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1 **Quantifying stakeholder understanding of an ecosystem service trade-off**

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29 **ABSTRACT**

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

53

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

## 56        **1. Introduction**

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

67        Interdependency between ecosystem services presents a principal challenge for sustainable  
68        landscape management (Cordingley *et al.* 2016). Interactions between provisioning and  
69        other ecosystem services are generally dominated by negative correlations or trade-offs, e.g.  
70        a decrease in runoff water quality with increased livestock grazing densities (Austrheim *et al.*  
71        2016), while synergies are often found between regulating and cultural services (Lee &  
72        Lautenbach 2016; Lin *et al.* 2018), such as the increase in biodiversity, pollination and  
73        biological pest control from flower strip planting (Westphal *et al.* 2015). Changes in land  
74        management to enhance a single service may often cause calculated but also inadvertent  
75        trade-offs, especially at larger spatial and temporal scales beyond those of the immediate  
76        management concern (Rodríguez *et al.* 2006). Agricultural intensification can, for example,  
77        negatively impact on pollinator diversity, which in turn can affect the yield of  
78        pollinator-dependent crops (Deguines *et al.* 2014). Trade-offs in river catchments are often  
79        expressed downstream of management decisions, and can lead to conflict between  
80        upstream and downstream users (Asquith *et al.* 2008). Downstream trade-offs maybe so  
81        severe that they become irreversible (Bennett *et al.* 2009), such as degraded aquatic  
82        ecosystems, which can, despite extensive restoration efforts, fail to recover to their original

83 reference state (Bernhardt & Palmer 2011). Therefore, investments in conservation,  
84 restoration and sustainable natural resource use are increasingly seen as ‘win-win’  
85 opportunities, generating substantial ecological, social and economic benefits (de Groot *et al.*  
86 *al.* 2010).

87 Multiple services, or bundles of ecosystem services, are often mapped to establish whether  
88 trade-offs exist based on co-occurrence (Raudsepp-Hearne *et al.* 2010; Turner *et al.*  
89 2014). This has led to an increased interest in the understanding and optimisation of  
90 ecosystem services for environmental management, with the aim of improving the delivery of  
91 regulating and cultural services without compromising provisioning services (Austin *et al.*  
92 2016; O’Sullivan *et al.* 2017; Weijerman *et al.* 2018). Catchments are, however, socio-  
93 ecological systems, and therefore a trade-off does not only arise due to relationships  
94 between ecosystem services, but also due to diverging stakeholder perceptions on  
95 ecosystem service provisioning (Martin-Lopez *et al.* 2012). Different stakeholder typologies  
96 may express varying preferences for ecosystem services, depending on their knowledge,  
97 values and connections to the landscape (Lamarque *et al.* 2011; García-Nieto *et al.* 2015).  
98 Stakeholders involved in agriculture in water-limited areas, for instance, are more aware of  
99 the ecosystem service benefits of maintaining water flows (Castro *et al.* 2014). Social  
100 contexts such as livelihoods, interests and traditions influence stakeholder perception of  
101 ecosystem services, which may lead to conflict among opposing stakeholder groups, i.e.  
102 between farmers and conservationists (Cebrián-Piqueras *et al.* 2017).

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

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

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

129 To our knowledge, there are no previous studies that assess stakeholder views on the shape  
130 of a PPF, or their perceptions on stakeholder utility functions within a trade-off. In response,  
131 we developed a novel stakeholder engagement methodology which elicits the perception of  
132 four key stakeholder groups working in land and water management. We quantified their  
133 assessment of both the shape and the uncertainty around the PPF in a trade-off between  
134 agricultural intensity and freshwater ecological health. We further quantified how participants  
135 perceived the utility functions of different stakeholder groups within that trade-off. Our  
136 objectives were to investigate stakeholder views to: (1) define the nature of, and the

