Cyfoeth Naturiol Cymru
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Modelling the response of the twaite shad (*Alosa fallax*) population in the Afon Tywi SAC to a modified temperature regime

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Mae gwangod yn rhywogaeth o bysgod mudol yn nheulu'r penwaig. Ar un adeg roeddent i'w gweld ledled y DU, ond mae'r rhywogaeth wedi dirywio'n fawr iawn erbyn hyn. Mae ymdrechion wedi'u gwneud i warchod y rhywogaeth hon gan gynnwys ei hamddiffyn o dan Gyfarwyddeb Cynefinoedd y Comisiwn Ewropeaidd, sy'n gofyn am fonitro rheolaidd, a chyflwyno lleoliadau a warchodir, yn benodol Ardaloedd Cadwraeth Arbennig. Mae afon Tywi yn Sir Gaerfyrddin yn un o'r tair afon a ddynodwyd yn Ardal Gadwraeth Arbennig ar gyfer y gwangod yng Nghymru. Mae cynefinoedd addas ar gyfer silio ar rannau helaeth ohoni. Hyd yma, mae'r broses silio wedi'i chyfyngu'n bennaf i rannau isaf yr afon rhwng Caerfyrddin a Llandeilo.

Mae cronfa ddŵr fawr ar Lyn Brianne sy'n cyflenwi dŵr i'r cyhoedd. Mae'r gronfa hon, sydd ym mlaenddyfroedd afon Tywi, yn rhyddhau dŵr oer i'r afon, gan newid y proffil tymheredd o'r hyn sy'n arferol. Mewn Adolygiad o Ganiatadau Cyfarwyddeb Cynefinoedd, nodwyd bod dylifiad dŵr oer o Lyn Brianne yn risg bosib i'r gwangod. Arweiniodd hyn at argymhelliad i gyflwyno system tynnu dŵr ar sawl lefel a fyddai'n dychwelyd tymheredd yr afon i'w gyflwr arferol ac yn lleihau unrhyw risg i'r gwangod.

Mewn asesiad rhagarweiniol gan Aprahamian (2013), daethpwyd i'r casgliad na fyddai system tynnu dŵr ar sawl lefel yn arwain at fudd amlwg i'r gwangod. Ond, dim ond unwaith y gwnaed yr asesiad hwn ac nid oedd yn ystyried yr ansicrwydd ynghylch proffiliau tymheredd yr afon. Mae'r adroddiad hwn yn rhoi sylw i'r cyfyngiadau hynny. Bydd yn gwerthuso beth fydd effaith dychwelyd proffil tymheredd yr afon i'w gyflwr arferol o dan wahanol senarios tymheredd a bydd yr ansicrwydd yn cael ei gynnwys fel bod y model yn mynd ati'n fwy cywir i adlewyrchu'r newidiadau blynyddol mewn tymheredd a gofnodir ar afon Tywi. Bydd hyn hefyd yn cymharu'r cyflwr hyn â'r cyflwr a ragwelir mewn senario tymheredd arferol.

Dulliau

Er mwyn asesu'r broses o gynyddu niferoedd gwangod, defnyddiwyd model ar sail unigol a ddatblygwyd yn wreiddiol gan Aprahamian *et al.* (2010). Mae'r model hwn yn defnyddio asesiadau stoc pysgod a thymheredd dŵr i amcangyfrif y cynnydd mewn niferoedd. Aseswyd proffiliau tymheredd afon yn cynrychioli cyflwr cyfoes cyfredol (wedi'i gofnodi) a chyflwr wedi'i normaleiddio (wedi'i rag-weld) er mwyn gweld effaith y newid arfaethedig yng nghyflwr arferol afon o'i gymharu â'r status quo a'r caniatâd presennol i ryddhau. Er mwyn ymestyn y canfyddiadau, ystyriwyd hefyd effaith newid yn yr hinsawdd ar y cyd â'r senarios tymheredd cyfredol ac arferol, a chyda hyn roedd modd rhag-weld y newidiadau yn y broses cynyddu niferoedd dros gyfnod o 100 mlynedd.

Addaswyd model Aprahamian et al. (2010) er mwyn efelychu'r broses cynyddu niferoedd mewn 4 rhan wahanol o afon Tywi o derfyn y llanw hyd at Ddolau Hirion; y 4 rhan sy'n cynrychioli ffin ddaearyddol yr Ardal Cadwraeth Arbennig. Mae'r model yn rhag-weld y cynnydd mewn niferoedd o'r data asesu stoc gan ddefnyddio cyfuniad o ôl-weld (edrych yn ôl) a rhag-weld (edrych ymlaen) a thymheredd y dŵr ar gyfartaledd rhwng mis Mehefin a mis Awst. Cyfyngwyd ar y model gan ddefnyddio data cyfartaledd tymheredd blynyddol yr afon wedi'i gofnodi gan Cyfoeth Naturiol Cymru ar gyfer cyflwr cyfoes a chyfredol a data tymheredd wedi'i fodelu a oedd yn rhag-weld tymheredd afon naturiol (ar ôl Carpentes *in prep*).

Canlyniadau

- Datgelodd modelau o ddata'r tymheredd gryn dipyn o amrywiadau o un flwyddyn i'r llall ac mae hyn yn effeithio ar y tebygolrwydd o lwyddiant wrth gynyddu niferoedd mewn blwyddyn benodol.
- Nid yw tymheredd cyfartalog dŵr yn codi'n uwch na'r trothwy tymheredd critigol, 17.8°C, bob amser. Gall y broses cynyddu niferoedd fethu ambell flwyddyn neu bob blwyddyn ar rannau o'r afon, ac mae'r cynnydd mewn niferoedd yn arbennig o afreolaidd yn rhannau uchaf yr afon yn Nolau Hirion.
- Rhagwelir nad yw newid yn y tymheredd i gyflwr naturiol yn effeithio fawr, os o gwbl, ar gyfradd cynyddu niferoedd gwangod ar afon Tywi.
- Mae dwy ran o'r afon yn cyfrannu'n sylweddol at gynyddu niferoedd gwangod, sef terfyn y llanw a Whitemill; mae'r un olaf yn cyfrannu dros 88% a 71% o gyfanswm y cynnydd mewn niferoedd mewn cyflwr tymheredd cyfredol a chyflwr tymheredd naturiol, yn y drefn honno. Nid yw rhannau eraill o'r afon yn Llandeilo a Dolau Hirion yn cyfrannu fawr ddim, os o gwbl, at gynyddu niferoedd gwangod.
- Yn sgil effeithiau newid yn yr hinsawdd, gwelwyd newidiadau yng nghyd-destun cyfraniad cymharol rhan o afon at gyfanswm y cynnydd mewn niferoedd, ond ni newidiodd hyn ar drefn y cyfraniad mewn rhestr. Yn yr hinsawdd fwyaf eithafol (+3°C fesul canrif), rhagwelir y bydd rhwng 8% a 16% yn fwy o gynnydd mewn niferoedd ar derfyn y llanw mewn cyflwr tymheredd cyfredol a chyflwr tymheredd naturiol, ond yn Whitemill, bydd rhwng 9% a 19% yn llai o gynnydd mewn niferoedd, yn y drefn honno. Ond, nid oes wahaniaeth pa broffil tymheredd a ddefnyddiwyd, pa un ai'r un cyfredol neu'r un naturiol, yn Whitemill y gwelwyd y cyfraniad mwyaf gydag o leiaf 62% o gyfanswm y cynnydd mewn niferoedd.

Casgliadau

Mae'r model yn dangos, mewn cyflwr cyfoes, ni fydd cael cyflwr tymheredd (arferol) diwygiedig yn **arwain at welliant amlwg ym mhoblogaeth gwangod ar afon Tywi.** Bydd rhannau isaf yr afon yn parhau i gyfrannu'n sylweddol at gynyddu niferoedd gwangod beth bynnag fydd y tymheredd. Nid yw rhannau eraill o'r afon yn Llandeilo a Dolau Hirion yn cyfrannu fawr ddim, os o gwbl, at gynyddu niferoedd gwangod.

Disgwylir i newid yn yr hinsawdd fod o fudd i’r gwangod yn y tymor hir, gan wella’r cynnydd mewn niferoedd yn rhannau isaf yr afon. Mae’n bosib hefyd y bydd hyn yn dwyn budd i rannau i fyny'r afon megis Llandeilo a Dolau Hirion, ond byddai angen cynhesu cryn dipyn ar y dŵr ac mae’n annhebygol y gwelir y manteision am sawl degawd. Mae rhannau isaf yr afon, yn enwedig Whitemill, yn cyfrannu’n sylweddol at gynyddu niferoedd gwangod, a dylid rhoi’r sylw pennaf i’r rhannau hyn o’r afon wrth geisio gwarchod gwangod ar afon Tywi.

Executive Summary

Background

Shad are a migratory fish species in the herring family, whose distribution thought the UK was once widespread, but has since greatly declined. Efforts to conserve this species include protection under the European Commission Habitats Directive, which requires regular monitoring and the introduction of protected locations, specifically Special Areas of Conservation (SAC). The Afon Tywi in Carmarthenshire is one of three rivers designated as an SAC for shad in Wales and has extensive areas of suitable habitat for spawning. To date, spawning has been largely restricted to the lower river reaches between Carmarthen and Llandeilo.

A large public water supply reservoir at Llyn Brianne in the headwaters of the River Tywi releases cold water in the Tywi changing its temperature profile from the norm. The influx of cold water from Llyn Brianne was identified as a possible risk to shad by a Habitats Directive Review of Consent (RoC), leading to a recommendation to introduce a multi-level draw-off that would return the river to its normal temperature state and mitigate any risk to shad.

A preliminary assessment by Aprahamian (2013) concluded that a multi-level draw-off would "*not result in a discernable benefit to shad*". However, this assessment was limited to a single model run and did not consider the uncertainty surrounding the temperature profiles of the river. This report addresses these limitations, evaluating the effect of returning the river temperature profile to normal conditions under a range of temperature scenarios with uncertainty incorporated such that the model more accurately reflects the annual changes in temperature that are recorded in the River Tywi and compares those conditions to those predicted under a normal temperature scenario.

Methods

Shad recruitment was assessed using an individual-based model originally developed by Aprahamian *et al.* (2010), which uses water temperature and fish stock assessments to estimate recruitment. River temperature profiles representing current (recorded) contemporary and normalised (predicted) conditions were assessed to compare the effect of the proposed change to a normal river state versus the status quo and current discharge consent. In order to increase the longevity of the findings, climate change impacts were also considered in conjunction with the current and normal temperature scenarios allowing changes in recruitment to be forecast over a 100 year period.

The Aprahamian et al. (2010) model was adapted to simulate recruitment in 4 different sections of the River Tywi from the tidal limit to Dolau Hirion; the 4 sections representing the geographical boundary of the SAC. The model predicts recruitment from stock assessment data using a combination of hindcasting (backward-looking) and forecasting (forward-looking) and average water temperature between the months of June and August. The model was parameterised using annual average river temperature data recorded by Natural Resources Wales for current contemporary conditions and modelled temperature data predicting natural river temperatures (after Carpenter *in prep*).

Results

- Models of the temperature data revealed significant interannual variability affecting the likelihood of recruitment success in a given year.
- Average water temperatures do not always exceed the critical temperature threshold of 17.8°C such that recruitment can fail in some or all years in river sections, with recruitment particularly irregular in the upper reaches of the river at Dolau Hirion.
- A change in the temperature regime to a natural state is predicted to have little or no effect on the recruitment rate of shad in the River Tywi.
- Two river sections make significant contributions to shad recruitment, namely the tidal limit and Whitemill; the latter contributing in excess of 88 and 71% of the total recruits under current and natural temperature regimes respectively. The other river sections at Llandeilo and Dolau Hirion make little or no contribution to shad recruitment.
- Climate change impacts led to changes in the relative contribution of a river section to total recruitment, but did not change the rank order of contribution. Under the most extreme climate scenario (+3°C per century), recruitment at the tidal limit is predicted to increased by between 8% and 16% under the natural and current temperature conditions, whereas at Whitemill, recruitment decreased by between 9% and 19% respectively. However, irrespective of whether the current or natural temperature profile was used, Whitemill remained the dominant contributor accounting for at least 62% of total recruits.

Conclusions

The model indicates that under contemporary conditions, a revised (normal) temperature regime will **not result in a discernable improvement in the twaite shad population in the River Tywi** and the lower reaches of the river will continue to make a significant contribution to shad recruitment irrespective of the temperature conditions. The upper reaches of the river, upstream from Llandeilo, make little or no contribution to shad recruitment.

Climate change is expected to be beneficial to shad in the long term, enhancing recruitment in the lower river sections. Upstream river sections such as Llandeilo and Dolau Hirion may also benefit, but significant warming would be required and benefits are unlikely to be seen for several decades. The relative contribution of the lower reaches, in particular, Whitemill to shad recruitment is significant and these sections of river should receive the greatest attention in efforts to conserve shad in the River Tywi.

1. Introduction

Shads (*Alosa* spp.) are migratory fish in the herring family (Clupeidae). Once widespread, their distribution has greatly declined due primarily to barriers to migrations (Aprahamian et al. 2002, Maitland and Hatton-Ellis 2003) and are now a protected species under the European Commission Habitats Directive. In Britain, spawning populations are largely restricted to rivers that drain from the Welsh uplands, including the Severn, Wye, Usk and Tywi. Temperature is known to regulate population dynamics of shad (Aprahamian and Aprahamian 2001, Aprahamian et al. 2010) with fluctuations in water temperature greatly affecting recruitment success on an annual basis.

The Afon Tywi in Carmarthenshire is one of three rivers in Wales designated as a Special Area of Conservation (SAC) for shad. Extensive areas of gravel along the lower and middle Tywi between Carmarthen and Llandovery provide suitable habitat for spawning (McEwen and Milan 2006), although most recent evidence suggests shad spawning mainly occurs in the lower river between Carmarthen and Llandeilo (Aprahamian et al. 1998, Garrett 2012) (Fig. 1).

