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Quantifying stakeholder understanding of an ecosystem service trade-off

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ABSTRACT

Sustainable management of global natural resources is challenged by social and environmental drivers, adding pressure to ecosystem service provision in many regions of the world where there are competing demands on environmental resources. Understanding trade-offs between ecosystem services and how they are valued by different stakeholder groups is therefore critical to maximise benefits and avoid conflict between competing uses. In this study we developed a novel participatory trade-off experiment to elicit the perception of 43 participants, from across four key stakeholder groups, working in land and water management (Environmental Regulators, Farming Advisors, Water Industry Staff and Catchment Scientists). Using the Production Possibility Frontier (PPF) concept, we quantified stakeholder assessment of both the shape and the uncertainty around the PPF in a trade-off between agricultural intensity and the ecological health of freshwater systems. The majority of stakeholder groups selected threshold and logistic decay trade-off curves to describe the relationship of the trade-off, and estimated the uncertainty around the curves to be intermediate or large. The views of the four stakeholder groups differed significantly regarding how they estimated stakeholder trade-off prioritisation; the largest difference in perspectives was identified between Environmental Regulators and Farm Advisors. The methodology considered the cultural, socio-economic and institutional specificities of an ecosystem service interaction and identified potential sources of conflict but also possible solutions for win-win opportunities to explore and share understanding between stakeholders. Valuing stakeholder knowledge as a form of expert data and integrating this into participatory decision-making processes for land and water management thus contributes considerable value beyond traditional approaches to ecosystem service assessments.

Keywords: Integrated Catchment Management, Land and water management, Land-use conflict, Participatory techniques, Production possibility frontier, Trade-off analysis.

1. Introduction

Sustainable management of natural resources is challenged by social and environmental drivers such as rapid population growth and changing climatic regimes. In turn, ecosystem service provision is under pressure in many regions where there are competing demands on environmental resources, leading to interactions and trade-offs within socio-ecological systems (Cumming *et al.* 2014). Thus, ecosystem services are spatially heterogeneous and temporally dynamic, responding to human and environmental pressures but also shifts in other ecosystem services. The ecosystem service concept has therefore gained recognition as an approach for addressing interactions within socio-ecological systems, both by research and policy-practitioner communities and those with a responsibility for land-based decision-making (Ma *et al.* 2016; Costanza *et al.* 2017).

Interdependency between ecosystem services presents a principal challenge for sustainable landscape management (Cordingley *et al.* 2016). Interactions between provisioning and other ecosystem services are generally dominated by negative correlations or trade-offs, e.g. a decrease in runoff water quality with increased livestock grazing densities (Austrheim *et al.* 2016), while synergies are often found between regulating and cultural services (Lee & Lautenbach 2016; Lin *et al.* 2018), such as the increase in biodiversity, pollination and biological pest control from flower strip planting (Westphal *et al.* 2015). Changes in land management to enhance a single service may often cause calculated but also inadvertent trade-offs, especially at larger spatial and temporal scales beyond those of the immediate management concern (Rodríguez *et al.* 2006). Agricultural intensification can, for example, negatively impact on pollinator diversity, which in turn can affect the yield of pollinator-dependent crops (Deguines *et al.* 2014). Trade-offs in river catchments are often expressed downstream of management decisions, and can lead to conflict between upstream and downstream users (Asquith *et al.* 2008). Downstream trade-offs maybe so severe that they become irreversible (Bennett *et al.* 2009), such as degraded aquatic ecosystems, which can, despite extensive restoration efforts, fail to recover to their original reference state (Bernhardt & Palmer 2011). Therefore, investments in conservation, restoration and sustainable natural resource use are increasingly seen as 'win-win' opportunities, generating substantial ecological, social and economic benefits (de Groot *et al.* 2010).

Multiple services, or bundles of ecosystem services, are often mapped to establish whether trade-offs exist based on co-occurrence (Raudsepp-Hearne *et al.* 2010; Turner *et al.* 2014).This has led to an increased interest in the understanding and optimisation of ecosystem services for environmental management, with the aim of improving the delivery of regulating and cultural services without compromising provisioning services (Austin *et al.* 2016; O'Sullivan *et al.* 2017; Weijerman *et al.* 2018). Catchments are, however, socio-ecological systems, and therefore a trade-off does not only arise due to relationships between ecosystem services, but also due to diverging stakeholder perceptions on ecosystem service provisioning (Martin-Lopez *et al.* 2012). Different stakeholder typologies may express varying preferences for ecosystem services, depending on their knowledge, values and connections to the landscape (Lamarque *et al.* 2011; García-Nieto *et al.* 2015). Stakeholders involved in agriculture in water-limited areas, for instance, are more aware of the ecosystem service benefits of maintaining water flows (Castro *et al.* 2014). Social contexts such as livelihoods, interests and traditions influence stakeholder perception of ecosystem services, which may lead to conflict among opposing stakeholder groups, i.e. between farmers and conservationists (Cebrián-Piqueras *et al.* 2017).

Combining trade-off analysis with stakeholder engagement offers potential to facilitate effective knowledge exchange between decision-makers, while also capitalising on important expertise and understanding that would be otherwise missed from trade-off analysis alone (Galafassi *et al.* 2017), as well as highlighting stakeholder typology differences in ecosystem service perception (Darvill & Lindo 2016). Including questionnaires as part of ecosystem service analysis, for instance, can help to capture the complexity of socio-ecological systems by incorporating stakeholder values and identifying drivers of change (Andersson *et al.* 2015;

Garcia-Llorente *et al.* 2015). Participatory mapping techniques can aid understanding of the spatial distribution of social benefits, especially for cultural services, which are difficult to estimate (Canedoli *et al.* 2017; Reilly *et al.* 2018). The use of participatory approaches are therefore vital for including the social demand of ecosystem service trade-offs, which is often neglected, and hence may avoid potential conflict of natural resource use and management (García-Nieto *et al.* 2013).

Another technique that integrates the supply and demand side of ecosystem service trade-offs is the production possibility frontier (PPF) concept. The PPF delineates the biophysical relationship between two ecosystem services and represents the maximum values they may attain within that trade-off. (Cavender-Bares *et al.* 2015; see section 2.1 for a more detailed description). The utility function indicates the point along the PPF where the utility of the two ecosystem services is maximised for a stakeholder. It is difficult to estimate PPFs and particularly utility functions of an ecosystem (Lester *et al.* 2013), but there are studies that approximate the PPFs of services between two (Lang & Song 2018) or multiple ecosystem services (Lautenbach *et al.* 2013). There is, however, considerable scope for including utility functions in trade-off analysis to characterise the social demand of ecosystem service interactions (Cord *et al.* 2017). The use of participatory research to assess perceptions of the PPF of a trade-off and associated utility functions can reveal differences in stakeholder priorities concerning more complex ecosystem service interactions.

To our knowledge, there are no previous studies that assess stakeholder views on the shape of a PPF, or their perceptions on stakeholder utility functions within a trade-off. In response, we developed a novel stakeholder engagement methodology which elicits the perception of four key stakeholder groups working in land and water management. We quantified their assessment of both the shape and the uncertainty around the PPF in a trade-off between agricultural intensity and freshwater ecological health. We further quantified how participants perceived the utility functions of different stakeholder groups within that trade-off. Our objectives were to investigate stakeholder views to: (1) define the nature of, and the uncertainty associated with, a specific water and land management trade-off; (2) estimate stakeholder prioritisation of the trade-off; (3) quantify how views varied in different catchments and across different stakeholder groups; and (4) assess the practical relevance of this participatory methodology for land and water management planning and decision-making.