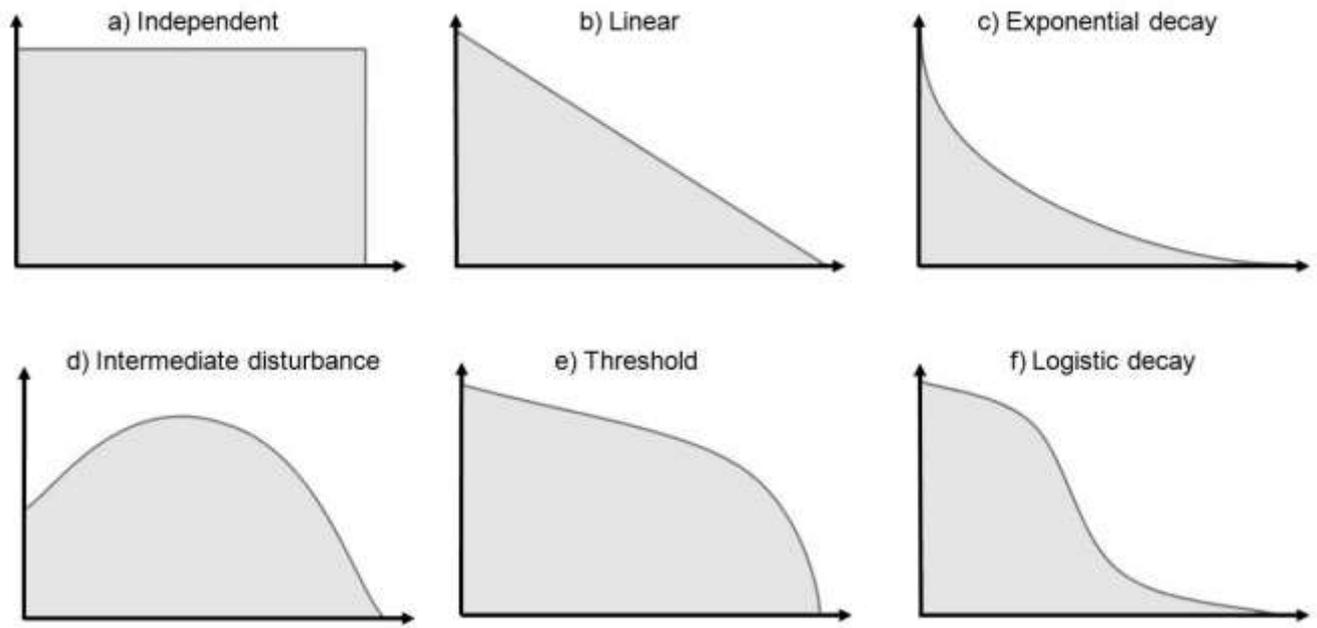
137 uncertainty associated with, a specific water and land management trade-off; (2) estimate  
138 stakeholder prioritisation of the trade-off; (3) quantify how views varied in different  
139 catchments and across different stakeholder groups; and (4) assess the practical relevance  
140 of this participatory methodology for land and water management planning and decision-  
141 making.

142

## 143 **2. Materials and methods**

### 144 *2.1 The 'production possibility frontier' (PPF) concept*

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

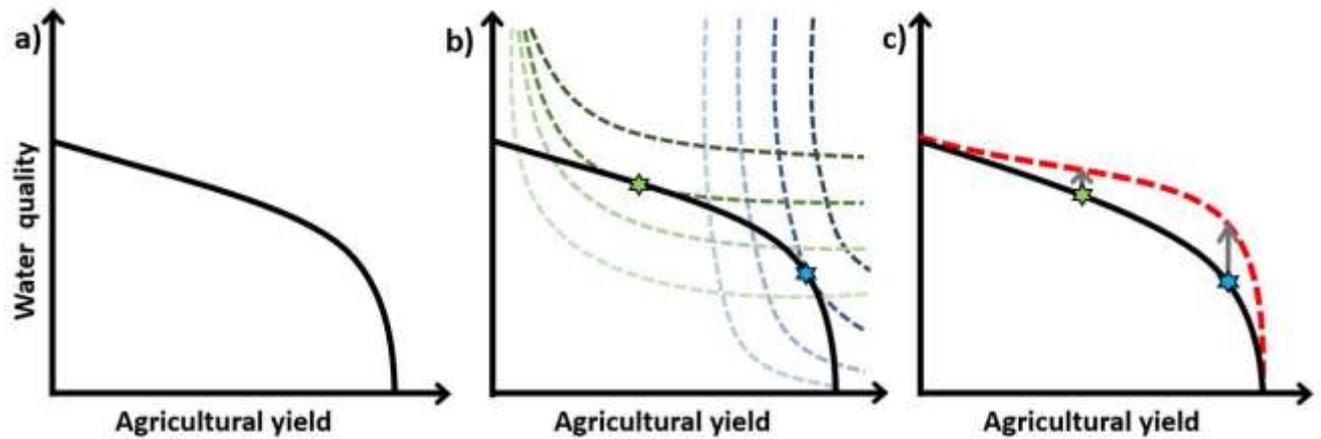


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155 **Fig. 1:** Illustrating the possible forms the trade-off between two ecosystem services may  
 156 take: (a) independent, (b) linear, (c) exponential decay, (d) intermediate disturbance  
 157 function, (e) threshold relationship, and (f) logistic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

158

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



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**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).