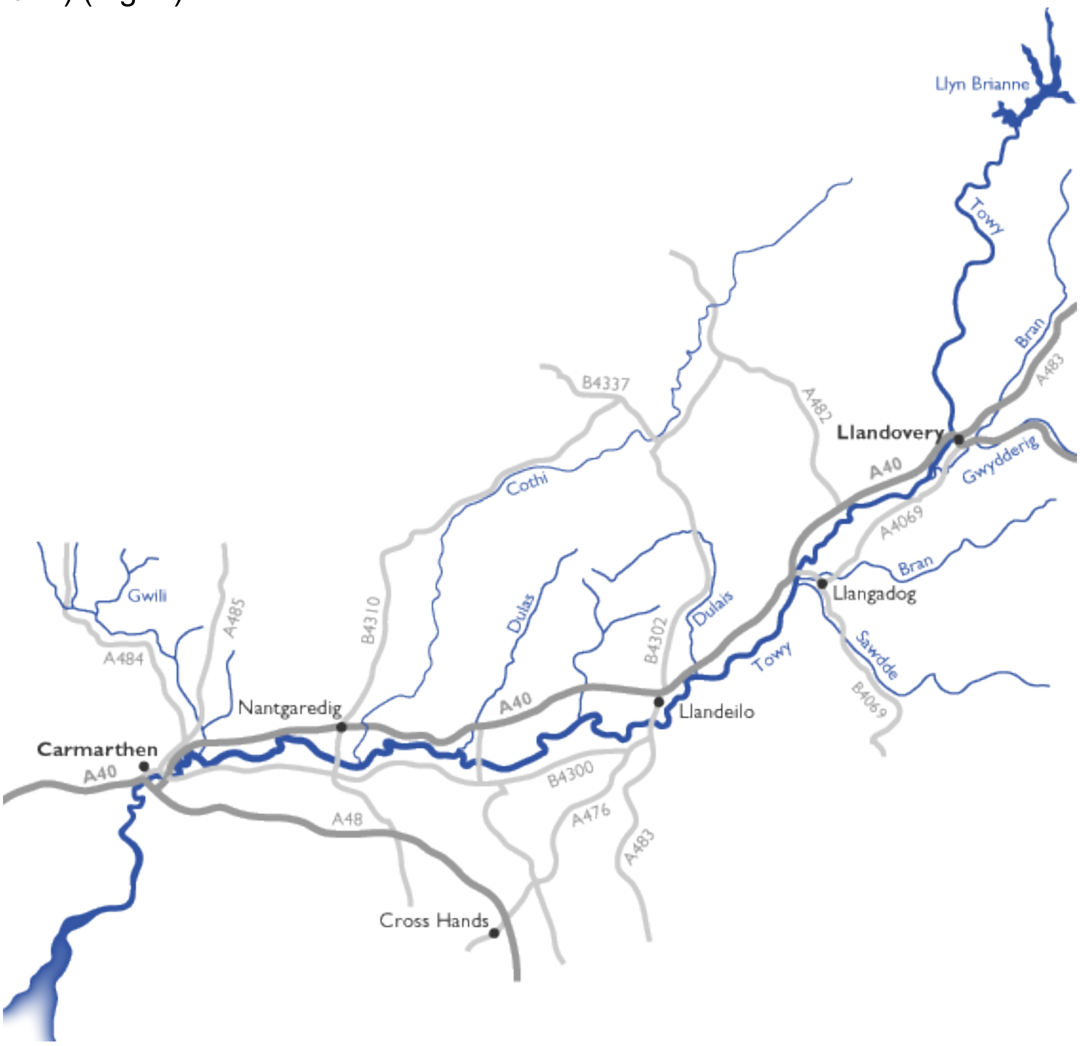

Figure 1 Schematic map of the Tywi (Towy) catchment; the main stem of the Tywi is shown in heavy blue. The Afon Tywi SAC runs from approximately Carmarthen to Llandovery. Redrawn with permission from www.fishpal.com. Not to scale.

In the headwaters of the Tywi at Llyn Brianne is a large public water supply. Constructed in the early 1970s, water is released from the reservoir into the Tywi in support of an abstraction point in the lower Tywi at Nantgaredig (Fig. 1) and to generate hydropower. The release of cold water from Llyn Brianne into the Tywi was identified as a potential source of risk to shad under a Habitats Directive Review of Consents (RoC) process (Smith 2005, West 2006, Tudor-Ward and West 2007), particularly as in summer months, Llyn Brianne stratifies resulting in a hypolimnion bottom layer much colder than that of the surface water. The water abstraction point from Llyn Brianne lies in the hypolimnion, such that any discharge from the reservoir into the river during summer months (generally at a temperature of ~4-5°C) could lead to notable cooling downstream. The RoC concluded a likely significant effect on shad and recommended that a multi-level draw-off be installed in order to normalise the release water temperature with that of the river.

To test the effect of reservoir discharges on river water temperature, hydrologists used a combination of empirical measurements and modelling approaches to determine the extent of temperature reductions (Carpenter in prep). This assessment concluded that downstream river water temperatures are affected as far as Whitemill, 9km from the tidal limit, and 69km from Llyn Brianne (Fig. 1); an effect especially pronounced in summer months (Carpenter in prep).

Further work has since been carried out in an attempt to quantify the impact of cold water releases on shad and provide an in-depth assessment of the benefits of a multi-level draw-off. Results suggested that cold-water releases could affect shad in the Tywi (Carpenter in prep), but that the effect would be confined to the upper reaches of the river and only then in warmer years. To further supplement this work, additional modelling was undertaken (Aprahamian, 2013) to assess the effects of changing the temperature regime of shad populations in the Tywi using a model developed by Aprahamian *et al*. (2010). This individual-based model (IBM) was developed specifically to evaluate the effect of temperature on shad population growth and development. Aprahamian (2013) evaluated two temperature regimes: (1) the ‘current’ (measured) temperature regime under the existing discharge consent, and (2) the predicted ‘natural’ temperature regime of the river – a scenario representing the river condition expected if the existing discharge (abstraction) licence was rescinded.

In contrast to the findings of Carpenter et al. (in prep), Aprahamian (2013) suggested that irrespective of a change in temperature regime, the upper reaches of the Tywi are unlikely to make a significant contribution to the shad population of the Tywi as a whole. Aprahamian concluded that the proposed multi-level draw-off would “*not result in a discernable benefit to the overall shad population*”. If so, the original conclusions of the RoC assessment could be re-evaluated in light of this evidence, supporting a conclusion of “no adverse effects” for the discharge licence. However, in order to comply with the requirements of the Habitats Regulations, there is a need for sufficient evidence to be confident beyond reasonable scientific doubt that the operation of the Llyn Brianne is not adversely impacting shad populations in the Tywi. The preliminary modelling work was insufficient in this regard because the underlying IBM model had only been run once and did not account for the uncertainty in river temperatures; a primary factor influencing shad recruitment (Aprahamian and Aprahamian, 2001).

To address this limitation and to further test the potential effect of an alteration in discharge regime on shad recruitment and stock success, I investigate the effect of a range of temperature scenarios on shad populations in the Tywi. This evaluation builds on the model developed by Aprahamian et al. (2010), but incorporates a stochastic component in to the model, allowing inter-annual changes in water temperature on shad recruitment and stock dynamics to be evaluated over the short- (annual) and long-term (decadal), and explicitly incorporates uncertainty (confidence) into the assessment. In addition, I also consider how changing climatic conditions might affect shad populations in the Tywi such that future implications of a change in temperature regime can be determined.

2. Methods

2.1. Tywi SAC Geographical Extent

Four river sections reflect the SAC boundary: (1) Tidal limit – Whitemill; (2) Whitemill – Llandeilo; (3) Llandeilo – Llangadog; and (4) Llangadog – Llandovery/Dolau Hirion (Fig. 1). In the model, the temperature conditions at four locations are considered, namely (i) the tidal limit; (ii) Whitemill; (iii) Llandeilo; and (iv) Llandovery/Dolau Hirion, and the likelihood and abundance of shad recruitment given current and predicted natural conditions determined (see Table 1 below for a summary of the contemporary temperature regimes and Table 2 for the climate scenario conditions considered).

2.2. Model description

The model is an individual-based model (IBM), which adopts a density-dependent stock-recruitment model to initially predict the number of eggs deposited by a reproductively mature female age-6 year ($E_{6(t+6)}$) based on a stock assessment 6 year previous, followed by a combination of hindcast and forecast modelling to infer stock-recruitment estimates for other years. The model uses data describing the fecundity of female (eggs per female) at age *t*, the number (proportion of the stock) that are virgin females, the number (proportion of the stock) that are reproductively mature females, the likelihood of repeat spawning once mature, and spawning mortality (see NRW Shad Model and Table A1 for model parameters).

The stock-recruitment relationship can be modelled using a Ricker relationship (Ricker 1954) as follows:

$$E_{6(t+6)} = aE_t e^{-bE_t} \qquad [1]$$

where E_t is the number of eggs deposited in year *t* (stock), $E_{6\ (t+6)}$ is the number of eggs deposited by fish age 6 year in year *t+6* (recruits), *a* is egg mortality, and *b* is a density-dependence coefficient. Population structure (proportions of virgin and mature females), fecundity estimates and spawning mortality can be used to calculate recruitment rates for shad of age 3-5 (hindcast) and 7-10 (forecast) based on the $E_{6(t+6)}$ model above.

2.3. River Water Temperature: Critical thresholds for recruitment and climate scenarios

Water temperature is strongly correlated with spawning success, explaining 77% of the variability in the Severn (Aprahamian and Aprahamian 2001). Although detailed spatial monitoring of water temperature has been carried out on the Tywi in recent years, there is only contemporary water temperature monitoring data (Carpenter in prep) and no data on adult shad stocks in the Tywi. Mean June to August water temperatures, even in the lower river, can be below the suggested minimum threshold for shad recruitment of 17.8°C (Aprahamian et al. 2010). However, the presence of a persistent shad population in the Tywi, especially downstream of Llandeilo, has led to suggestions that this critical temperature threshold may not apply to the Tywi population for two reasons.

First, the River Tywi has greater habitat variability than the lower Severn, including features such as warm-water backwaters that may offer refugia that are not present in the River Severn (Hatton-Ellis, pers. comm.) as well as a sheltered shallow estuary, which provides good juvenile habitat and warms rapidly potentially offsetting cooler conditions in the river (Hatton-Ellis, pers. comm.).

Second, some fish species have been shown to adapt both physiologically and genetically (over multiple generations) to temperature (Colosimo et al. 2003). While temperature adaptation has not been shown for shad, the Tywi shad population is genetically distinct from other Severn Estuary populations (Alexandrino & Faria 2004, Hardouin et al. 2013), suggesting that this population may be isolated from that of the Severn population and potentially tolerant to lower water temperatures.

2.4. River Temperature Data

Natural Resources Wales provided water temperature data from 16 monitoring stations on the River Tywi, comprising daily mean, maxima and minima water temperature values over several years (see Appendix B for a list of monitoring locations). This data was truncated to include data from the months, June – August, when spawning most commonly occurs (Aprahamian 1982). When annual temperature data are grouped (pooled), in all cases, annual mean temperature estimates are below the critical threshold of 17.8°C required for spawning (Table 1). However, interannual variability is such that average temperatures can exceed this critical temperature in some years;

fluctuations that may explain the intermittent and interannual recruitment success that has been reported (Aprahamian & Aprahamian, 2001).

The temperature regime under natural conditions was predicted using a modelling approach (Carpenter in prep). These values were used in the recruitment model to predict changes in recruitment under the natural temperature regime scenario (Table 1).

2.5. Simulating the likelihood of the critical temperature threshold (17.8°C) being exceeded

Using the variability in temperature identified for the river as a whole, maxima and minima temperature could be determined and the likelihood of recruitment in any year given the annual variability in mean river water temperature estimated. This analysis used a random number generator to generate a frequency distribution of temperature values, defined by the mean temperature (1st June – 31st August) and variability (standard deviation) derived from annual water temperature monitoring (NRW, *unpublished data*). Markov Chain Monte Carlo (MCMC) simulation was used to estimate the likelihood of water temperatures exceeding the 17.8°C required for recruitment (Aprahamian et al. 2010), drawn from a distribution of 2,000 temperature values (iterations) and the confidence estimated. This clearly shows the potential for water temperatures to exceed the 17.8°C required for recruitment (Table 1) in the River Tywi, although confidence intervals suggest that this is an occasional occurrence. The mean temperature data shown in Table 1 were used in the model to simulate interannual variation in water temperature for each river section.

	Current Temperature Regime§			Predicted Temperature Regime&		
River Section	**Mean**	**Lower CL**	**Upper CL**	**Mean**	**Lower CL**	**Upper CL**
1 Dolau Hirion	11.9	9.1	14.9	14.5	11.1	17.7
2 Llangadog	15.4	10.2	20.7	15.1	10.0	20.1
3 Llandeilo	15.5	11.8	19.1	15.4	11.9	18.8
4 Whitemill	16.9	12.5	21.1	16.7	11.6	21.7
5 Tidal limit	16.3	12.1	20.6	16.1	10.8	21.1

§Current temperature data are derived from daily temperature recordings

&Predicted temperatures were available for Dolau Hirion and Llandeilo only (after Carpenter, pers comm.). Predictions for Llangadog, Whitemill and the Tidal limit were derived from Aprahamian (NRW Report).

Table 1. River section mean temperature (°C) and 95% confidence limits under current and natural temperature scenarios. Daily temperature data for each river section was used to generate "seasonal" averages (1st June – 31st August; 2005-2013) and standard deviation (SD) calculated for those data. Mean temperatures and the lower and upper confidence limits (CL) were estimated using Monte Carlo simulations (2000 iterations) based on a random number drawn from a frequency distribution defined by the seasonal average and SD for the river section (e.g. 11.9 ± 1.4 for Dolau Hirion).

