally need to go beyond simple, market-orientated valuation approaches (Carpenter et al., 2009; Chan et al., 2012a, 2012b; Daily et al., 2009; Plieninger et al., 2013). While there is increasing recognition of the role these populations may play in regulating and sustaining freshwater ecosystems and ecosystem function (Holmlund and Hammer, 1999), or their direct role in human wellbeing (Lawrence and Spurgeon, 2007), quantifying the non-material benefits that Atlantic salmon populations sustain is challenging and often costly as they tend to be specific to local settings. For example, while surveys using choice experiments concur that programs aimed at increasing numbers of returning salmon could generate substantial benefits (e.g., Lewis et al., 2019; Riepe et al., 2019), there is ample evidence that substitutions for declining populations, such as fish stocking and nature reserves, rarely replace losses of all services (e.g., Holmlund and Hammer, 1999). In this context, citizen science initiatives could be used - alongside more traditional measures on the amount of time fished and the number and size of salmon caught - to collect data on distance walked and levels of enjoyment thereby providing a more complete indication of the societal benefits associated with Atlantic salmon (Krasny et al., 2014).

5. Conclusions

The overall aim of this work was to understand the practical value of the ES cascade framework to reconcile conservation and ES sustainability targets. Despite bringing together datasets covering more than four decades from across England and Wales, our results show that only some linkages along the ES cascade could be evidenced. Our research demonstrates that current monitoring programmes focused on juvenile Atlantic salmon density can ensure a key early-warning system for ES provision, but that linking Atlantic salmon conservation to ES sustainability requires monitoring of each step of the ES cascade that links the biological resource to the service. Trying to quantify and link trends across the ES cascade highlighted how much lack of data at some steps of the cascade, namely on *returning adult numbers* as a measure of potential ES use, currently constitutes a key barrier to reconcile conservation and ES sustainability targets and to operationalising the ecosystem service concept.

As discussed by the authors of the ES cascade framework (Potschin-Young et al., 2018), implementing the framework enables a better understanding of the problem at hand, in this case aligning Atlantic salmon conservation with ecosystem service sustainability. We conclude that the ES cascade is a valuable and flexible tool for the implementation and mainstreaming of the ecosystem service concept. In the case of the Atlantic Salmon, our research highlights the challenge of measuring ES in ways that explicitly relate biological resources to human resource use. It also highlights that monitoring that captures multiple life stages and engages citizens would be a step forward in reconciling Atlantic salmon conservation and ES sustainability goals.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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