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## 2.2 Study catchments and stakeholder sample

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Three catchments from across Scotland were selected on account of their diverse geomorphologies, land cover types, stakeholder communities and land and water

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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

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~ 600 km<sup>2</sup> (South Esk and Ayr) to just under 3000 km<sup>2</sup> (Spey). Moors and heathland is the most dominant land cover type in the Spey (29%; Table 1) and the Esk catchment (33%),

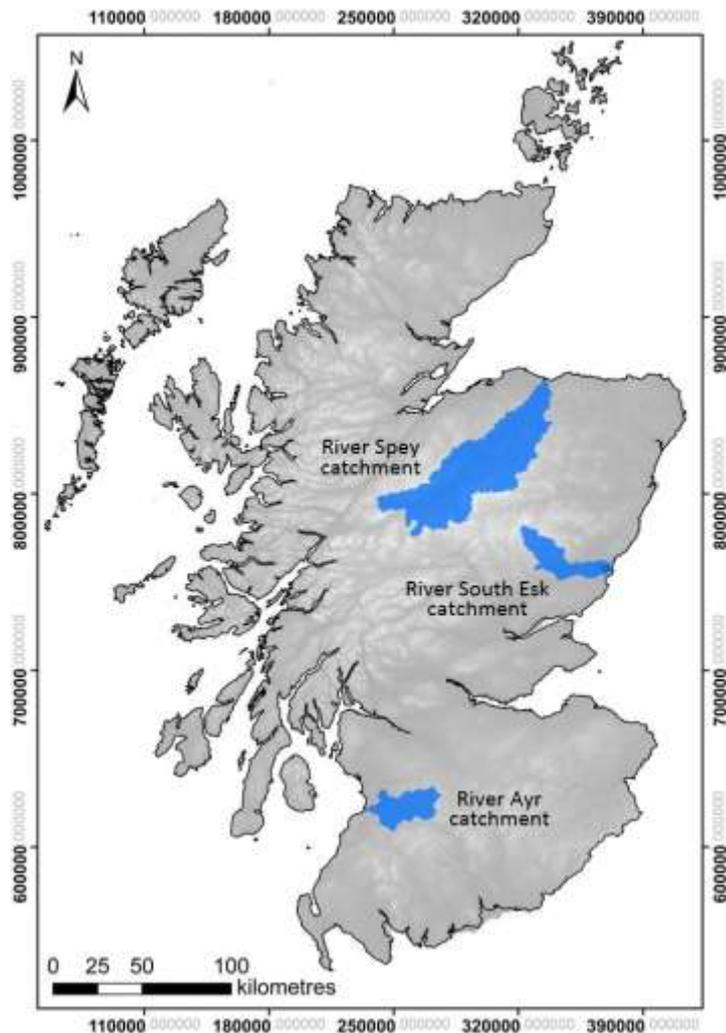
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followed by sparsely vegetated land in the mountainous areas of the Spey (23%) and arable land in the Esk catchment (31%). Dairy production is a key local industry in the Ayr

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catchment with pasture accounting for 39% of the land cover.

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

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

202

203 **Table 1:** Land cover types in the three study catchments as a percentage of overall area covered  
 204 (rounded to the nearest whole number).  
 205

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%

206

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

223 We investigated the trade-off between agricultural intensity and a measure of aquatic health,  
 224 because diffuse pollution from agriculture continues to challenge the ecological status of

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

### 237 *2.3 Questionnaire design and data collection*

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

245 The interviewer explained the axes to the participant and asked what they perceived the  
246 shape of the trade-off between those two factors to look like in their river catchment, under  
247 the current land management practices in their respective catchment and disregarding other  
248 management that may impact on ecological status, such as urban developments.  
249 Participants were required to select the shape (out of four options; Fig. 1b, c, e or f), that  
250 they considered best represented the true PPF in their catchment. The independent and  
251 intermediate disturbance shapes were not given as an option, as there is evidence that

252 increased agricultural intensity negatively impacts the ecological status of aquatic  
253 ecosystems (Stoate *et al.* 2009). On identifying a PPF typology to associate with the trade-  
254 off, participants were then asked to select 95% confidence intervals around the PPF, which  
255 could either be of small, intermediate or large uncertainty. This provided a measure of how  
256 confident they were that their chosen PPF corresponded to the true underlying PPF in their  
257 catchment.