2.6. Climate Scenarios

The model predicts recruitment of shad over short (annual) and long-term (up to 100 year) timescales and compares the current and naturalised temperature regimes. Climate scenarios may also be modelled using temperature increases year-on-year. Data used in each scenario were those from the contemporary current and natural temperature regimes (Table 1) and the addition of a "climate" adjustment factor, based on UK future climate predictions (UKCP, DEFRA 2009). The climate scenarios evaluated were as follows:

Scenario	Current Temperature Regime	Natural Temperature Regime	Data Source
Contemporary	River section mean (current) + Standard Deviation (SD)	River section predicted mean (natural) + Standard Deviation (SD)	NRW pers. Comm.; Aprahamian 2013.
Climate Scenario 1	River section mean and SD + 1°C per century	River section mean + 1°C per century	UKCP09
Climate Scenario 2	River section mean + 2°C per century	River section mean + 2°C per century	UKCP09
Climate Scenario 3	River section mean + 3°C per century	River section mean + 3°C per century	UKCP09

Table 2. Climate scenarios used in the model to determine the benefits of changing the temperature regime of the River Tywi for shad.

2.7. Uncertainty simulations: Temperature effects on recruitment

To incorporate inter-annual variability in water temperature, the model was developed to include a stochastic (variable) temperature component. For each year in the model, a random water temperature is generated, drawn from a known distribution of water temperatures (e.g. 11.9 ± 1.4°C for Dolau Hirion under current contemporary conditions, Table 1). Therefore, in some cases such as Dolau Hirion, recruitment may not occur in a given year as a result of mean annual water temperatures being too cold (i.e. < 17.8°C; see upper confidence limit in Table 1).

Temperature scenarios used in the model were based on recorded river temperature data provided by Natural Resources Wales. Egg deposition was calculated after Aprahamian & Aprahamian (2001) wherein the number of eggs deposited by each cohort at age-6 was determined using the following relationship:

$$Log_e X_6 = 0.851 \cdot T - 13.341$$

[2]

where T is the mean water temperature (^oC) in year, t.

The four temperature scenarios modelled were: **current** and **naturalised** for scenarios 1 - 4. The current (baseline) scenario reflects present day conditions and incorporates mean June to August water temperature data. Climate scenarios were based on medium emission predictions (DEFRA 2010) and adopted a 1, 2 and 3^{o}C average temperature increase for scenario 1 respectively (Table 2). In the absence of future river temperature data, the standard deviation remains the same as the observed data years although greater inter-annual fluctuations in temperature are predicted under future climate scenarios (DEFRA 2010). For the purposes of the model, temperatures were independently modelled for time step (i.e. t = 1 yr) and the number of eggs deposited calculated as follows:

$$E_{6t} + e^{(Log_e X_{6t} + ((T_t - 17.8)\cdot 0.851))} F_6 \qquad [3]$$

where F_6 is the fecundity of an age-6 shad. The water temperature (T_t) for a given year is drawn from a random, normal distribution of temperature values based on the known variability for each scenario (Tables 1 and 2).

Hence, the total number of eggs deposited over the lifetime of a particular cohort (Y_t) in a given year (t) could be estimated as follows:

$$Y_t = \sum_{i=5}^{3} (e^{((Log_e X_{i+1} R_{i+1}) + S)}) F_i + a(e^{(\log_e E_t + ((T_t - 17.8)\cdot 0.851))}) e^{-bE_t}$$

$$+ \sum_{i=7}^{12} (e^{((Log_e X_{i-1}) - S)}) F_i \qquad [4]$$

where R_i is the proportion of repeat spawners of age class i, S is the instantaneous rate of spawning mortality, and E_t is the total egg deposition in year, t. Other components are defined above.

Markov Chain Monte Carlo (MCMC) simulation (PopTools; www.cse.csiro.au/poptools) was used to estimate the mean recruitment and surrounding variance and 95% confidence intervals for each year based on this distribution of temperatures (see Zuur et al. 2012). A total of 5,000 simulations were run for each year of the model and each temperature scenario.

3. Results

3.1. Likelihood of critical temperature threshold being exceeded

The likelihood that average water temperatures would exceed 17.8°C in a given year marginally decreased in the natural conditions in three of the four areas (Llandeilo to the tidal limit) (Table 3). In contrast, there was a marked increase in the likelihood of recruitment in the Dolau Hirion upper reach of the river, where under current conditions, recruitment may be precluded by colder water temperatures, but may improve under the natural temperature regime. However, in the event of such an increase, recruitment is still expected to be highly intermittent between any given year, with less than a 2% chance of recruitment success.

3.2. Temperature conditions required for shad recruitment

A deterministic model was used to illustrate the relationship between temperature, stock size and recruitment. In this model, no variability in water temperature on an inter-annual basis was used i.e. a static temperature value was applied in the model (Fig. 3). As shown, at temperatures < 17.8°C, there is no recruitment. At temperatures of 17.8°C and greater, recruitment is successful, with higher temperatures supporting increased recruitment success.

Temperature Scenario: Current

Threshold	1 Dolau Hirion	2 Llandeilo	3 Whitemill	4 Tidal limit
Under	2000	1796	1286	1489
Above	0	204	714	511
Probability of exceeding threshold (p.a.)	0.0%	10.2%	35.7%	25.6%
Number of Years between recruitment	2000	10	3	4
Number of iterations	2000			

Temperature Scenario: Natural

Threshold	1 Dolau Hirion	2 Llandeilo	3 Whitemill	4 Tidal limit
Under	1971	1889	1524	1691
Above	29	111	476	309
Probability of exceeding threshold (p.a.)	1.5%	5.6%	23.8%	15.5%
Number of Years between recruitment	69	18	4	6
Number of iterations	2000			

Table 3. The likelihood of water temperatures exceeding the long-term average of 17.8°C in a given year by river section under the current temperature regime (top) and the predicted temperature regime under natural conditions (bottom).

3.3. Effect of modified temperature regime on shad recruitment in the River Tywi

A change in the temperature regime from current (modified) to a natural state is predicted to have little if not no effect on the shad population of the River Tywi (Figs. 4 & 5). At the tidal limit and Whitemill sections of the river, no change in recruitment success is predicted (Fig. 4) and these sections are expected to continue to make a significant contribution to the shad population of the River Tywi. At Llandeilo, the model suggests recruitment occurs under current conditions (Fig. 5), but suggests considerable variability in recruitment on an inter-annual basis. The model indicated that a return to natural conditions may be of marginal detriment to shad (Table 3, Fig. 5), but anomalies in the temperature modelling results used to estimate natural temperature conditions introduce uncertainty, making it difficult to attribute any change in recruitment in this river section to a return to a natural temperature profile.

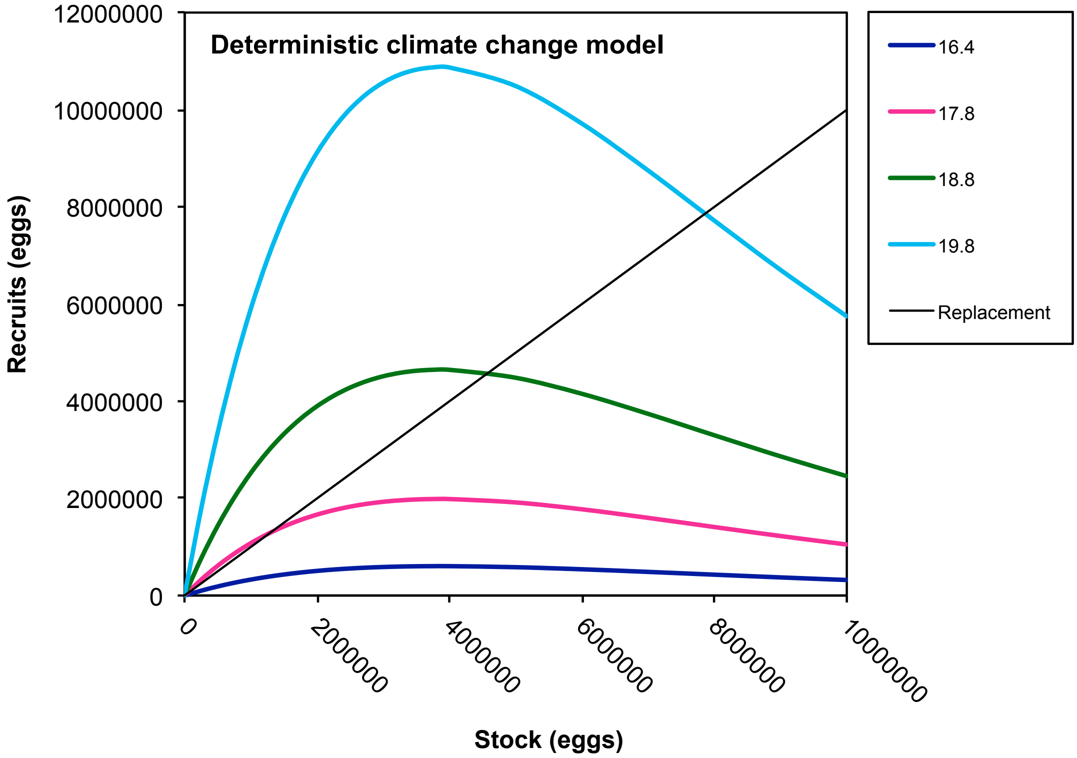

Figure 2. Deterministic model describing the relationship between stock size and recruitment (t+6) under 4 different temperature scenarios (16.4 – 19.4°C). Population persistence occurs when the model simulation line is above the replacement line.

From a long-term perspective, without an increase in temperature, this river section is unlikely to make a significant contribution to the population, irrespective of the temperature regime. Upstream from Llandeilo at Dolau Hirion, benefits of a change in temperature regime are indicated[1] (Fig. 5), although results suggest that these changes will be insufficient to support persistent recruitment and this section of river is unlikely to make any

[1] It is notable that the model begins with a standing stock (based on estimates from the River Severn) and the likelihood of population persistence in this areas declines rapidly under natural contemporary conditions. The recruitment shown is therefore an artefact of the modelling approach and of the underlying data used, and the predicted decay in recruitment rate to 0 is evidenced by the absence of shad in this river section (NRW pers comm.).

significant contribution to the shad population of the Tywi in the future (Fig. 5 and Table 3).

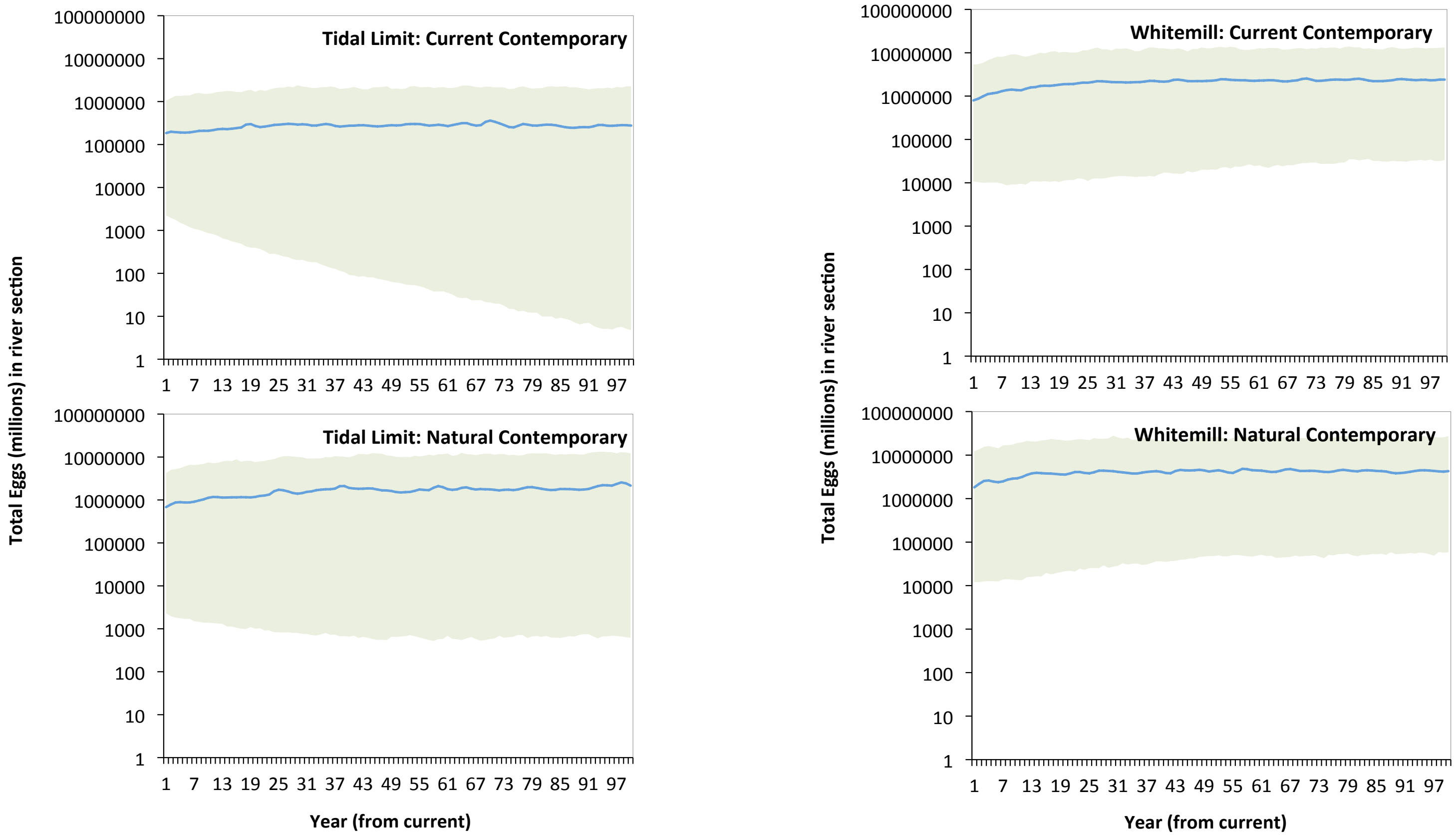

Figure 3. Predicted recruitment (log eggs) over time of shad under current (top) and natural (bottom) temperature regimes at the tidal limit and Whitemill. 95 % confidence intervals are shown by shading.