2. Materials and methods

2.1 The 'production possibility frontier' (PPF) concept

Depending on the biogeophysical constraints on a pair of ecosystem services, together with how they are managed, the PPF may take a number of different forms which are often non-linear in nature (Fig. 1; Koch *et al.* 2009). In an exponential decline PPF, the ecosystem service on the x-axis correlates with a sharp decrease even at small increases of the other ecosystem service (Fig. 1c). In contrast, the response is initially more resilient on the threshold (Fig. 1e) and logistic decay (Fig. 1f) function with a rapid decline once a threshold is passed. With the intermediate disturbance function PPF, moderate increases in one ecosystem service have a synergistic effect on the other, but larger increases are detrimental to it (Fig. 1d).

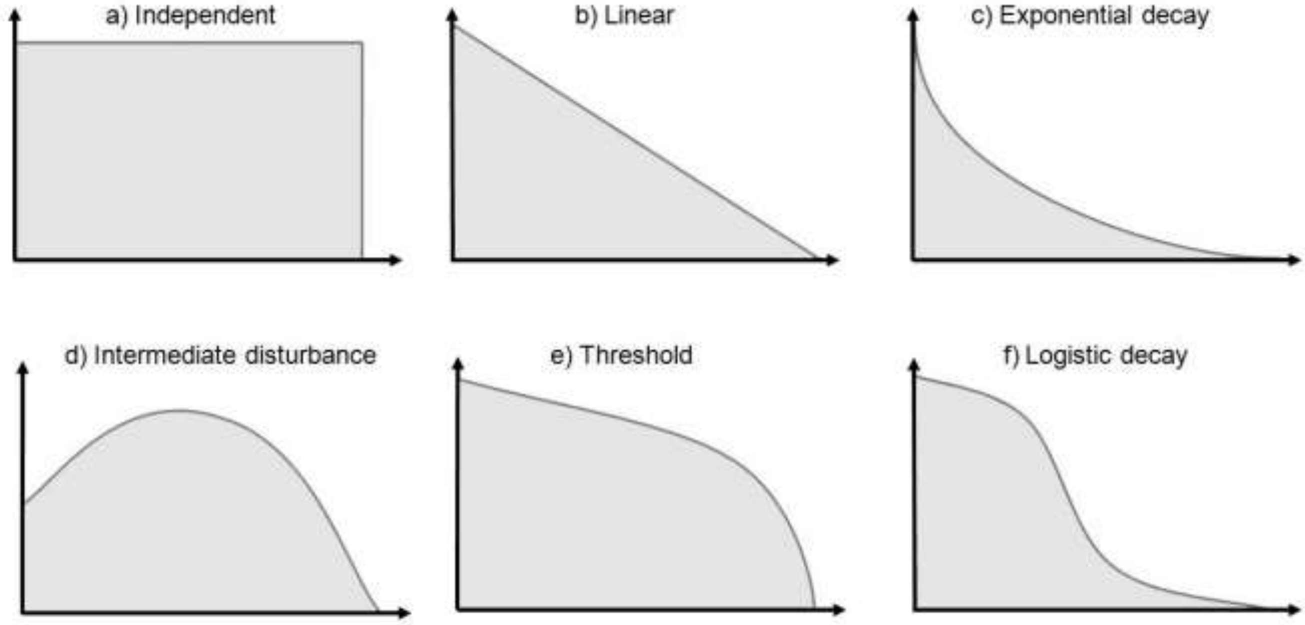

Fig. 1: Illustrating the possible forms the trade-off between two ecosystem services may take: (a) independent, (b) linear, (c) exponential decay, (d) intermediate disturbance function, (e) threshold relationship, and (f) logistic decay (Koch *et al.* 2009).

Isoclines of stakeholder utility values are plotted over the PPF function (Fig. 2a and b), which represent the utility value that a stakeholder places on the ecosystem services in a specific trade-off. The utility function of a given stakeholder is the point where the isoclines meet the PPF, and represents where the trade-off should be balanced to maximise utility for the stakeholder. When plotting multiple trade-off preferences, the distance between the utility functions can highlight potential conflict between stakeholders' positions on how a trade-off should be managed to balance the preferences of multiple stakeholders. Taking the example of the trade-off between agricultural yield and downstream water quality: although the PPF represents the maximum output within a trade-off scenario (Fig. 2a), the area under the PPF curve may be increased by implementing management that does not negatively impact on yield while preserving water quality, such as through efficient fertiliser use (Fig. 2c; Ewing & Runck 2015). In turn, this then allows the utility values of both stakeholders with competing demands to be improved.

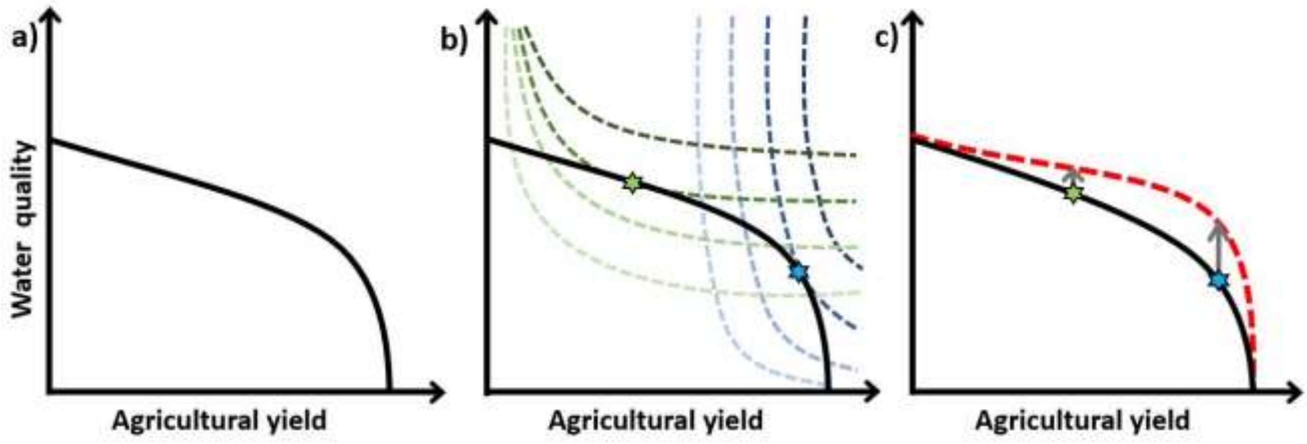

Fig. 2: (a) The 'production possibility frontier' (PPF; black line) of a trade-off between two ecosystem services delimits its biophysical constraints. (b) Stakeholder preferences within the trade-off, called 'utility functions' (green and blue star) are constrained by the PPF and by the utility value of the stakeholders indicated by the isoclines (green and blue dotted lines). (c) The PPF may be altered by changing the management of the ecosystem, which may benefit both stakeholders. Adapted from King *et al.* (2015).

2.2 Study catchments and stakeholder sample

Three catchments from across Scotland were selected on account of their diverse geomorphologies, land cover types, stakeholder communities and land and water management pressures. The River Spey in the north-east, the South Esk in the east and the River Ayr catchment in the south-west of Scotland (Fig. 3). The catchments vary in size from ~ 600 km^2 (South Esk and Ayr) to just under 3000 km^2 (Spey). Moors and heathland is the most dominant land cover type in the Spey (29%; Table 1) and the Esk catchment (33%), followed by sparsely vegetated land in the mountainous areas of the Spey (23%) and arable land in the Esk catchment (31%). Dairy production is a key local industry in the Ayr catchment with pasture accounting for 39% of the land cover.