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

269 After completing the first exercise, stakeholders were asked to complete the exercise a  
270 second time, however this time the shape of the trade-off was pre-determined and all  
271 participants were asked to place utility functions for the four stakeholder groups on the same  
272 PPF (Fig. 1e). The threshold PPF was selected here, due to findings from Ewing and Runck  
273 (2015) that this shape represented the relationship between agricultural yield and a measure  
274 of water quality (nitrate concentrations), in their study on corn production in the mid-western  
275 United States. Therefore, each participant completed two figures as outputs, (a) one PPF of  
276 their choice including confidence intervals and four utility functions and (b) one threshold  
277 PPF with four utility functions. This allowed better comparison of utility functions between  
278 participants as responses would be more comparable when recorded on the same PPF.

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

## 282 *2.4 Analysis*

283 The responses from all participants were converted to numerical values by measuring the  
284 distance to the start of the utility functions on the x-axis and the diameter of their utility  
285 function to the nearest millimetre after ensuring the plots were standardised in terms of their  
286 scale on the tablet computer. Both the measurements of utility function starting position and  
287 diameter were scaled to values from 0 to 1 by dividing values by the total length of the x-axis  
288 after which basic descriptive statistics were obtained and statistical analysis undertaken  
289 using SPSS version 23 (IBM 2012). To compare responses between catchments and  
290 stakeholder groups a non-parametric statistical test (Kruskall Wallis) was used, as variances  
291 were often significantly different per Levene's homogeneity of variances test. As 16  
292 participants chose the threshold PPF in the first exercise, which was also the PPF that all  
293 stakeholders responded to in the second exercise, their responses for the utility functions  
294 could be used as a control. For those responses, pair-wise comparisons were made  
295 between the utility functions from the first and second exercise using a Wilcoxon Signed  
296 Rank Test. The same test was used to compare within and between stakeholder group  
297 responses. Pearson's Chi-Squared Test of Association was used to analyse the association  
298 between the PPF and confidence intervals that were selected and which stakeholder  
299 grouping the respondents belonged to. The 'exponential decay' and 'linear' functions were  
300 chosen infrequently by participants and those typologies were therefore categorised as  
301 'others' for the purposes of statistical comparison of their count data with the 'logistic decay'  
302 and 'threshold curve' responses. Similarly, only the results for 'intermediate' and 'large'  
303 uncertainty intervals were compared, as counts for 'small' confidence intervals were  
304 insufficient for statistical analysis. Rstudio software version 1.1.453 was used to produce the  
305 bar plot charts (RStudio 2016).

306 **3. Results**

307 *3.1 Selection of the PPF and confidence intervals*

308 Most stakeholders selected either the logistic decay (40%) or the threshold function (37%) to  
309 describe the shape of the PPF in their catchment. Four participants from the Farm Advisor  
310 stakeholder group, however, did not agree with any of the four shapes, as two of them  
311 thought the PPF would follow more of an intermediate disturbance curve. Two other Farm  
312 Advisors agreed it was a threshold relationship, but that it would never reach bad ecological  
313 status even at the highest agricultural intensities. There was no significant association  
314 between the PPF function selected and the stakeholder group or the catchment that the  
315 participant was associated with (see Table 2 for a summary of all the statistical outputs).  
316 However, most Environmental Regulators (67%) selected the logistic decay, while most  
317 Farm Advisors (88%) selected either the threshold curve or did not agree with any of the  
318 shapes offered. The confidence intervals chosen by stakeholders were mostly the  
319 intermediate (49%) or large (44%) confidence intervals and there was no significant  
320 association between the uncertainty selected and the stakeholder group the participant  
321 belonged to. However, Catchment Scientists predominantly chose large confidence intervals  
322 (73%) while Environmental Regulators were more likely to select intermediate uncertainty  
323 around the PPF (69%). The other two stakeholder groups selected both intermediate and  
324 large confidence intervals at equal proportions with 45% of Farm Advisors and 44% of Water  
325 Industry Staff choosing intermediate uncertainty and 45% of Farm Advisors and 44% of  
326 Water Industry Staff selecting large uncertainty.