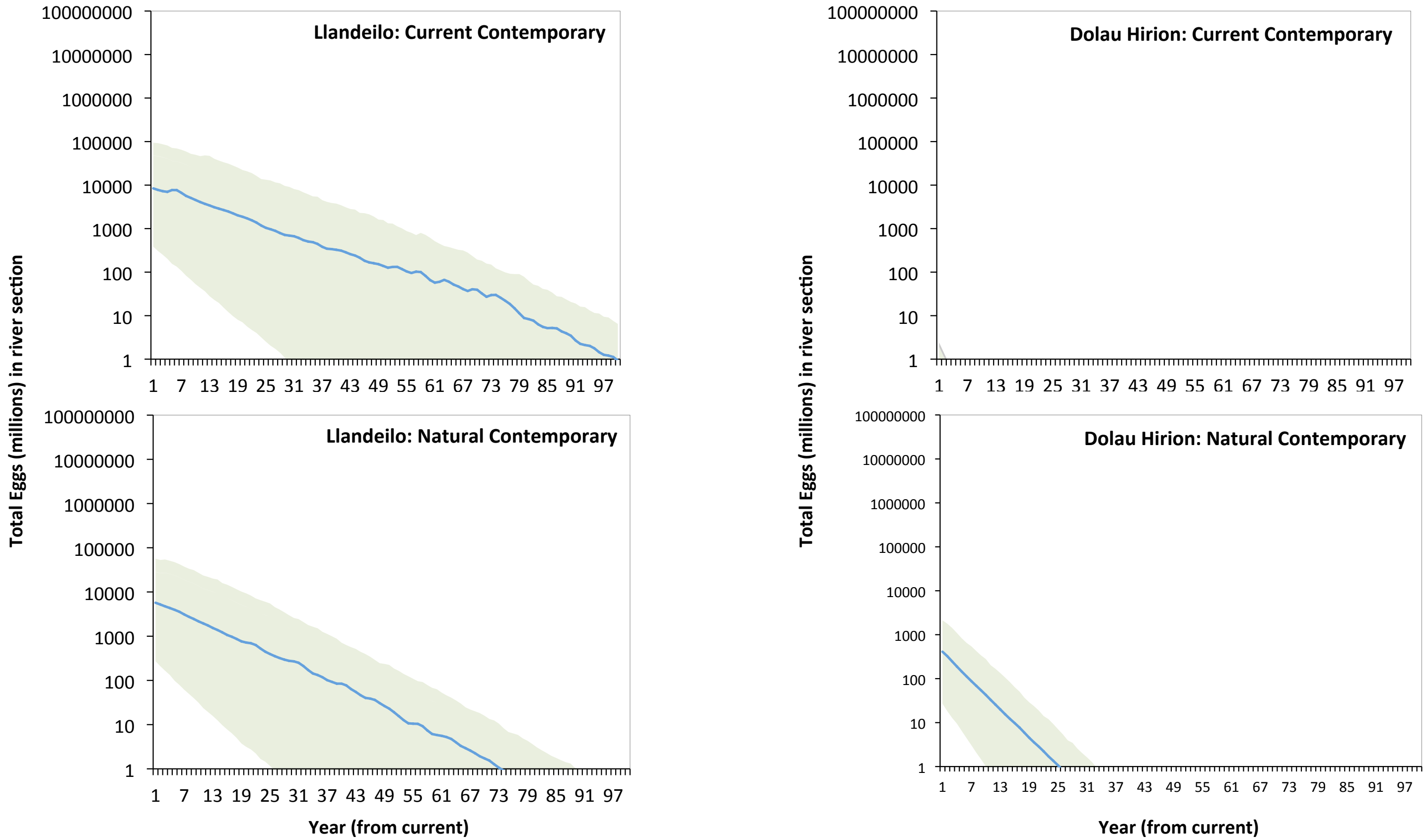

Figure 4. Predicted recruitment (log eggs) over time of shad under current (top) and natural (bottom) temperature regimes at the Llandeilo and Dolau Hirion. 95 % confidence intervals are shown by shading.

3.4. Climate Change Impacts

Under all climate change scenarios, marginal increases in recruitment are predicted at the tidal limit and Whitemill (Figs. 5, 6, 11 & 12). At these two locations, recruitment rates are already sustainable (Fig. 3) under the current thermal regime and the recruitment contribution from these sections is not predicted to change with a reversion to a natural condition. Any benefits that might be seen include a reduction in the interannual recruitment variability, in that recruitment success in any given year is predicted to increase under climate change scenarios (Figs. 5, 7 and 9).

Increasing water temperatures led to marked improvements in recruitment success in the Llandeilo river sections (Figs. 6, 8, 10 - 12) under all climate scenarios. All three scenarios led to sustainable recruitment in this river section, although only climate scenarios 2 and 3 led to recruitment in any given year (Figs. 8 and 10), whereas under contemporary and climate scenario 1, temperatures could still fall below the threshold level required for recruitment success (shown by the lower confidence interval band intersecting the x-axis). A similar response was seen under both current and natural thermal regimes. This indicates that temperatures in this river section are currently marginal for recruitment success and suggests that even a small increase in mean temperature (>0.1°C) could lead to greatly improved recruitment success; an increase predicted to occur within a decade (UKCP 09; DEFRA, 2009).

At Dolau Hirion, the river section furthest from the river mouth, climate scenarios 1 and 2 are predicted to have no impact on recruitment rate, but in the most extreme climate scenario (Scenario 3; 0.3°C temperature increase per decade), recruitment is predicted to increase in the future suggesting that climate change may result in a change in the conditions of the river, to the extent that recruitment may become viable in this section (Figs. 6, 8, and 10), if the river were returned to a “natural” condition. However, suitable conditions are not predicted for at least 48 year (Figs. 10, 12). No improvement is predicted under the current thermal regime, irrespective of the climate scenario used, and recruitment is not predicted to occur in this river section.

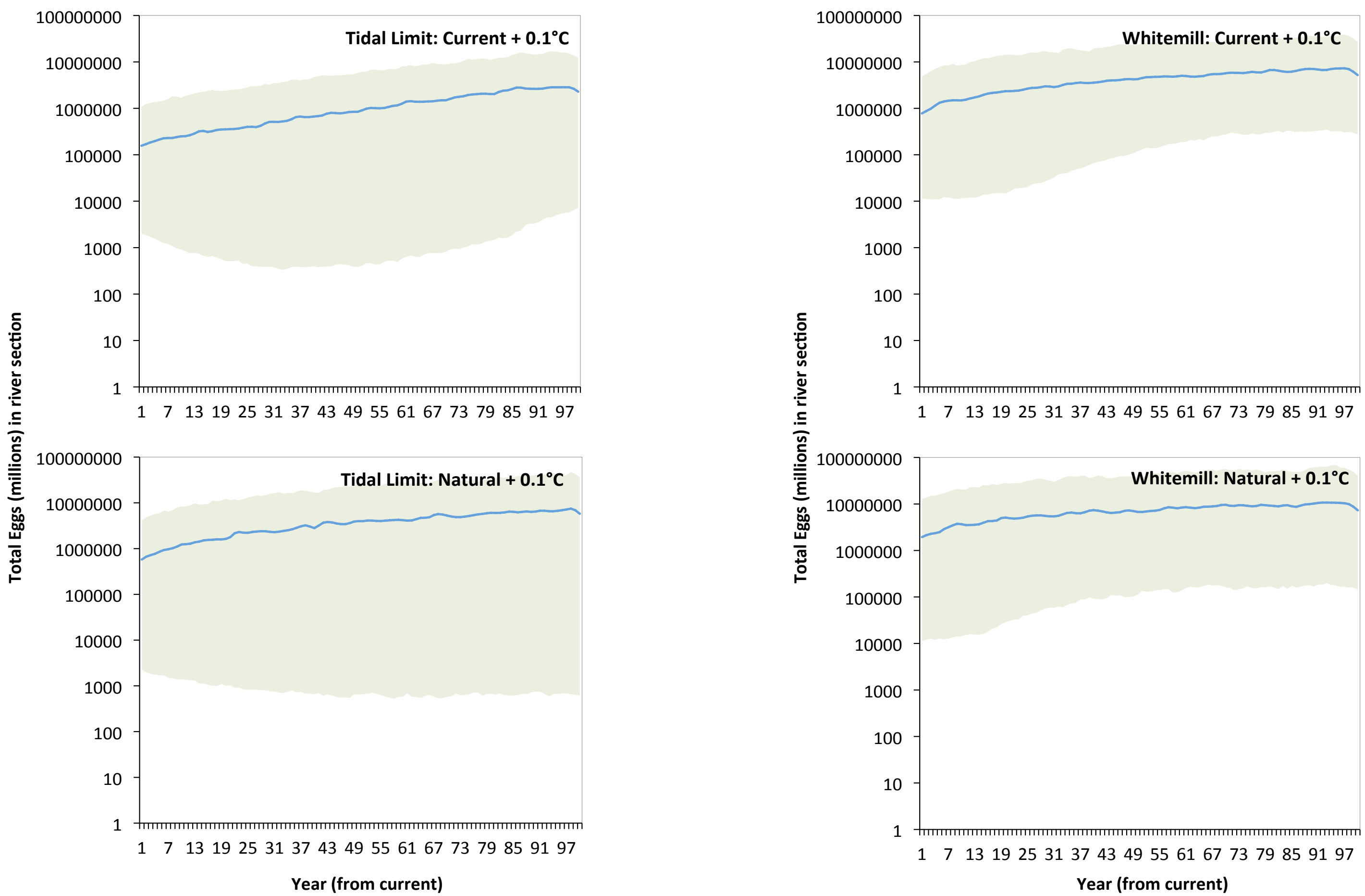

Figure 5. Predicted recruitment (log eggs) over time of shad under current (top) and natural (bottom) temperature regimes at the Tidal Limit and Whitemill under Climate Scenario 1 (+0.1°C per decade). 95 % confidence intervals are shown by shading.

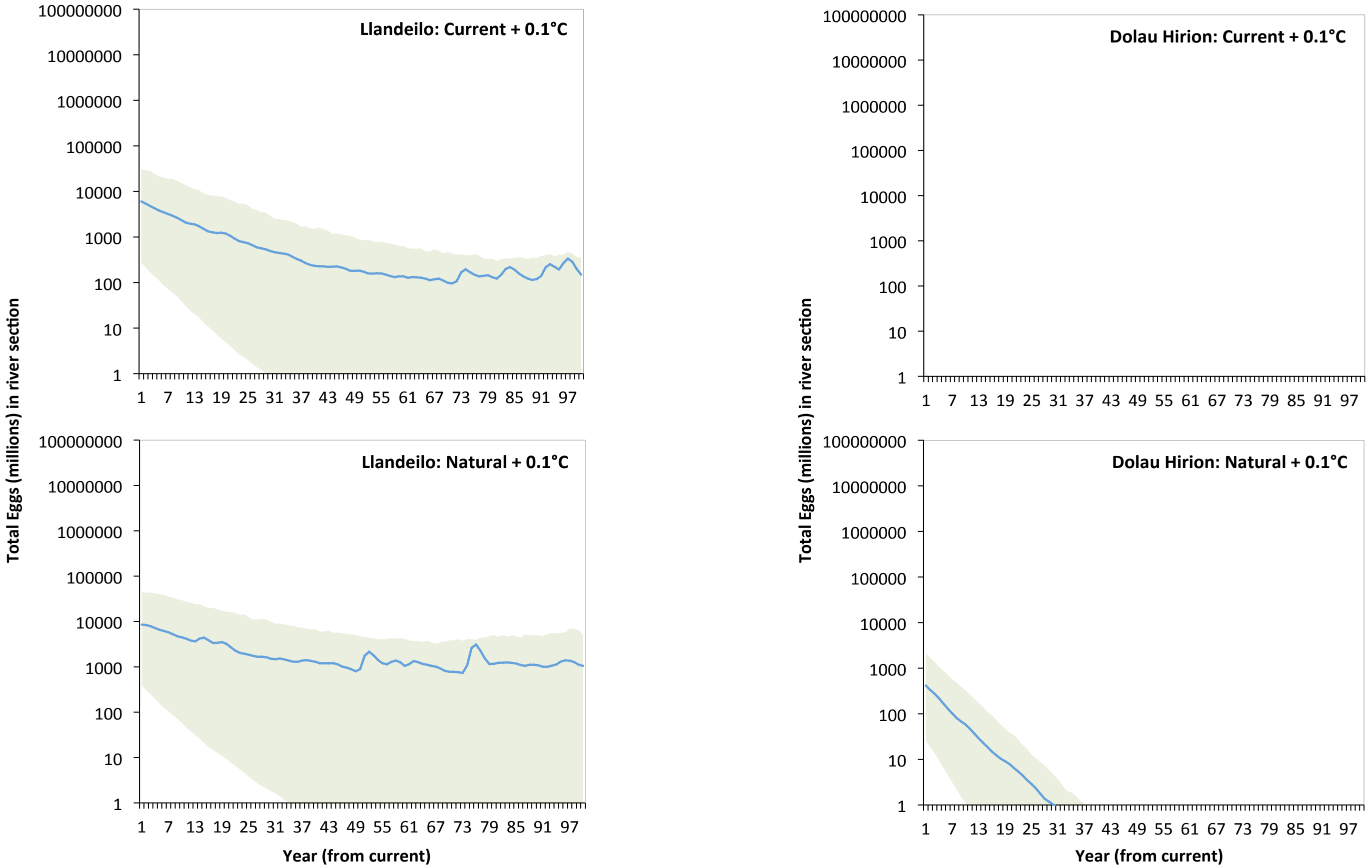

Figure 6. Predicted recruitment (log eggs) over time of shad under current (top) and natural (bottom) temperature regimes at Llandeilo and Dolau Hirion under Climate Scenario 1 (+0.1°C per decade). 95 % confidence intervals are shown by shading.