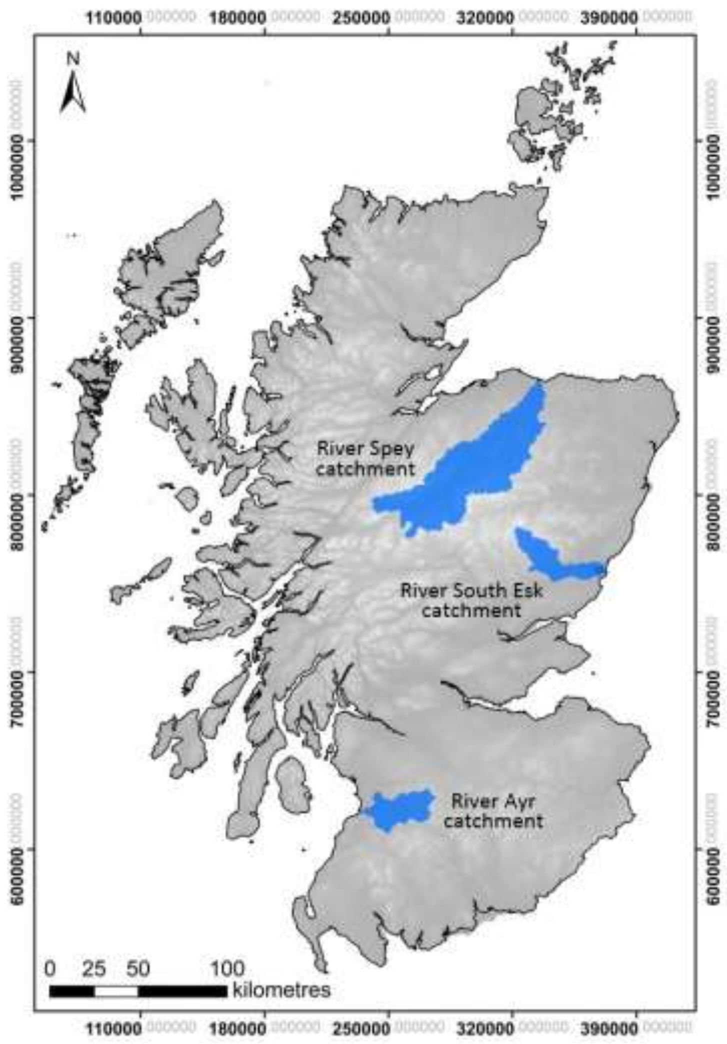

Fig. 3: The three study catchment areas: The River Spey in the north-east, the South Esk in the east and the River Ayr catchment in the south-west of Scotland.

In general, the uplands of the three catchments are dominated by rough grazing, commercial forestry, and sporting estates, while the lowlands accommodate arable land and improved grazing. Tourism and angling represent important local industries, with whisky production also being significant, particularly in the Spey. There are competing pressures on water resources in all three catchments via diffuse pollution from farming practices and point source inputs from sewage discharge, in addition to abstraction for potable water, large hydropower schemes, food and drink manufacture and irrigation.

Table 1: Land cover types in the three study catchments as a percentage of overall area covered (rounded to the nearest whole number).

Land cover type	Spey catchment	Esk catchment	Ayr catchment
Moors & heathland	29%	33%	11%
Coniferous forest	16%	8%	9%
Pastures	9%	12%	39%
Sparsely vegetated areas	23%	0%	0%
Natural grasslands	9%	10%	14%
Arable land	2%	31%	7%
Peat bogs	7%	1%	10%
Transitional woodland-shrub	3%	1%	2%
Broad-leaved forest	2%	1%	1%
Urban areas	1%	1%	2%

A total of 43 stakeholders participated in the study, completing a survey on PPF characterisation for a specific trade-off within their respective catchments. Three to five individuals from four key stakeholder groups were interviewed in each of the three study catchments. The four stakeholder groups were selected through a preliminary desk-based exercise that ranked the importance of the stakeholder groups for land and water management, and their influence on management decisions. Participants belonged to one of four key stakeholder groups: Environmental Regulators (*n*=12; all staff from the Scottish Environment Protection Agency), Water Industry Staff (*n*=9; all from Scottish Water, Scotland's public water and wastewater company), Catchment Scientists (*n*=11; from Universities and research institutes across Scotland) and Farm Advisors (*n*=11; from the National Farmers Union Scotland, as well as independent farm consultants). Criteria for selection of participants was: (i) evidence of experience in their respective catchment, e.g. an individual was required to have worked for at least a year in the catchment, or written a publication or report linked to the catchment; and (ii) expertise on land and water management issues. Participants were initially identified through a desktop search with additional stakeholders identified via recommendations from initial stakeholders.

We investigated the trade-off between agricultural intensity and a measure of aquatic health, because diffuse pollution from agriculture continues to challenge the ecological status of many waterbodies in Scotland and the UK, as regulated under the EU Water Framework Directive (WFD). Ecological status, as defined by the WFD is a robust measure of aquatic ecosystem health, integrating a number of physical, chemical and biological indicators. Ecological status was therefore used as a measure in our study because it is a well understood term amongst the four stakeholder groups, and has direct policy implications. Implicit within this measure are the delivery of a number of ecosystem services, as improved ecological status will lead to increased provisioning services, such as water supply and fish stocks, as well cultural services, such as tourism and recreation. Agricultural intensity was selected, in preference to the ecosystem service of a particular agricultural yield, as this measure includes other land management practices such as livestock farming, slurry spreading and silage production and is therefore much more applicable to a variety of river catchments.

2.3 Questionnaire design and data collection

Surveys were conducted one-to-one using a tablet computer as part of a mixed method survey, integrating qualitative and quantitative data and approaches from environmental science and social science research. Participants were presented with a blank trade-off graph with agricultural intensity on the x-axis (ranging from 0 to 1) and ecological status on the y-axis (on a scale between 0 and 1). The WFD measure ranges from high ecological status, to good, moderate, poor and bad as the ecological quality of a waterbody deteriorates.

The interviewer explained the axes to the participant and asked what they perceived the shape of the trade-off between those two factors to look like in their river catchment, under the current land management practices in their respective catchment and disregarding other management that may impact on ecological status, such as urban developments. Participants were required to select the shape (out of four options; Fig. 1b, c, e or f), that they considered best represented the true PPF in their catchment. The independent and intermediate disturbance shapes were not given as an option, as there is evidence that increased agricultural intensity negatively impacts the ecological status of aquatic ecosystems (Stoate *et al.* 2009). On identifying a PPF typology to associate with the trade-off, participants were then asked to select 95% confidence intervals around the PPF, which could either be of small, intermediate or large uncertainty. This provided a measure of how confident they were that their chosen PPF corresponded to the true underlying PPF in their catchment.

After choosing the PPF and the confidence intervals, participants were asked to consider how they perceive utility functions to vary across different stakeholder groupings. Here participants were presented with coloured circles on the tablet (which corresponded to each of the four stakeholder groups), to place on the PPF at the point where they perceived maximum utility for each group. The size of the utility functions could be enlarged by the participants, allowing a range of maximum utility to be selected for each stakeholder group instead of selecting one point along the PPF. The interviewer explained that enlarging utility functions could hence include an estimate of the uncertainty in identifying the true mean of the stakeholder group's utility function, but also to account for within stakeholder group variation of utility functions. Finally, participants were given the opportunity to review the figure and ensure their response accurately represented their views.

After completing the first exercise, stakeholders were asked to complete the exercise a second time, however this time the shape of the trade-off was pre-determined and all participants were asked to place utility functions for the four stakeholder groups on the same PPF (Fig. 1e). The threshold PPF was selected here, due to findings from Ewing and Runck (2015) that this shape represented the relationship between agricultural yield and a measure of water quality (nitrate concentrations), in their study on corn production in the mid-western United States. Therefore, each participant completed two figures as outputs, (a) one PPF of their choice including confidence intervals and four utility functions and (b) one threshold PPF with four utility functions. This allowed better comparison of utility functions between participants as responses would be more comparable when recorded on the same PPF.