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

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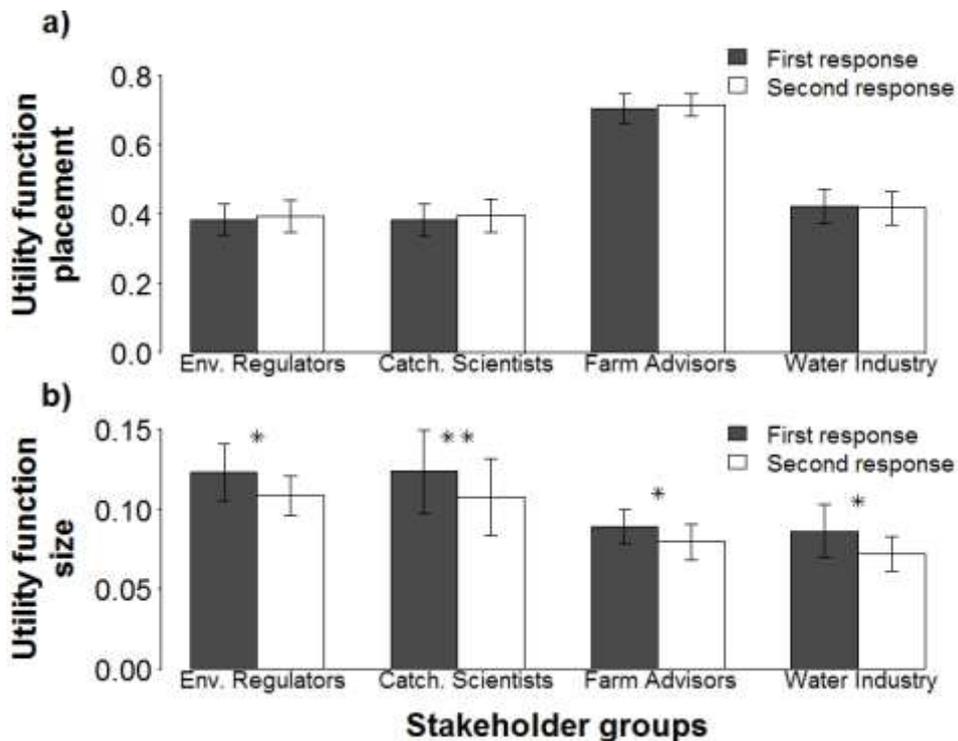
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332 **Table 2:** Summary of all the statistical testing undertaken in the study.