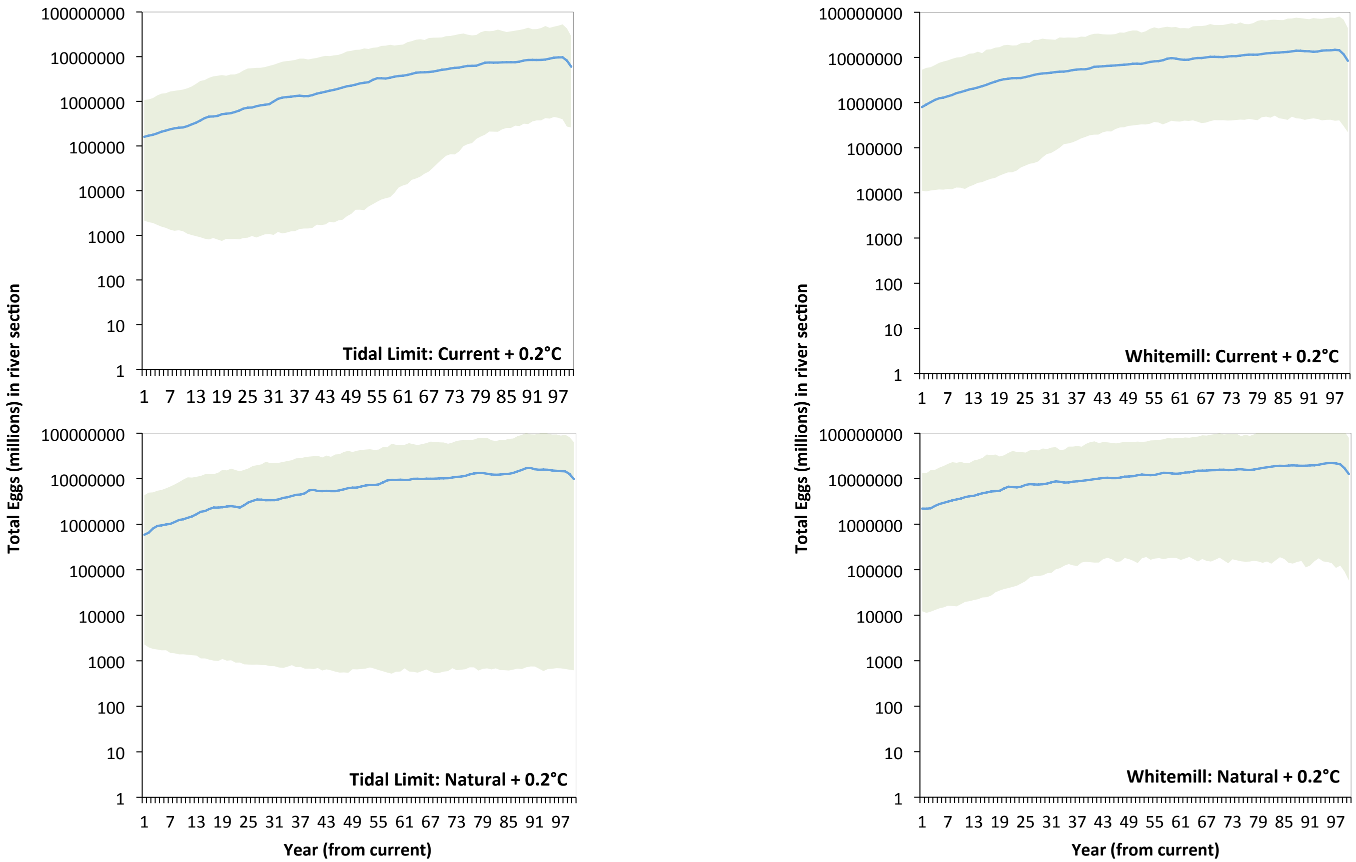

Figure 7. Predicted recruitment (log eggs) over time of shad under current (top) and natural (bottom) temperature regimes at the tidal limit and Whitemill under Climate Scenario 2 (+0.2°C per decade). 95 % confidence intervals are shown by shading.

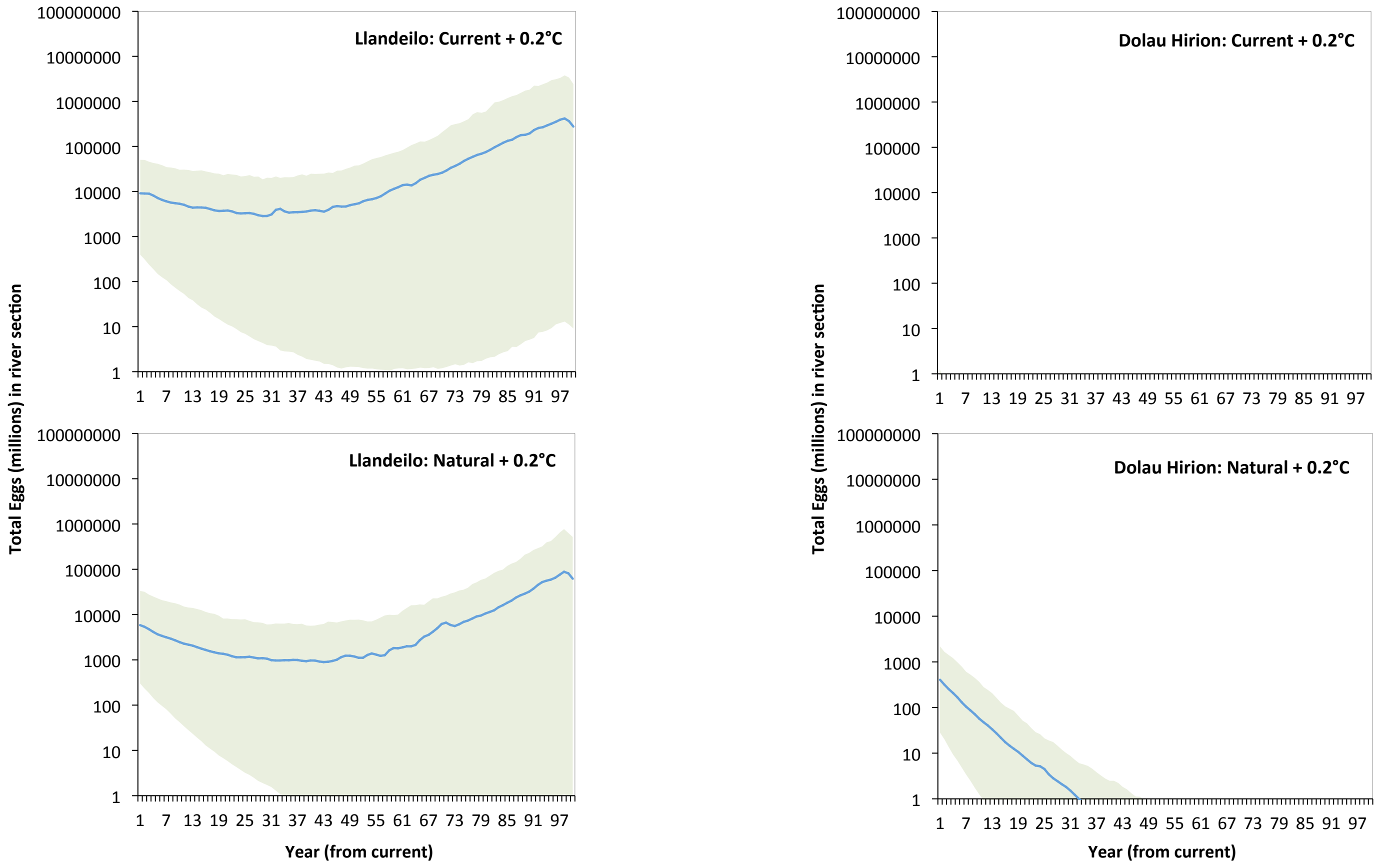

Figure 8. Predicted recruitment (log eggs) over time of shad under current (top) and natural (bottom) temperature regimes at Llandeilo and Dolau Hirion under Climate Scenario 2 (+0.2°C per decade). 95 % confidence intervals are shown by shading.

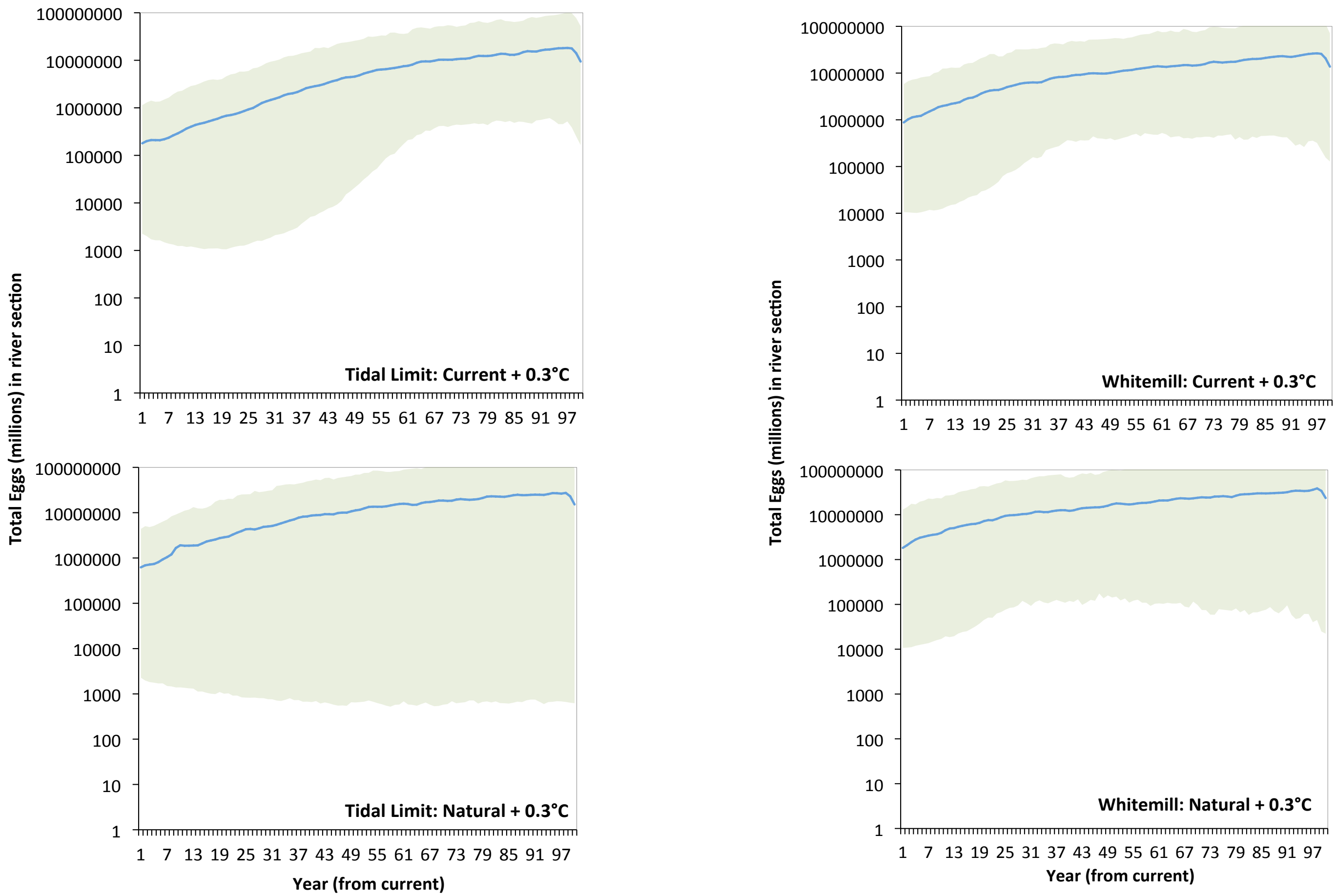

Figure 9. Predicted recruitment (log eggs) over time of shad under current (top) and natural (bottom) temperature regimes at the tidal limit and Whitemill under Climate Scenario 3 (+0.3°C per decade). 95 % confidence intervals are shown by shading.

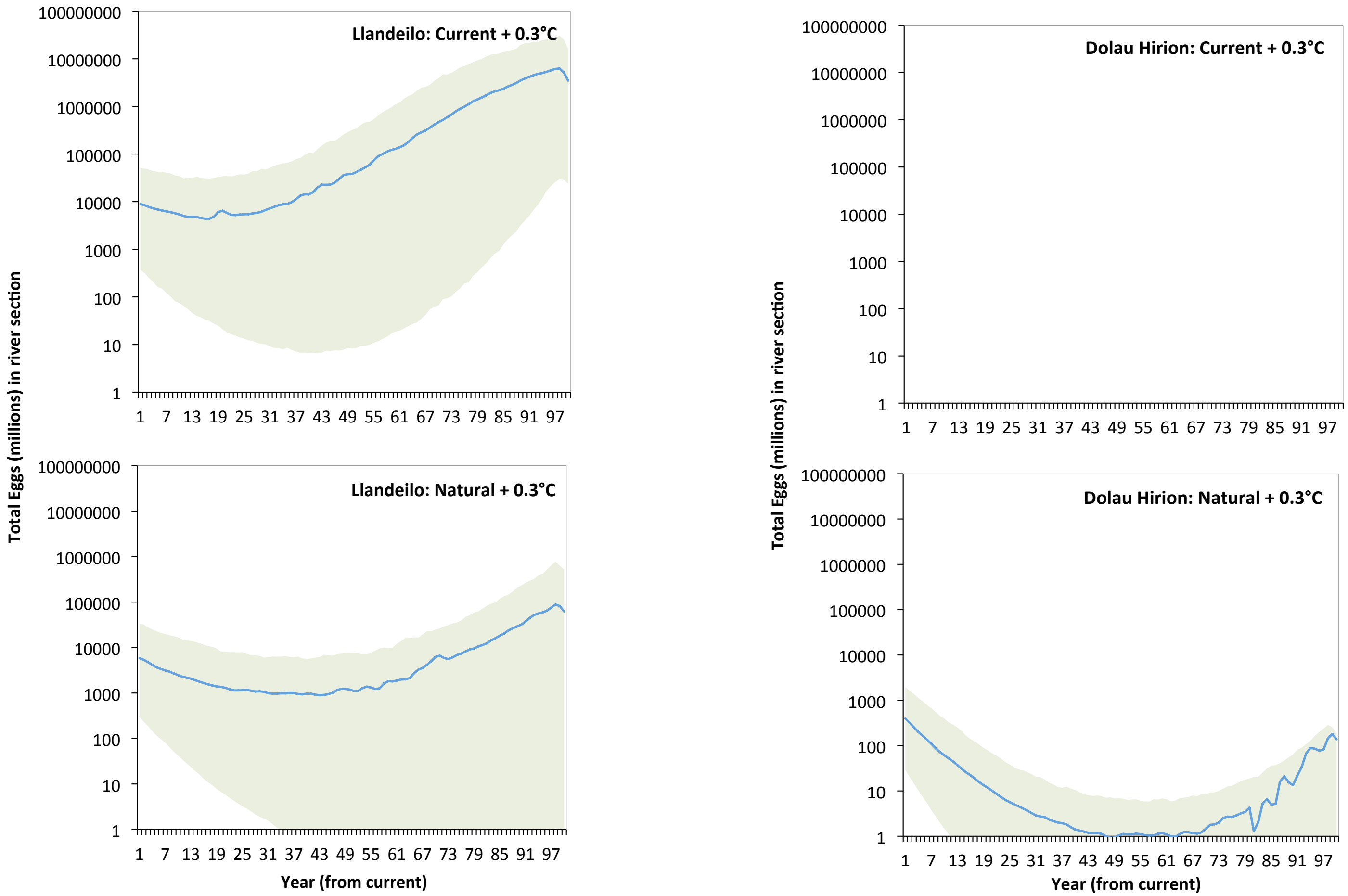

Figure 10. Predicted recruitment (log eggs) over time of shad under current (top) and natural (bottom) temperature regimes at Llandeilo and Dolau Hirion under Climate Scenario 3 (+0.3°C per decade). 95 % confidence intervals are shown by shading.