Furthermore, responses from participants that selected the threshold PPF in the first exercise could then be used as a control response to assess the accuracy of the placement of the utility functions when repeated.

2.4 Analysis

The responses from all participants were converted to numerical values by measuring the distance to the start of the utility functions on the x-axis and the diameter of their utility function to the nearest millimetre after ensuring the plots were standardised in terms of their scale on the tablet computer. Both the measurements of utility function starting position and diameter were scaled to values from 0 to 1 by dividing values by the total length of the x-axis after which basic descriptive statistics were obtained and statistical analysis undertaken using SPSS version 23 (IBM 2012). To compare responses between catchments and stakeholder groups a non-parametric statistical test (Kruskall Wallis) was used, as variances were often significantly different per Levene's homogeneity of variances test. As 16 participants chose the threshold PPF in the first exercise, which was also the PPF that all stakeholders responded to in the second exercise, their responses for the utility functions could be used as a control. For those responses, pair-wise comparisons were made between the utility functions from the first and second exercise using a Wilcoxon Signed Rank Test. The same test was used to compare within and between stakeholder group responses. Pearson's Chi-Squared Test of Association was used to analyse the association between the PPF and confidence intervals that were selected and which stakeholder grouping the respondents belonged to. The 'exponential decay' and 'linear' functions were chosen infrequently by participants and those typologies were therefore categorised as 'others' for the purposes of statistical comparison of their count data with the 'logistic decay' and 'threshold curve' responses. Similarly, only the results for 'intermediate' and 'large' uncertainty intervals were compared, as counts for 'small' confidence intervals were insufficient for statistical analysis. Rstudio software version1.1.453 was used to produce the bar plot charts (RStudio 2016).

3. Results

3.1 Selection of the PPF and confidence intervals

Most stakeholders selected either the logistic decay (40%) or the threshold function (37%) to describe the shape of the PPF in their catchment. Four participants from the Farm Advisor stakeholder group, however, did not agree with any of the four shapes, as two of them thought the PPF would follow more of an intermediate disturbance curve. Two other Farm Advisors agreed it was a threshold relationship, but that it would never reach bad ecological status even at the highest agricultural intensities. There was no significant association between the PPF function selected and the stakeholder group or the catchment that the participant was associated with (see Table 2 for a summary of all the statistical outputs). However, most Environmental Regulators (67%) selected the logistic decay, while most Farm Advisors (88%) selected either the threshold curve or did not agree with any of the shapes offered. The confidence intervals chosen by stakeholders were mostly the intermediate (49%) or large (44%) confidence intervals and there was no significant association between the uncertainty selected and the stakeholder group the participant belonged to. However, Catchment Scientists predominantly chose large confidence intervals (73%) while Environmental Regulators were more likely to select intermediate uncertainty around the PPF (69%). The other two stakeholder groups selected both intermediate and large confidence intervals at equal proportions with 45% of Farm Advisors and 44% of Water Industry Staff choosing intermediate uncertainty and 45% of Farm Advisors and 44% of Water Industry Staff selecting large uncertainty.

Although the surveys were carried out across three diverse river catchments, no statistically significant differences were found between the catchments in any of the measures. Hence, data were aggregated and only differences between stakeholder typologies are presented.

Table 2: Summary of all the statistical testing undertaken in the study.

Variables compared	Statistical test	Test statistic	Value	DF	P-value
PPF shapes and confidence intervals selected by stakeholder group and catchment					
PPF selected & Stakeholder grouping	**Chi-squared Test of association**	Pearson	9.162	6	>0.05
PPF selected & Catchment		Pearson	3.237	4	>0.05
Uncertainty selected & Stakeholder grouping		Pearson	6.644	3	>0.05
Uncertainty selected & Catchment		Pearson	0.957	2	>0.05
First and control response of utility function placement for each stakeholder group (Fig. 3a)					
Environmental Regulators	**Wilcoxon Signed Rank Test**	Wilcoxon statistic	45.0	15	>0.05
Catchment Scientists		Wilcoxon statistic	42.5	15	>0.05
Farm Advisors		Wilcoxon statistic	93.0	15	>0.05
Water Industry Staff		Wilcoxon statistic	62.0	15	>0.05
First and control response of utility function diameter for each stakeholder group (Fig. 3b)					
Environmental Regulators	**Wilcoxon Signed Rank Test**	Wilcoxon statistic	99.5	14	**<0.05**
Catchment Scientists		Wilcoxon statistic	84.0	13	**<0.01**
Farm Advisors		Wilcoxon statistic	66.0	12	**<0.05**
Water Industry Staff		Wilcoxon statistic	84.5	14	**<0.05**
Position of utility function of own group compared to response of other groups (Fig. 6a &b)					
On PPF chosen by stakeholder					
Environmental Regulators	**Wilcoxon Signed Rank Test**	Wilcoxon statistic	12.0	10	>0.05
Catchment Scientists		Wilcoxon statistic	41.5	9	>0.05
Farm Advisors		Wilcoxon statistic	25.0	9	>0.05
Water Industry Staff		Wilcoxon statistic	33.0	6	**<0.05**
On threshold PPF					
Environmental Regulators		Wilcoxon statistic	45.0	10	**<0.01**
Catchment Scientists		Wilcoxon statistic	21.0	9	>0.05
Farm Advisors		Wilcoxon statistic	62.0	9	**<0.01**
Water Industry Staff		Wilcoxon statistic	36.0	6	**<0.05**
Difference in utility function placement between groupings: Kruskall-Wallis Test (Fig. 7)					
On PPF chosen by stakeholder	H-value	Adjusted for ties	175.96	9	**<0.001**
Utility function positioning for the four stakeholder groupings: Kruskall-Wallis Test (Fig. 4)					
On PPF chosen by stakeholder	H-value	Adjusted for ties	59.83	3	**<0.001**
On threshold PPF	H-value	Adjusted for ties	36.50	3	**<0.001**
Utility function positioning by respondent's stakeholder group: Kruskall-Wallis Test (Fig.5)					
On PPF chosen by stakeholder					
Environmental Regulators	H-value	Adjusted for ties	2.08	3	>0.05
Catchment Scientists	H-value	Adjusted for ties	1.20	3	>0.05
Farm Advisors	H-value	Adjusted for ties	1.87	3	>0.05
Water Industry Staff	H-value	Adjusted for ties	6.24	3	>0.05
On threshold PPF					
Environmental Regulators	H-value	Adjusted for ties	15.91	3	**<0.001**
Catchment Scientists	H-value	Adjusted for ties	5.87	3	>0.05
Farm Advisors	H-value	Adjusted for ties	13.98	3	**<0.01**
Water Industry Staff	H-value	Adjusted for ties	16.98	3	**<0.001**

3.2 *Utility function responses*

When comparing the two responses of those participants who selected the threshold PPF in the first exercise (n=16), there was no significant difference in the position that the participants placed the utility functions on the threshold curve for the repeated PPF exercise (Fig. 3a), although their diameter was significantly smaller (Fig. 4b).