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

333 3.2 Utility function responses

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



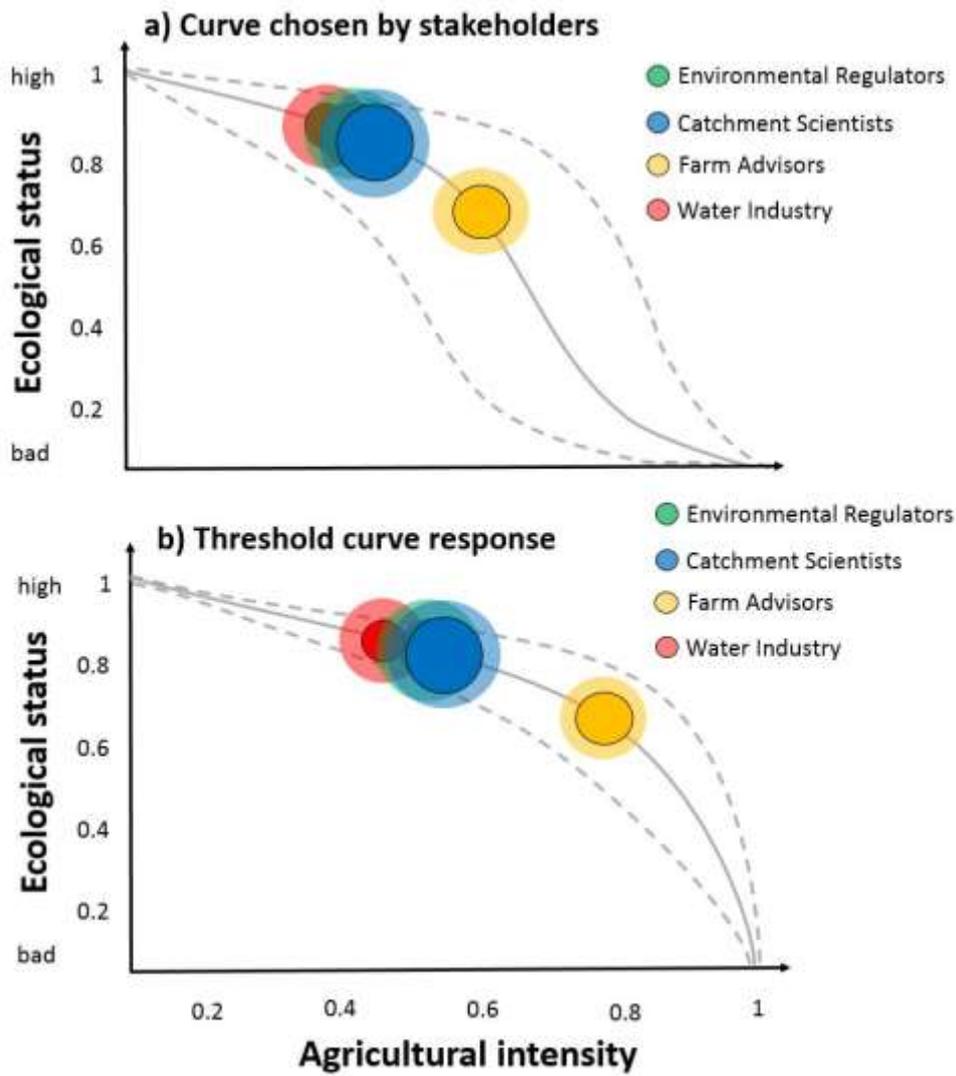
338 **Fig. 4:** Differences between (a) the position, and (b) the size of the utility functions from  
 339 those participants (n=16) that used the threshold function both for their first (black) and  
 340 second (white) response. Significantly different pairs are given at  $p < 0.05^*$  and  $p < 0.01^{**}$ .  
 341 Error bars indicate  $\pm 1$  standard error.  
 342

343  
 344 When collating all responses from stakeholders, the combined PPF from the first exercise  
 345 (Fig. 5a) represented an intermediate shape between the two dominant responses (logistic  
 346 decay and threshold curve) and its confidence intervals fell between intermediate and large,  
 347 as those were the two most prevalent replies.

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

351 Water Industry Staff, Environmental Regulators and Catchment Scientists (in that order)  
352 were all located in close proximity to one another at around 0.85 for ecological status and  
353 0.45 for agricultural intensity, while utility functions for the farm advisory group were  
354 positioned towards greater agricultural intensity (~ 0.6).

355 Utility functions on the pre-defined threshold PPF in the second exercise (Fig. 5b) delivered  
356 consistent rank ordering of the four stakeholder groups with the first exercise. The utility  
357 functions were, however, shifted towards greater agricultural intensity while remaining at a  
358 similar ecological status, with the Farm Advisors now located at an agricultural intensity  
359 ~0.75 to 0.8. In both exercises the utility function for the Farm Advisors were placed on the  
360 area of the PPF curve where its slope started decreasing, but before the rapid decline of  
361 ecological status.