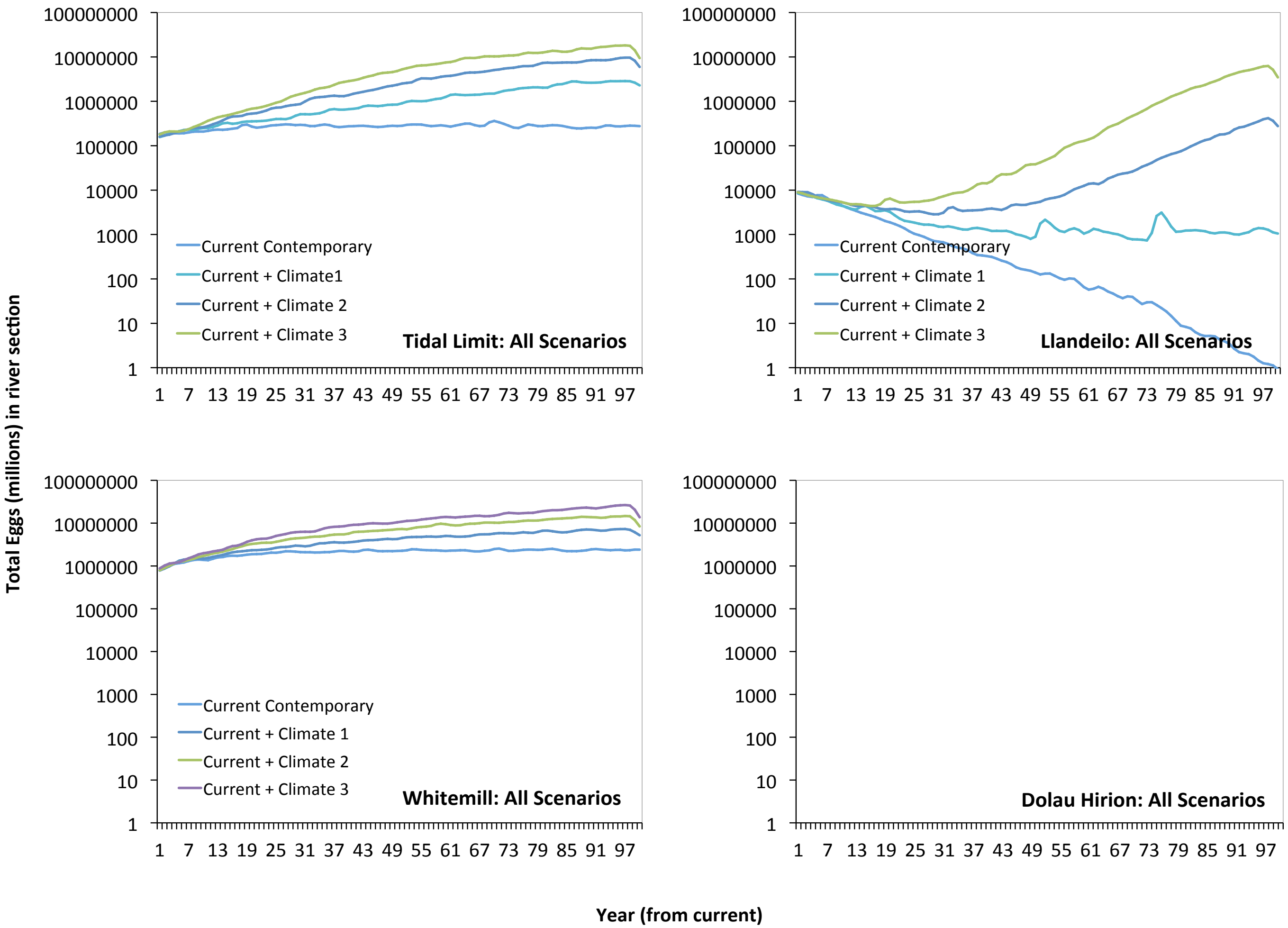

Figure 11. Comparison of predicted recruitment (log eggs) over time of shad under current contemporary and climate temperature scenarios. NB No recruitment is predicted at Dolau Hirion under any scenario.

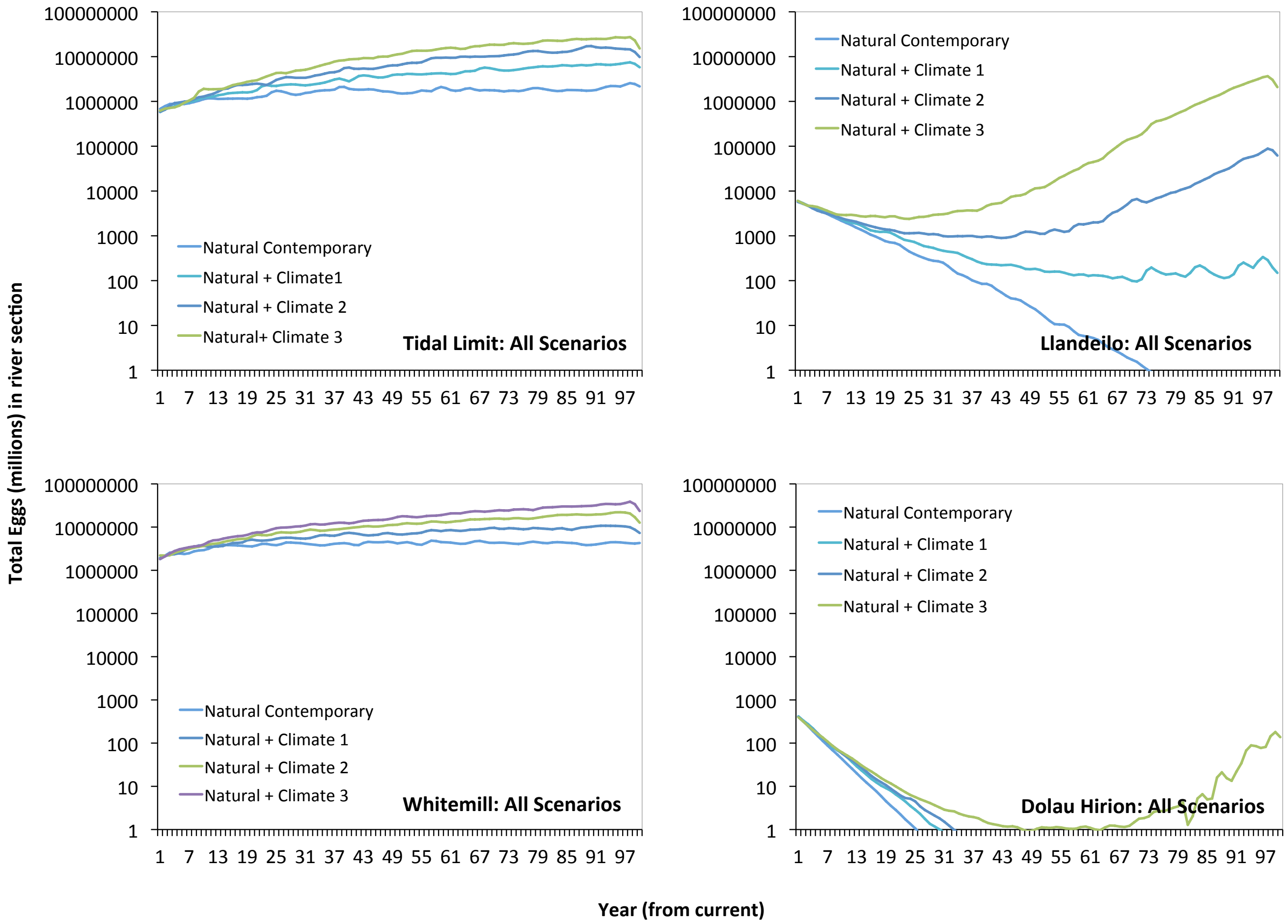

Figure 12. Comparison of predicted recruitment (log eggs) over time of shad under normalised contemporary and climate temperature scenarios.

3.5. Relative Contribution of River Sections to the River Tywi shad po

The Whitemill section of the River Tywi makes the greatest contributior shad population in terms of the number of recruits under current conter and natural contemporary conditions. Under current contemporary con this river sections contributes ~88 % of the total egg abundance, follow tidal limit section (~12 %) and the remaining two sections, Llandeilo an Hirion contributing <1 % between them (Table 4). Under natural conditi relative contribution is lower (~71 %), but this section remains the domi recruitment contributor.

Under climate change scenarios, there is a change in the relative contr river sections, but not the rank order of contribution. The tidal limit regic predicted to increase its contribution, increasing to a maximum of 28 % %, under the current and natural temperature regimes respectively. An is also predicted in the Llandeilo river section, with a greater increase p under the current thermal regime than under a naturalised state. Howe recruitment contribution from this section remains relatively small at bet and 3 %. As a result, the importance (contribution) of the Whitemill rive decreases, reducing to between 62 and 69 % depending on the therma but remains an important section of the river for supporting a persistent population in the River Tywi.

	River Section (% Contribution)			
Scenario	**Tidal Limit**	**Whitemill**	**Llandeilo**	**Dola Hiric**
Current Contemporary	12	88	<0.001	NC
Current + Climate 1	19	81	<1	NC
Current + Climate 2	26	74	<1	NC
Current + Climate 3	28	69	3	NC
Natural Contemporary	29	71	<0.001	<0.0
Natural + Climate 1	33	67	<1	<0.0
Natural + Climate 2	36	64	<1	<0.0
Natural + Climate 3	37	62	1	<0.0

NC – No contribution
NB – numbers are rounded to the nearest whole number such that the total percentag exceed 100.

Table 4. Relative contribution (% of total eggs) produced per river section in te the number of eggs (recruits) produced per annum.

4. Conclusions

- Model simulations suggest that under contemporary conditions, the revised temperature regime will not result in a discernable improvement in the twaite shad population in the River Tywi. The disproportionate contribution of the downstream reaches of the river (i.e. the tidal limit and Whitemill) to the river population is expected to be unaffected, and the contribution of the upper river sections is not expected to improve, supporting the findings of Aprahamian (2013).

- Upstream from Llandeilo, conditions suitable for shad recruitment may improve under the most extreme climate scenario (Scenario 3) to the extent that recruitment could occur, but recruitment is likely to remain highly intermittent and the contribution of this river section is expected to be nominal, if recruitment were to occur at all.

- The forecast increase in temperature over time (Murphy et al. 2009) is predicted to be beneficial to shad in the UK (Lassalle et al. 2008, Lassalle et al. 2009, Aprahamian et al. 2010) and the results from this study support these previous findings. Under all three climate scenarios tested here, recruitment rates were predicted to increase in all river sections, irrespective of the temperature regime employed. Benefits of climate change appear significant only in the upper reach of the River Tywi at Llandeilo, and potentially at Dolau Hirion, but only if the thermal conditions were returned to a “natural” state and in conjunction with significant warming (scenario 3) due to climate.

- The benefits to shad recruitment from climate change are dependent on the current temperature profile of the river at a given section. At the tidal limit and Whitemill river sections, temperatures currently support high levels of recruitment and climate change is expected to further support this success. At Llandeilo, further upstream, climate change scenarios 2 and 3 are predicted to lead to long-term (> 100 year) recruitment success in all years, whereas under scenario 1, while recruitment success may increase, there may continue to be years when recruitment may fail due to low water temperatures. The relative contribution of this river section may increase, but persistent annual contributions are unlikely. The model suggests that contemporary conditions in this section of the river are currently borderline for recruitment of shad, accounting for the limited contribution to the overall shad population (Table 4). Changing the temperature regime to a “natural” condition is not predicted to result in any further increase in recruitment success.

- The model results suggest that a change in the temperature regime is unlikely to have discernable benefits to the shad population of the River Tywi. Although there appears to be potential for one section of the river to benefit (Dolau Hirion) if a revised temperature regime were introduced, these benefits are reliant upon sufficient climate change occurring (scenarios 2 and 3) before those benefits are realised, which in all cases, are not expected to occur within the next 48 year and likely to be very small in terms of contribution to the total river recruitment.

- The relative contribution to shad recruitment by different river sections is marked, with the Whitemill section predicted to contribute more than 70% of the total eggs in the River Tywi under contemporary conditions. This section of the river is clearly vital to the persistence of shad in the River Tywi.

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6. Appendices

6.1. Appendix A: Model development

The adult population of *A. fallax* entering the Severn Estuary at the start of the freshwater phase of their spawning migration was sampled between 1979 and 1997. Counts of *A. fallax* were obtained from the catches of Atlantic salmon *Salmo salar* L. putcher net fishermen operating near Lydney on the Severn Estuary (51.689 N, 2.564 W). The putcher rank consists of 650 conical shaped traps constructed from metal bar 6 mm in diameter, designed to sieve fish on both the flood and ebb tides, for details see Aprahamian (1981). Between 1979 and 1988 the size of the traps and their arrangement in the rank changed; after 1988 fishing effort was constant. The changes affected the size of the opening of the traps as opposed to the spacing of the bars and thus, their selectivity was considered not to be affected. Sampling was conducted on a daily basis to ensure both tides were sampled, to avoid bias from variation in diurnal patterns of behaviour or catchability (Aprahamian, 1981).