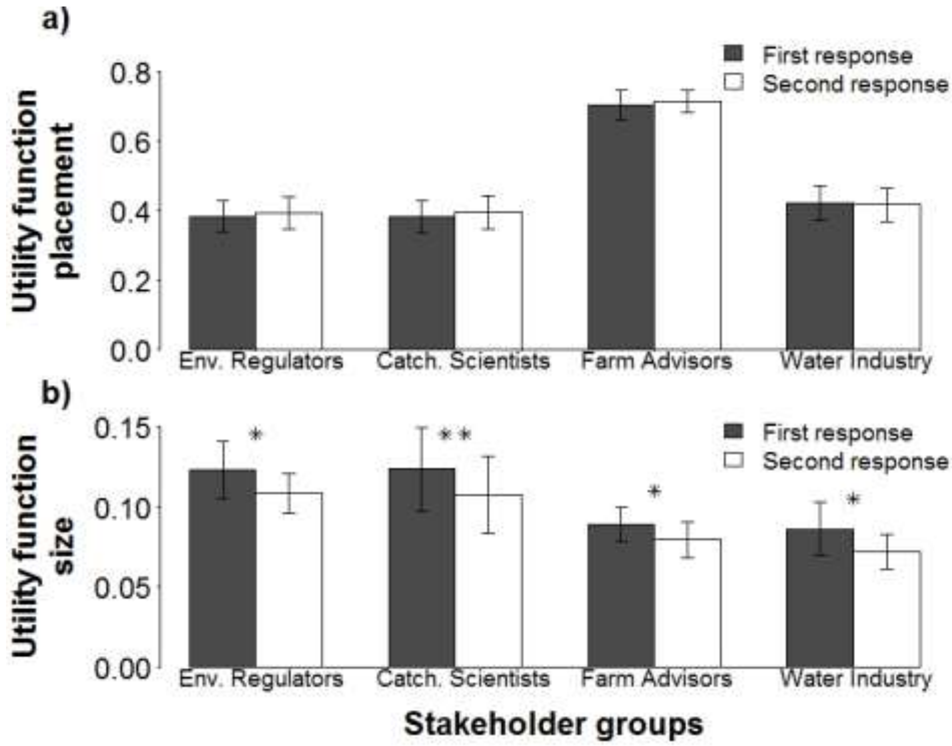

Fig. 4: Differences between (a) the position, and (b) the size of the utility functions from those participants (n=16) that used the threshold function both for their first (black) and second (white) response. Significantly different pairs are given at $p<0.05$* and $p<0.01$**. Error bars indicate ± 1 standard error.

When collating all responses from stakeholders, the combined PPF from the first exercise (Fig. 5a) represented an intermediate shape between the two dominant responses (logistic decay and threshold curve) and its confidence intervals fell between intermediate and large, as those were the two most prevalent replies.

In both the first (Fig. 5a) and the second exercise (Fig. 5b), the utility functions of the four stakeholder groups were identified as being significantly different from one another ($p<0.001$, $H=59.83$ and 36.50 respectively). In exercise 1 (Fig. 5a) the utility functions for

Water Industry Staff, Environmental Regulators and Catchment Scientists (in that order) were all located in close proximity to one another at around 0.85 for ecological status and 0.45 for agricultural intensity, while utility functions for the farm advisory group were positioned towards greater agricultural intensity (~ 0.6).

Utility functions on the pre-defined threshold PPF in the second exercise (Fig. 5b) delivered consistent rank ordering of the four stakeholder groups with the first exercise. The utility functions were, however, shifted towards greater agricultural intensity while remaining at a similar ecological status, with the Farm Advisors now located at an agricultural intensity ~0.75 to 0.8. In both exercises the utility function for the Farm Advisors were placed on the area of the PPF curve where its slope started decreasing, but before the rapid decline of ecological status.

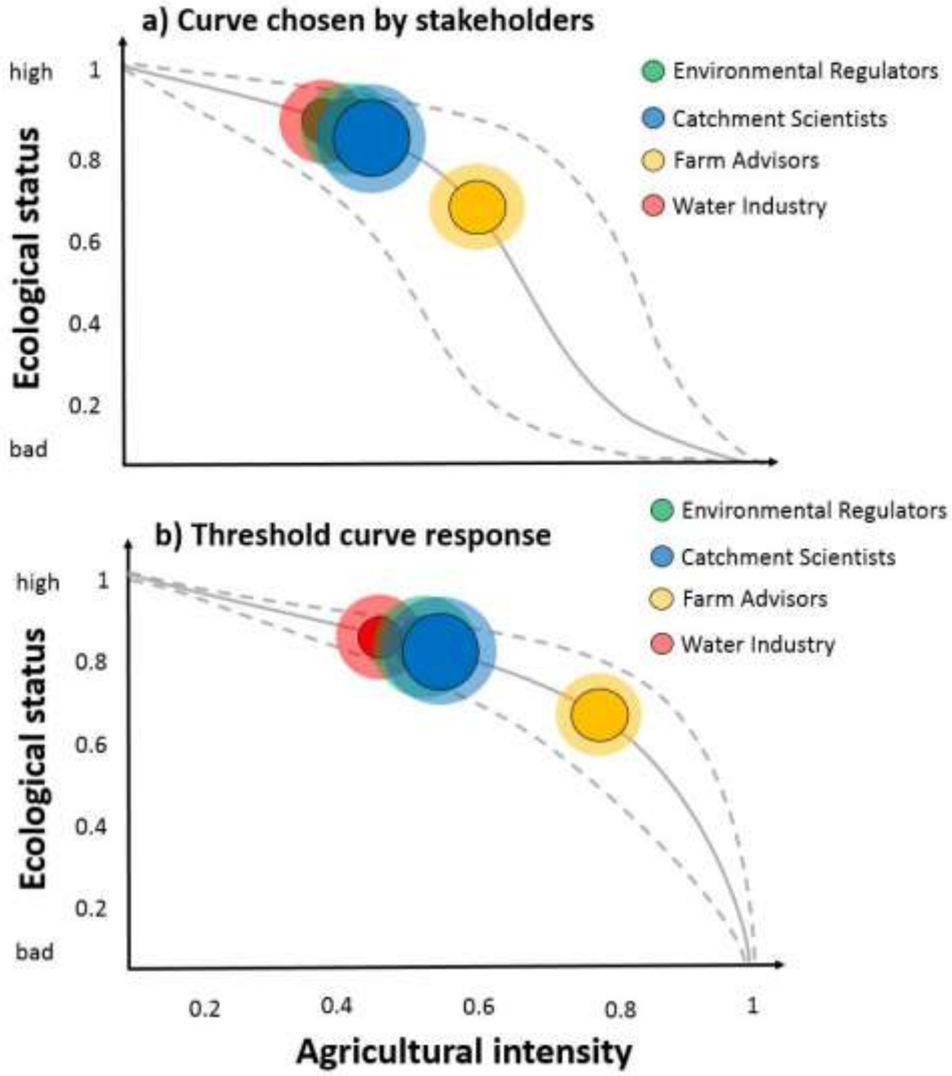

Fig. 5: Mean stakeholder responses of the four stakeholder groups' utility functions. The solid circles indicate where the four stakeholder groups were perceived to prioritise the trade-off (halos indicate + the standard error). The participants responded on a PPF curve (a) chosen by themselves, and (b) on the threshold PPF curve.

3.3 *Comparing responses depending on stakeholder grouping*

When stakeholders had to consider how they expected other stakeholder groups would perceive PPF functions, utility functions were placed differently depending on which stakeholder group the participant belonged to. This was the case on the threshold PPF in the second exercise (Fig. 6), however not when comparing responses from the first exercise where PPFs differed. Neither did utility functions differ significantly between the three study catchments in either exercise 1 or 2. In the second exercise, responses by Catchment Scientists were most similar to the mean (Fig. 6b), while Water Industry Staff placed their own utility function at higher ecological status (Fig. 6d). Compared to the mean, Environmental Regulators estimated the utility functions to be at higher agricultural intensity (Fig. 6a) while the Farm Advisors reported utility functions towards lower agricultural intensity (Fig. 6c).

Only the utility functions of Catchment Scientists were not perceived differently by the four stakeholder groupings. The utility functions of Farming Advisors were placed at significantly higher agricultural intensities by Environmental Regulators and significantly lower by Farm Advisors ($p<0.05$, $H=13.98$). Utility functions for Environmental Regulators and Water Industry Staff were also perceived differently depending on the group affiliation of the respondents ($p<0.001$, $H=15.91$ and 16.98 respectively).