Sampling was carried out between 15th April and 19th June, the main migration period through the estuary (Aprahamian, 1981). Samples of the catch or sub-samples (50 fish) of the catch if the number of fish caught exceeded 50, were taken in order to partition the run according to sex, age and spawning history. Age and spawning history were determined from analysis of scales (Baglinière *et al*. 2001). As the timing of the migration through the estuary differed between years (Aprahamian, 1988) the migration was divided up into eight periods (week) of between 13 / 14 tides and one of 18 tides. The latter was the first period and took account of the number of days required to install the putcher rank. The periods were ranked according to catch per unit effort (CPUE) and the top five periods used to calculate an index of the size of the spawning stock (mean catch per tide). This was because in some years no, or relatively few, samples were taken towards the end of the run. The proportion of the available tides sampled ranged from 5% to 67% (mean = 31% year^{-1}) and the number of fish aged ranged from 110 to 617 (mean 359 fish year^{-1}).

The CPUE (X) for each age class (i) was calculated separately for males and females as follows:

$$X_i = \sum_{j=1}^{7} \sum_{k=1}^{5} x_{ijk} 5^{-1} \qquad (1)$$

where x is the mean catch of shad per tide of fish age i, spawning number j (spawning number 1 is a fish spawning for the first time or virgin spawner, spawning number 2 is a fish spawning for the second time it will have one spawning mark on its scale) in period k.

To reduce the possibility of bias derived from sampling too few tides, the index was estimated using the change in abundance between successive age groups. Subjectively, a value of 10% of the 127 tides available between 15th April and 19th June was taken as the threshold. In those years where < 10% of the tides were sampled (1979, 1982-1984), the index was calculated as follows:

$$\Delta_{ij} = Log_e(X_{ij(t)}) - Log_e(X_{ij(t+1)})$$

where Δ_{ij} is the instantaneous rate of change between successive age groups for fish of a particular age (*i*) and spawning number (*j*), X_{ij} is the mean catch per tide for the five periods, of fish of a particular age (*i*) and spawning number (*j*), and *t* is the year.

In 1979, CPUE was back calculated using the 1980 CPUE data and the instantaneous rate of change between the years 1980 and 1981. For the period between 1982 and 1984, the CPUE for fish age 6 years and older in 1982, 7 years and older in 1983 and for fish aged 8 years and older from 1984 were estimated from the 1981 CPUE data and the instantaneous rate of change between the years 1980 and 1981. The other age classes were back calculated from the 1985 CPUE data and the instantaneous rate of change between the years 1980 and 1981 and between 1985 and 1996. This was done to make allowance for any possible change in efficiency as a result of the change in construction material and because it provided the closest approximation to the age structure recorded in 1983 and 1984. Only samples where the number of fish from a particular age group and spawning number were ≥ 5 were used to estimate the instantaneous rate of change.

Selectivity (C_i) was estimated from the catch curve for each age group as follows:

$$C_i = e^{((Log_e X_{i+1} R_{i+1}) + S)} X_i^{-1}$$

where *R* is the proportion of repeat spawners of age class *I*, and *S* is the instantaneous rate of spawning mortality (here 0.6651), derived from the catch curve.

A correction factors was applied to each age class as follows: (1) Age Class 3, 4 or 5 yr - a factor of 13.11, 3.64 and 1.81 was applied respectively; Age Class 6 - 10 yr, a value of 1.00 was used in each case.

An index of the total number of eggs deposition (*E*) in year, *t* was calculated as follows:

$$E_t = \sum_{i=3}^{12} X_{i(t)} F_i C_i$$

where the fecundity of age class *i* (F_i) is calculated (after Aprahamian, 1982) as:

$$F_i = 34324 \cdot I^{0.538}$$

where l = age in years.

Recruitment

The CPUE at age 6 yr (X_6) was used as a proxy for recruitment. Age at maturity can vary between cohorts by up to a year, however, in general > 98% of fish have matured (Aprahamian and Lester 2001). For the 1974 and 1975 year classes and those between 1979 and 1991, the age 6 years CPUE was determined directly from catch data using equation 1. For the 1973 and for the 1976 to 1978 year classes, the index was estimated from the CPUE and the instantaneous rate of change as outlined above. The 1972 index was estimated from the number of 7 yr old fish caught in 1979, assuming that 68% of fish age 6 yr survive to age 7 yr. The survival rate was determined from the relationship between the number of fish age 6 yr caught in year t and the number of 7 yr old fish caught in year t_{+1}, for the 1973 to 1990 year classes (Aprahamian and Lester 2001).

Quantitative monthly sampling of juvenile *A. fallax* has been carried out at Hinkley Point 'B' Nuclear Power Station since October 1980 (P. Henderson, Pisces Conservation Ltd., UK). Sampling dates were chosen to coincide with intermediate range tides in the spring-neap cycle. Sampling was standardised, so that on each visit six consecutive samples were collected over a 1 hr period using plastic baskets covered with 6 mm mesh and positioned to collect all the debris washed from two of the four drum screens, which filter the cooling water entering the power station. The debris was sorted and the number of *A. fallax* captured per hr recorded and the standard length of the fish measured. The method is selective towards juvenile fish with the majority of *A. fallax* caught being of age 0+ (Holmes and Henderson 1990).

For the 1992 to 1996 year classes the recruitment of age 6 year old *A. fallax* was estimated from the relationship between the number of juvenile *A. fallax* caught at Hinkley Point 'B' Nuclear Power Station between 1st June in year t and 31st May in year t_{+1}, and the CPUE index of 6 year old female shad caught in the putcher fishery in year t_{+6} (Aprahamian and Aprahamian 2001).

Model parameters

The model parameters derived from field sampling of stock structure (see Model development above for a full description) were as follows:

Female A ge (Yr)	Fecundity (eggs per female)	Female repeat s pawner (proportion)	Mature female (average abundance)	No. of eggs (fecundity x female abundance)	No. of m ature (virgin) females	No. of mature (repeating) females
<1	ND	ND	ND	ND	ND	ND
1	ND	ND	ND	ND	ND	ND
2	ND	ND	ND	ND	ND	ND
3	74537	0.000	1.39	103364	1.39	0.00
4	80307	0.068	10.49	842277	9.78	0.71
5	86078	0.381	14.17	1219627	8.78	5.39
6	91849	0.801	9.09	835325	1.81	7.29
7	97620	1.000	4.68	456531	0.00	4.68
8	103391	1.000	2.40	248636	0.00	2.40
9	109162	1.000	1.24	134990	0.00	1.24
10	114932	1.000	0.64	73085	0.00	0.64

Table A1. Average composition of run (CPUE of 44 fish per tide), age breakdown, fecundity and proportion of repeat spawners. ND – No data

6.2. Appendix B: Water temperature monitoring station locations and data records.

Location	River	Type	NGR	WISKI data set ref	Period of record	Distance from tidal limit (km)
Nant Bustach u/s Brianne Reservoir	Nant Bustach	River	SN 78468 53400	Brianne Flume/060S0589W	From 3/8/93 to date	u/s reservoir
Brianne Air Temp		Air	SN 79314 48516	Llyn Brianne - Air temp/060304	From 13/10/98	80
Brianne release	Tywi	River	SN 79290 48526	Llyn Brianne - Release temp	From 4/10/98 to date	80
Ystradffin	Tywi	River	SN 78547 47239	WT Ystradffin/826787	From 29/3/2005 to date - data missing	78.5
Craig Clungwyn	Doethie	River	SN 77615 47074	WT Doethie/826765	From 29/3/05 to date - good record but data gaps 2009	76.7
T3 Rhandirmwyn	Tywi	River	SN 76081 44673	WT Tywi T3/826762	From 29/3/05 to date - good record but data gaps 2009	73
Gwenffrwd u/s conf with Tywi	Gwenffrwd	River	SN 76359 45092	WT Gwenffrwd/826761	From 09/5/12 to date	73.5
Dolau Hirion	Tywi	River	SN 76163 36232	WT Dolau Hirion/826776	From 29/3/05 to date - good record but data gaps 2009	61.6
Llandovery Bridge	Tywi	River	SN 76184 34861	WT Llandovery Bridge/826758	From 29/3/05 to 14/10/05	60.3
Llwynjack	Llandovery Bran	River	SN 75683 33254	WT Llwynjack Bran/826784	From 09/05/12 to date	58
Llangadog	Tywi	River	SN 69500 28633	WT Llangadog/826778	From 24/03/05 to date - good record but some data missing 2005 and 2009	50
Llandeilo	Tywi	River	SN 62637 22004	WT Llandeilo/826773	From 24/03/05 to date - considerable missing data from 2005 to 2009	35
Llanegwad	Tywi	River	SN 51324 21078	WT Llanegwad/826771	From 18/3/05 to 10/12/07 - poor record - data missing	17
Pontargothi	Cothi	River	SN 50400 21900	WT Cothi/826774	From 09/5/12 to date	16.7
Whitemill	Tywi	River	SN 46890 21543	WT Whitemill/826780	From 18/03/05 to date - data missing in 2006, 2007 and 2009	10
Tidal limit	Tywi	River	SN 44176 20306	WT Tidal limit/826784	From 18/03/05 to date - good record but some missing data 2005 and 2009	0

6.3. Appendix C – Summary figures comparing recruitment in river sections under current and natural (with and without climate change) conditions

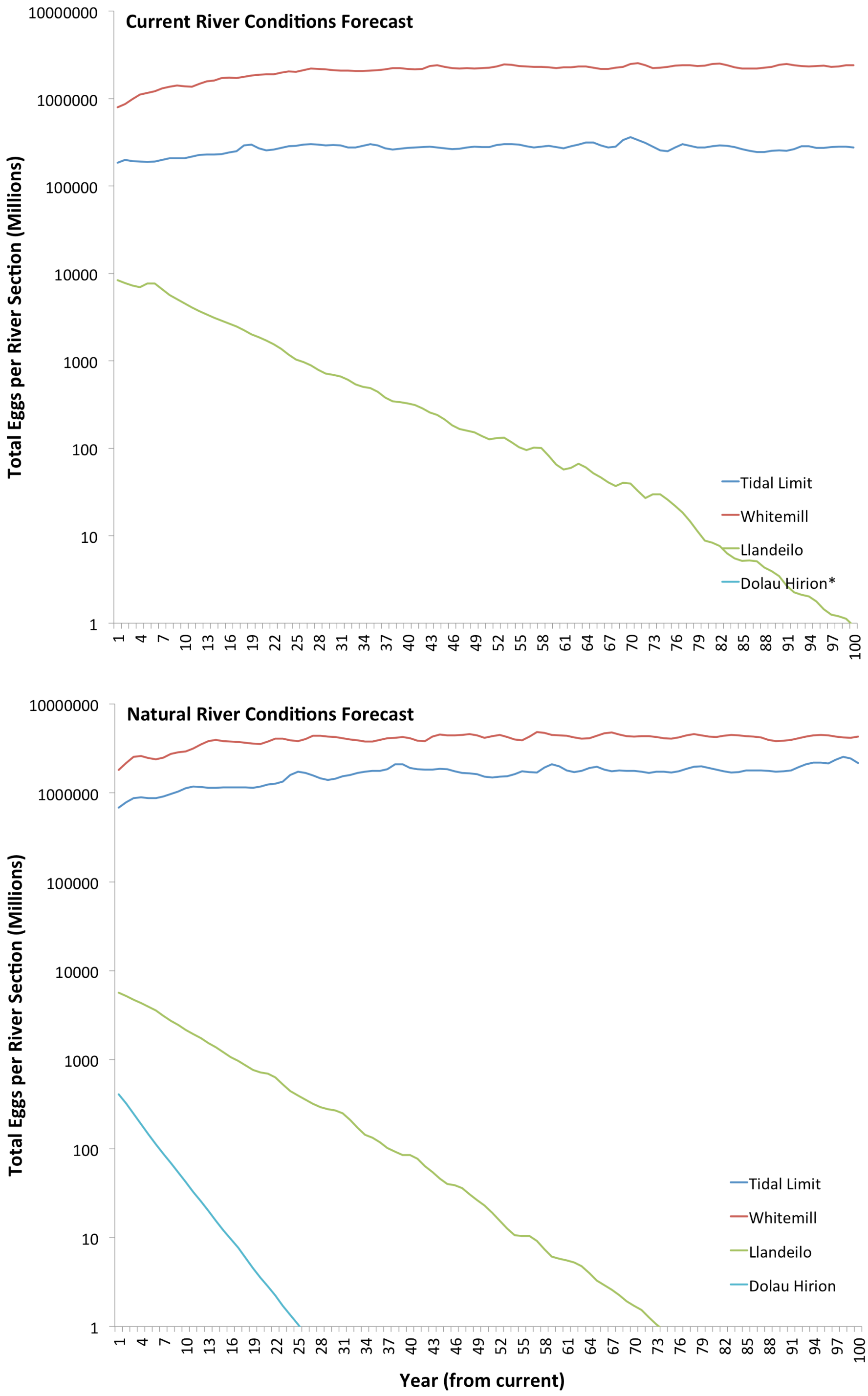
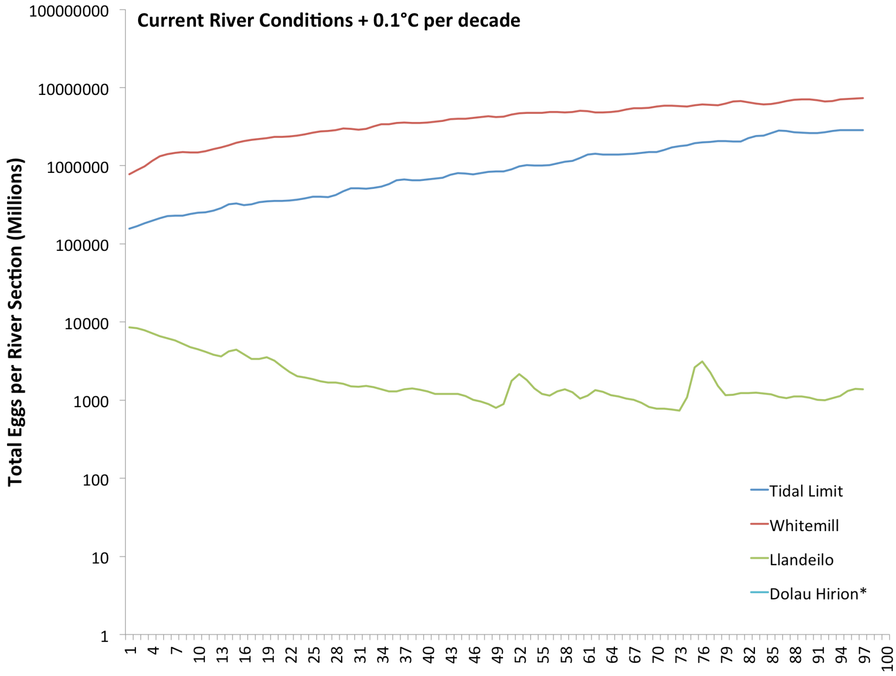


Figure C1. Summary of predicted recruitment (million eggs) over time of shad under current (top) and natural (bottom) conditions in all 4 reaches of the River Tywi. Total eggs for the River Tywi can be calculated from the sum of river section eggs. Confidence intervals are not shown to aid clarity. * The Dolau Hirion river section is not shown for the current conditions, as recruitment is not predicted under this scenario.