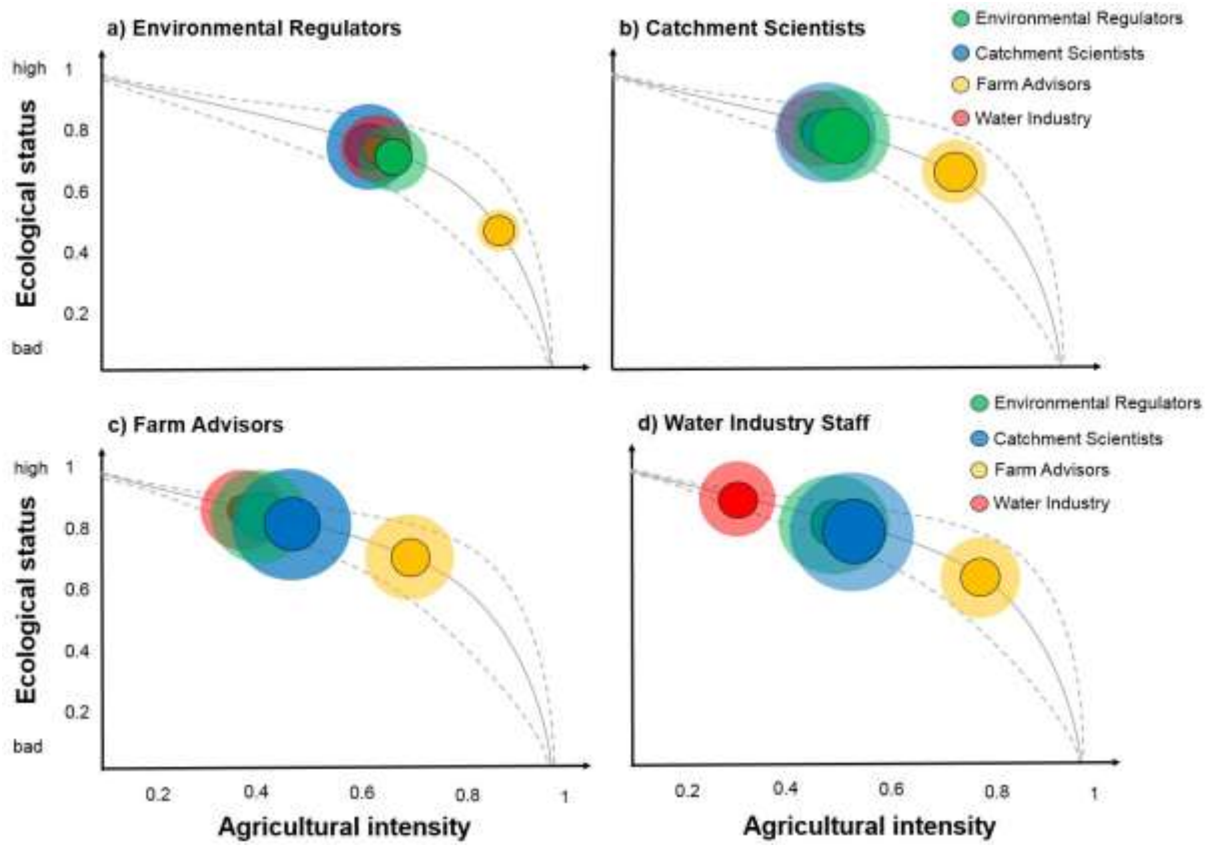

Fig. 6: Mean responses on the threshold PPF curve, by each stakeholder group: (a) Environmental Regulators, (b) Catchment Scientists, (c) Farm Advisors, and (d) Water Industry Staff. The solid circles indicate the perceived trade-off prioritisation of the four stakeholder groups (halos indicate + standard errors).

When comparing how participants viewed the utility functions of their own stakeholder group, as opposed to how the other three groups estimated them, a number of significant differences were identified (Fig. 7). Water Industry Staff scored their own utility functions at significantly higher ecological status compared to other groups' perceptions, both when they chose their own PPF ($p<0.05$, $W=33.0$), and particularly, on the threshold PPF ($p<0.05$, $W=36.0$). On the threshold PPF, Farm Advisors also scored their own utility functions at significantly lower agricultural intensity compared to others ($p<0.01$, $W=62.0$), while Environmental Regulators placed their own utility functions at significantly higher agricultural intensity compared to others ($p<0.05$, $W=45.0$). When comparing the mean differences of all utility function placements between stakeholder groups, the largest difference was between Environmental Regulators and Farm Advisors, while the responses of Catchment Scientists were most similar within their own group (Fig. 8; $p<0.001$, $H=175.96$). Utility function placement by Environmental Regulators was also more similar within their group while Farm Advisors and Water Industry Staff differences within their own group were more similar to the mean difference in utility function scoring.

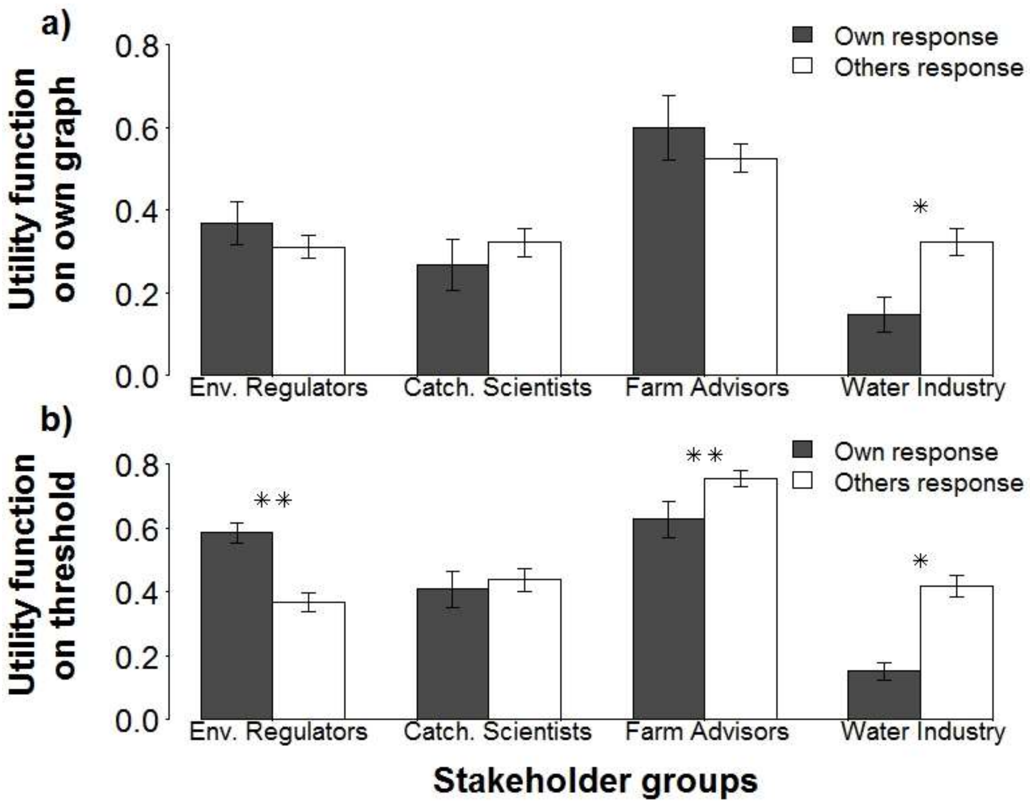

Fig. 7: Differences between the position of the utility functions on the x-axis of the trade-off graph, depending on whether they estimated their own group (black) vs. when others identified their stakeholder group (white), on both their first response using the graph chosen (a) by themselves, and (b) on the threshold curve. Significantly different pairs are given at p<0.05* and p<0.01**. Error bars indicate ± 1 standard error.

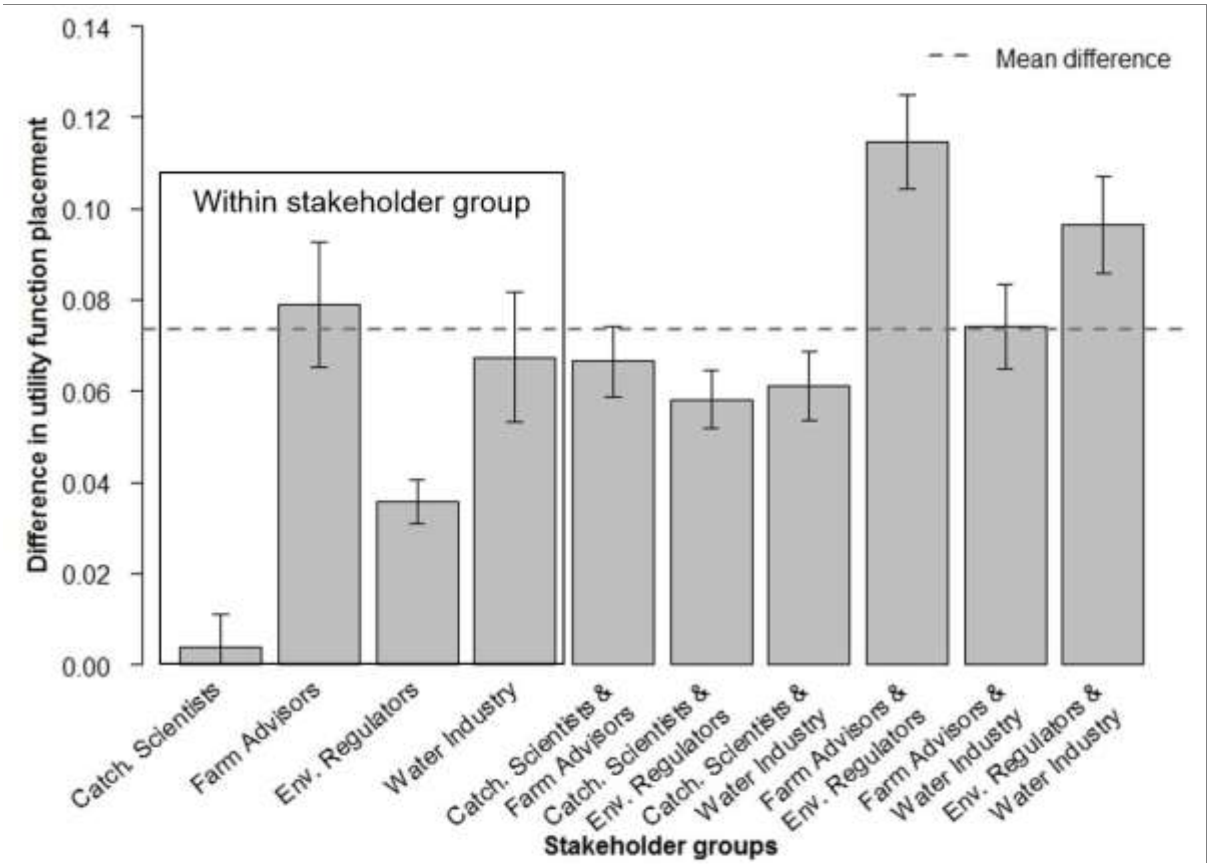

Fig. 8: Mean differences between utility function placements by individuals within their own stakeholder group, and between the other stakeholder groups. Error bars indicate ± 1 standard error.

3. Discussion

Using a novel mixed-method approach we have identified differences in trade-off prioritisations across the stakeholder groups surveyed, highlighting the importance of including participatory approaches in ecosystem service trade-off analysis. Expert judgment is vital for implementing the ecosystem service concept in practice and making use of existing knowledge and expertise may at times be preferable to collating large amounts of data through ecosystem service assessments (Jacobs *et al.* 2015). Our trade-off analysis was able to elicit robust responses as shown by the consistent rank ordering of the four stakeholder groups in both the self-determined PPF and the threshold PPF, as well as through the consistency in placement of the utility functions by the control group of participants who made a repeat response on the threshold function.

Our methodology provided a rapid and engaging method for assessing stakeholder perceptions, knowledge and preferences of an ecosystem service trade-off relationship while incorporating perceived social demand of the ecosystem service interaction by key stakeholder groups. The results highlighted differences in how stakeholder typologies view PPFs and utility functions in their catchment, indicating potential for conflict between stakeholders and possible barriers to integrated decision-making

The finding that a number of Farm Advisors did not agree in either of the proposed PPFs is of particular practical relevance for land and water management decision-making and further highlights the lack of a common underpinning understanding between some stakeholder groups and a need for ‘engagement as mediation’ (Reed *et al.* 2018). While farmers are aware of some of the effects of agriculture on aquatic health, their understanding may be more relevant for their day-to-day activities (Lamarque *et al.* 2011), and may benefit from strengthening their knowledge on how agricultural management effects ecological status of water bodies. Arguably, the agricultural advisors surveyed in our study have a greater understanding of the effects of agricultural intensification on the environment than regular farmers, but still show significantly differing views to other stakeholder groups. Farm advisors with in-depth knowledge of the effects of agricultural management on ecological status could act as intermediaries between environmental regulators and farmers and other farm advisors, since communicators with a shared worldview are more likely to resonate with that particular audience (Kahan *et al.* 2012).

If stakeholders do not agree on the underlying biophysical limits within a trade-off, they are unlikely to reach agreement when it comes to determining how the trade-off should be managed as divergent stakeholder perceptions act as a major barrier to collaboration (Porras *et al.* 2018). Estimating PPFs for contentious trade-offs could therefore provide a mechanism to improve stakeholder understanding of ecosystem functioning. Researchers could play a leading role here as actors to promote stakeholder cooperation and knowledge sharing, aid implementation of innovative land management practice, and advise the farming community on the environmental and socio-economic consequences from unsustainable agricultural practices (Schröter *et al.* 2015). This is supported by our findings that the Catchment Scientists responded not only most similarly within their group but their responses also corresponded closely to the mean from all stakeholders, which may indicate more precise and balanced insights into the socio-ecological system, reflecting their role as outside observers, seeking unbiased, objective descriptions of reality (Rose & Parsons 2015). Catchment Scientists were also the only group not to differ in where their utility function was placed by the other three stakeholder groups, which again perhaps reflects on their impartiality.

At a more theoretical level, the variability observed for the other stakeholder group responses may reflect the challenge of making cross-disciplinary trade-off assessments and the disciplinary nature of expertise partly informing the principle of expert judgements (Fish *et al.* 2009). Catchment Scientists also tended to select large confidence intervals while Environmental Regulators were more likely to select intermediate uncertainty around the mean of the PPF. Arguably, regulators and policy makers are less comfortable with acknowledging higher levels of uncertainty relative to those working in academic fields where communication of uncertainty is considered an important component of reporting results (Morss *et al.* 2005). Ecosystem service trade-off relationships are, however, complex and vary depending on heterogeneous and stochastic biogeophysical processes, but also due to spatial and temporal differences in land use, which introduces uncertainty into trade-off analysis and may have influenced the variability in the confidence intervals reported by our participants (Lu *et al.* 2014).