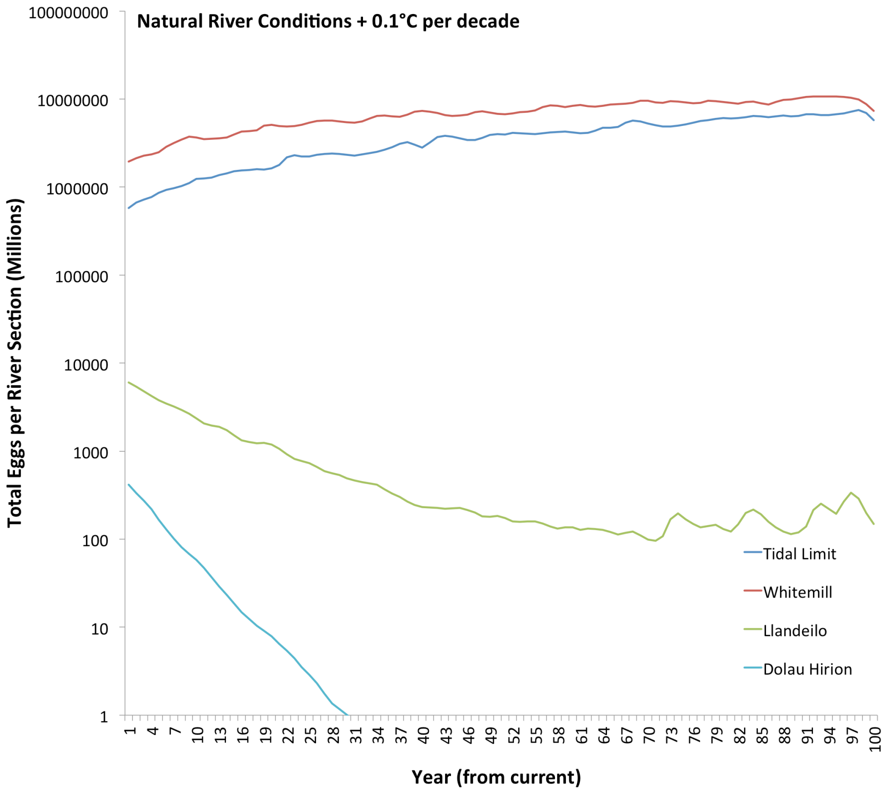


Figure C2. Predicted recruitment (million eggs) over time of shad under current (top) and natural (bottom) conditions in 4 reaches of the River Tywi. Shown are mean recruitment estimates for (i) climate scenario 1 (+ 0.01°C per annum). Confidence intervals are not shown to support clarity. *The Dolau Hirion river section is not shown for the current conditions, as recruitment is not predicted under this scenario.

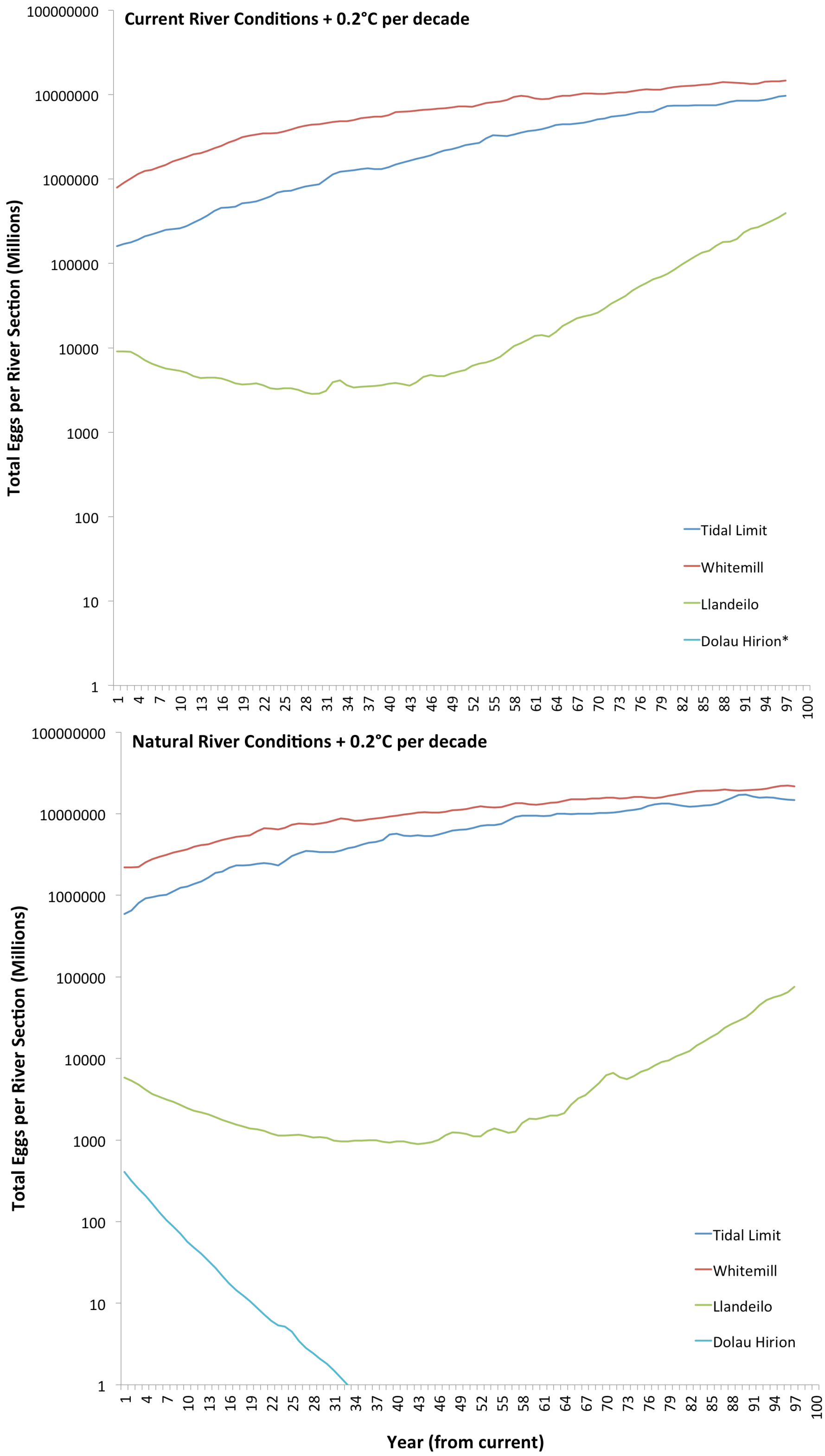
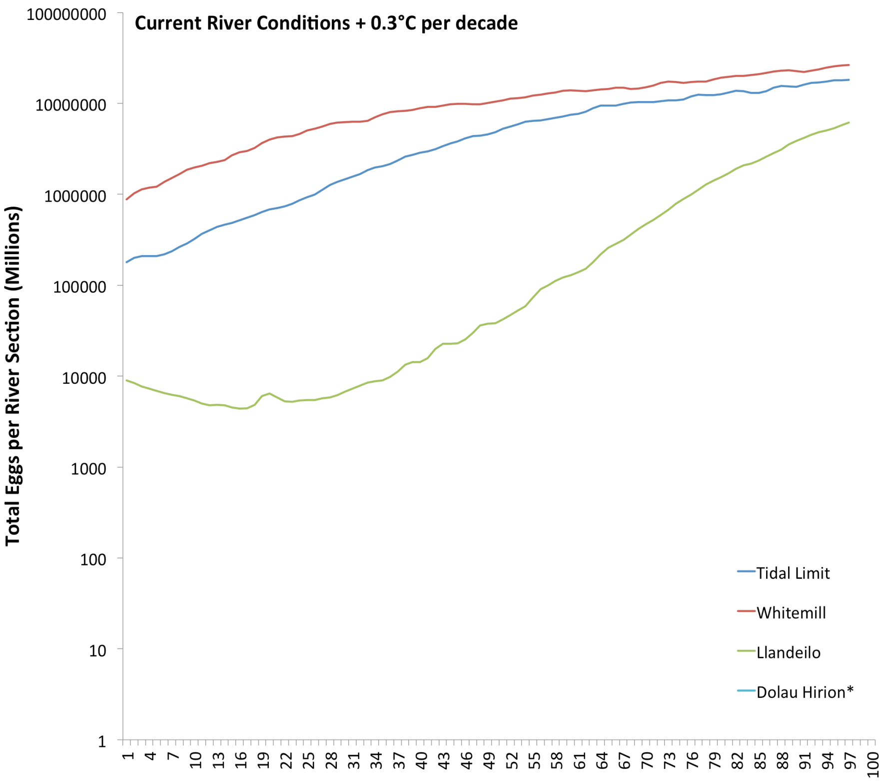


Figure C3. Predicted recruitment (million eggs) over time of shad under current (top) and natural (bottom) conditions in 4 reaches of the River Tywi. Shown are mean recruitment estimates for (i) climate scenario 2 (+ 0.02°C per annum). Confidence intervals are not shown to support clarity. * The Dolau Hirion river section is not shown for the current conditions, as recruitment is not predicted under this scenario.



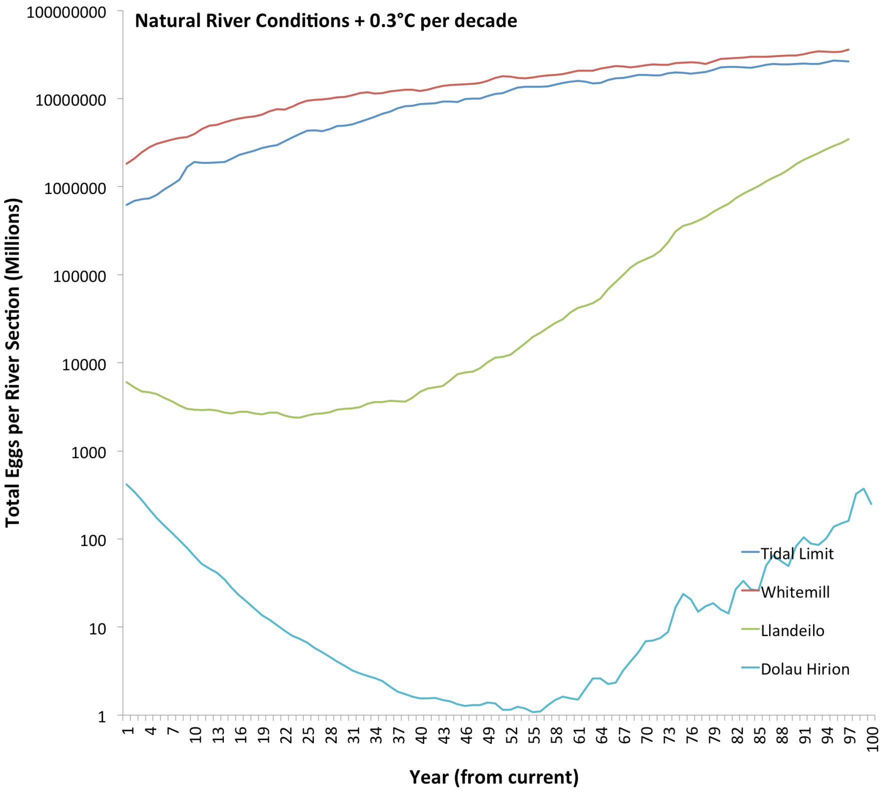


Figure C4. Predicted recruitment (million eggs) over time of shad under current (top) and natural (bottom) conditions in 4 reaches of the River Tywi. Shown are mean recruitment estimates for (i) climate scenario 3 (+ 0.03°C per annum). Confidence intervals are not shown to support clarity. * The Dolau Hirion river section is not shown for the current conditions, as recruitment is not predicted under this scenario.

Data Archive Appendix

Data outputs associated with this project are archived at [NRW to insert relevant server pathway and / or reference numbers] on server–based storage at Natural Resources Wales.

Or

No data outputs were produced as part of this project.

The data archive contains: [Delete and / or add to A-E as appropriate. A full list of data layers can be documented if required]

[A] The final report in Microsoft Word and Adobe PDF formats.

[B] A full set of maps produced in JPEG format.

[C] A series of GIS layers on which the maps in the report are based with a series of word documents detailing the data processing and structure of the GIS layers

[D] A set of raster files in ESRI and ASCII grid formats.

[E] A database named [name] in Microsoft Access 2000 format with metadata described in a Microsoft Word document [name.doc].

[F] A full set of images produced in [jpg/tiff] format.

Metadata for this project is publicly accessible through Natural Resources Wales' Library Catalogue http://194.83.155.90/olibcgi by searching 'Dataset Titles'. The metadata is held as record no [NRW to insert this number]

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