In our study participants had to estimate the potential impacts of increased agricultural intensity on WFD ecological status for their entire catchments. This contributed a large amount of uncertainty to their judgement, which is likely why we did not see any differences between catchments. This may be addressed in future studies, however, by estimating PPFs within a study catchment using spatially explicit models such as InVEST (Integrate Valuation of Ecosystem Services and Trade-offs) or SWAT (Soil and Water Assessment Tool; Cord *et al.* 2017). Given that measures we used in our application of the methodology were relatively broad and incorporated a number of ecosystem services, differences in stakeholder perception of these may have influenced the results as well. When interpreting the results it is important to remember that the stakeholder responses incorporated their cultural values, as well as their perception of the socio-economics of the trade-off and their views on the institutional specificities of their own and the other stakeholder groups. Incorporating expert judgements can deliver benefits to ecosystem service assessments; however, it may be difficult to disentangle such perceived judgements from the underlying socio-ecological processes. Although expert judgements are more liable to biases than other techniques due to tendencies such as overconfidence and anchoring (Mach *et al.* 2017), they may also assess trade-offs and uncertainties in ways that are not otherwise possible and can provide logical arguments to support their judgements (Singh *et al.* 2017). Expert knowledge may also provide time-integrated assessments, as opposed to momentary snapshots and can interpolate or extrapolate when ecosystem services may not be measured directly (i.e. Martin *et al.* 2012). Making use of a ‘thought experiment’, such as that used in our methodology, can extract stakeholder experience and acquired instinct to capture estimations which could not have been measured in the field.

There were also clear differences between Farm Advisors and Environmental Regulators in estimating utility functions. Farm Advisors scored utility functions toward lower agricultural intensity for their own, together with the other groupings; whereas the Environmental Regulators perceived all stakeholder groups to prefer higher agricultural intensity than the mean results suggested. Given the natural potential of these two groups for conflict due to their competing priorities, this misconception, or lack of understanding of the opposing group’s interests may further exacerbate tensions (Petersen-Perlman *et al.* 2017). These differences are likely due to the nature of their professions, for example, environmental regulators are driven by EU legislation to avoid declines in ecological status of water bodies, while a priority for farm advisors is often the financial viability of agricultural systems. This is an important point because respondents were asked to participate as professionals and not as individuals, though it is difficult to ascertain whether personal preference could ultimately influence their choice (Nordén *et al.* 2017). This is particularly true when ecosystem service interactions are antagonistic, which might lead to tensions and inconsistencies in professional judgements and personal views (Barnaud *et al.* 2018).

If land management policies continue to increasingly focus on providing multiple ecosystem services, farmers may end up as the main 'losers' due to reduced provisioning services, exacerbating conflicts between farmers and regulators (Kovács *et al.* 2015). Adapting the approach used in one-to-one interviews here for the context of a group discussion may therefore present an opportunity for stakeholders to articulate their utility functions and allow different organisations to improve their mutual understanding of each other's priorities and conflicting goals in a non-confrontational and abstract setting (Cebrián-Piqueras *et al.* 2017). Reducing bias in how stakeholders view their catchments could positively affect the capability of people to cooperate effectively and may, in turn, help to highlight 'win-win' opportunities in land and water management (Vallet *et al.* 2018). Although unprompted, when discussing PPFs and utility functions at the start of the exercise, a number of Farm Advisors, Environmental Regulators and Catchment Scientists mentioned that their work aims to change the shape of the PPF in their catchment to allow for higher agricultural intensity without compromising ecological status. The difference in the placement of utility functions on the threshold PPF illustrates this as utility functions shifted towards higher agricultural intensity without compromising ecological status. This presents a potential win-win opportunity, particularly between Farm Advisors and Environmental Managers to improve their utility functions by shifting the PPF through land-based management techniques, such as expansion of riparian buffer zones and agro-forestry, and increased production of legumes (Howe *et al.* 2014).

Arguably, the shape of the PPF can help determine how a trade-off should be managed, with more fragile relationships, such as an exponential decline pointing towards land sparing, while a more resilient relationship may allow more land sharing (Maskell *et al.* 2013). If a catchment is able to sustain greater agricultural intensity without compromising ecological status of its water bodies, it may be more resilient i.e. due to deep soils buffering agricultural inputs. The tendency of Farm Advisors to select the threshold PPF and for a number of them to disagree that increased agricultural intensity decreases ecological status, indicates that they believe their catchments to be relatively resilient and able to sustain larger amounts of agriculture without impacting ecological status, or even having a positive effect on it. This contrasted with Environmental Regulators who more frequently identified with the logistical decay function, which represents a more fragile relationship between the two services, and may imply that larger areas of the catchment should be given over to land-sparing and mitigation measures to ensure good ecological status.

The ease of application and simplicity of our methodology make it a promising approach for embedding stakeholder views into ecosystem service trade-off analysis. This is important because even though the recognition of the nuances and complexities of ecosystem service trade-offs has improved, quantitative evidence and an accurate characterisation of how ecosystem service interactions manifest is needed to ensure sustainable management of ecosystems and to maximise the benefits they provide to humans (Spake *et al.* 2017). Our approach also has generic transferability to allow for the capture of views from other users, such as local residents or tourists, as these stakeholders are often the most impacted by ecosystem service trade-offs (Turkelboom *et al.* 2018). This may be especially useful in assessing the impacts of potential management options on cultural ecosystem services, such as landscape aesthetics, which are inherently difficult to estimate.

The flexibility of this method means it may easily be applied to elicit stakeholder views on how an ecosystem reacts to other land use changes, environmental pressures, or more specific ecosystem services, such as increases in tree cover or point source pollution.

Although our approach is limited by only assessing the trade-off between two ecosystem services, future application of it could include multiple conflicting objectives. The methodology could also be used in conjunction with catchment modelling software to find optimum levels for certain ecosystem service provisioning, or with multi-objective programming to include PPFs of a number of trade-offs (e.g. Groot *et al.* 2018). Spatio-temporal simulation models such as InVEST (Han *et al.* 2017), ARIES (ARtificial Intelligence for Ecosystem Services; Villa *et al.* 2014), or SWAT (Francesconi *et al.* 2016) are often used to model ecosystem service trade-offs and their coupling to participatory research to help moderate outputs may provide a useful avenue for future research. We consider that this methodology could potentially be incorporated into awareness-raising programmes in catchments as part of a participatory approach to engage stakeholders. In doing so it could promote discussion of otherwise implicit decision-making, build shared mutual understanding to facilitate future cooperation, or assess whether stakeholders could be offered compensatory payments for utility losses (King *et al.* 2015; Brunet *et al.* 2018). The ease of use of the methodology could also allow for longitudinal analysis of how stakeholder perceptions change over time, which is an aspect of integrated catchment management that we know very little about (Stosch *et al.* 2017). Finally, allowing stakeholders to score utility functions on PPF curves offers a solution to integrating social demand into trade-off assessments, which often defy measurement and are hence widely underrepresented (Satz *et al.* 2013).

5. Conclusion

This study shows the importance of participatory trade-off analysis due to the differences in how stakeholders prioritise trade-off preferences arising from ecosystem service interactions. Valuing stakeholder knowledge as a form of expert data and integrating this into participatory decision-making processes for land and water management thus contributes considerable value beyond traditional approaches to ecosystem service assessments. Our results suggest that to achieve sustainable management of socio-ecological systems it is insufficient to focus on optimising ecosystem service trade-offs alone, as this fails to capture the social dimensions associated with end-user interactions when balancing the often competing demands of different stakeholder groups. Using participatory trade-off analysis can therefore reveal potential sources of conflict and/or synergies between stakeholder groups. In turn, approaches like this can support interdisciplinary research to better our understanding of the socio-ecological complexity of catchment systems and the management of ecosystem service interactions to deliver multiple benefits for stakeholders with differing environmental management remits.

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