362

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

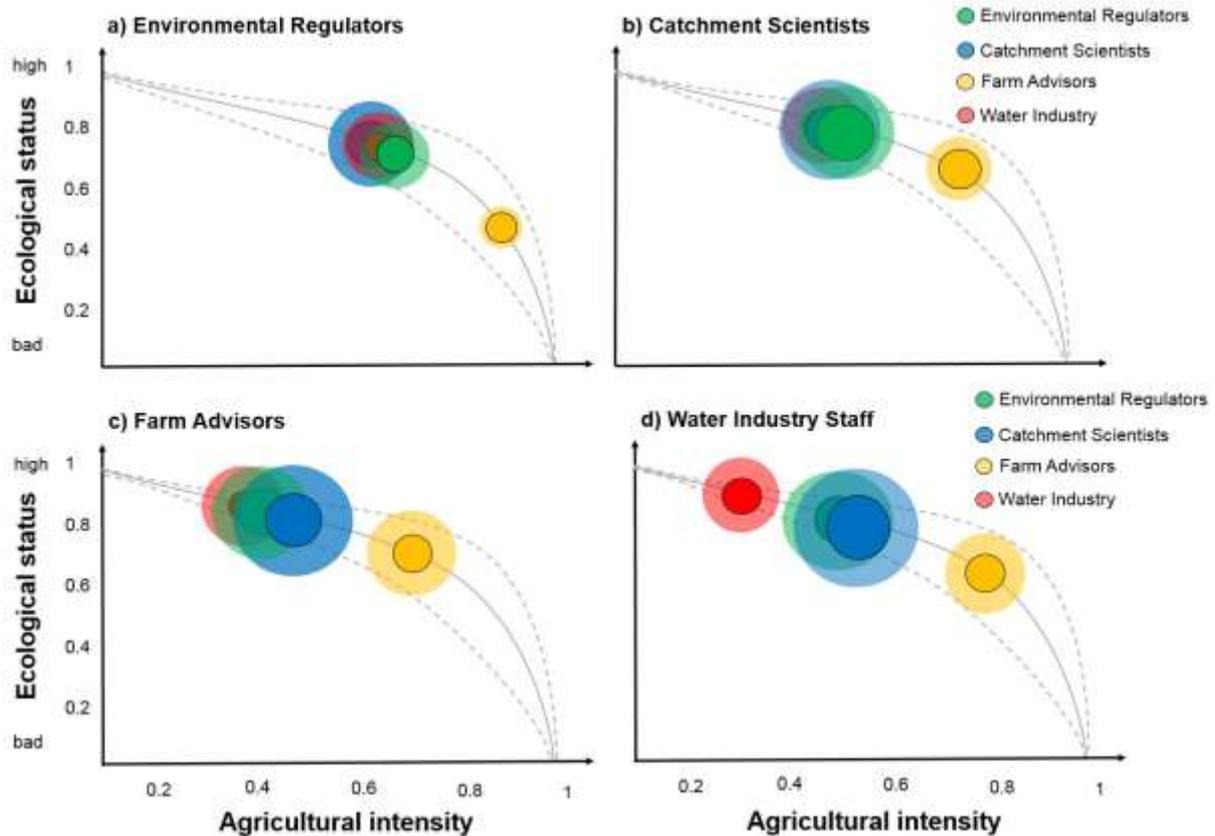
367

368 3.3 Comparing responses depending on stakeholder grouping

369

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

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



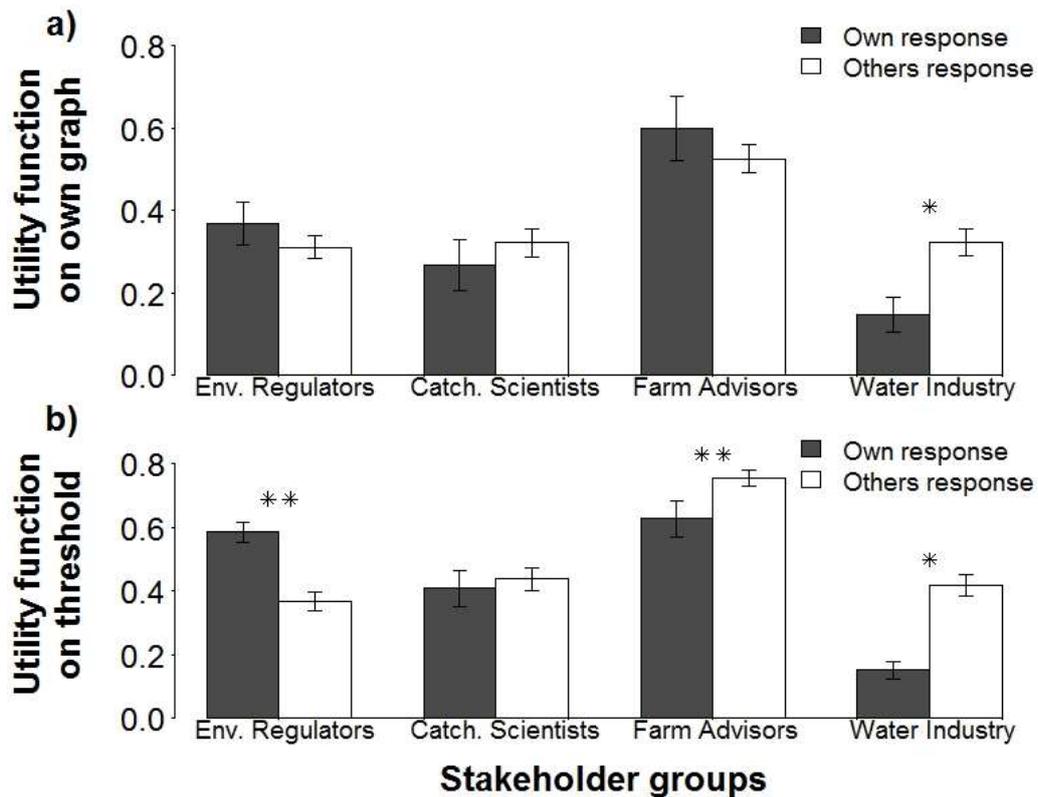
387

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

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

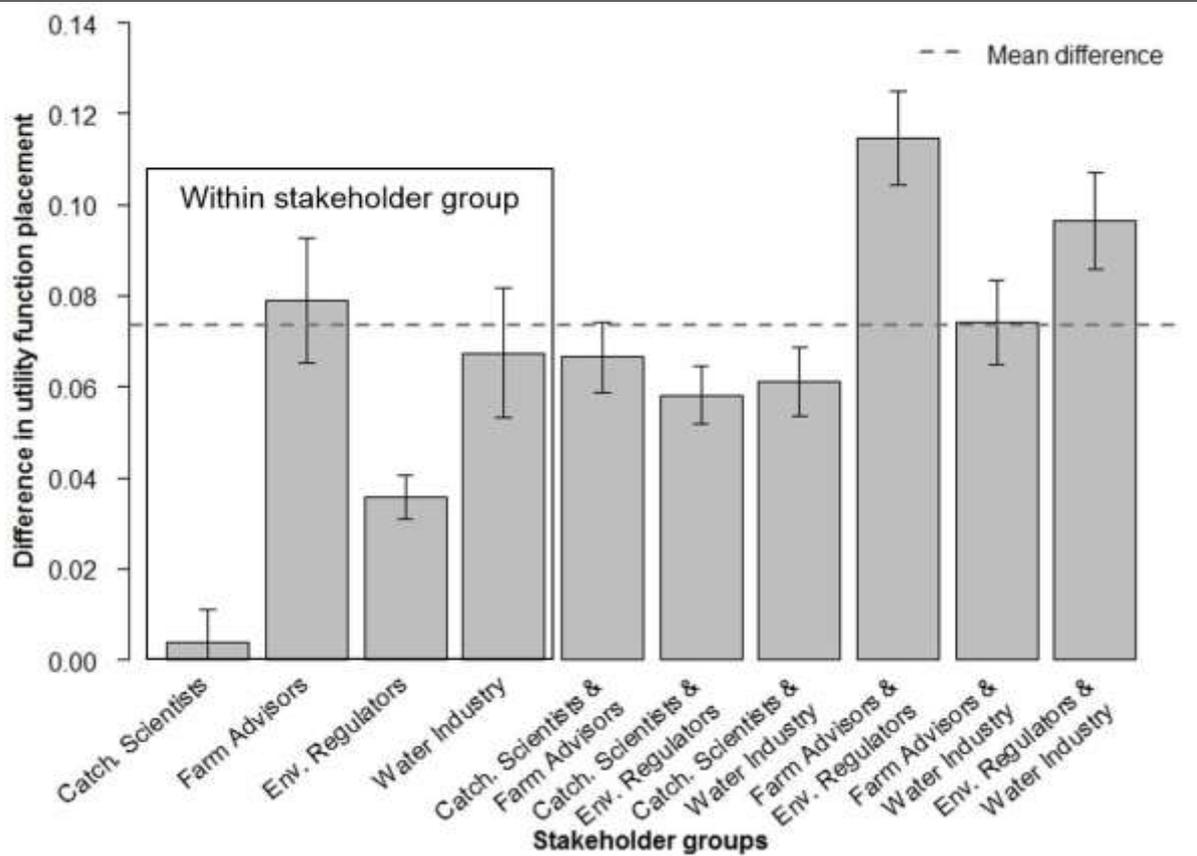
404 placement by Environmental Regulators was also more similar within their group while Farm  
 405 Advisors and Water Industry Staff differences within their own group were more similar to the  
 406 mean difference in utility function scoring.

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**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  $\pm 1$  standard error.



415

416 **Fig. 8:** Mean differences between utility function placements by individuals within their own  
 417 stakeholder group, and between the other stakeholder groups. Error bars indicate  $\pm 1$   
 418 standard error.

419

420 **3. Discussion**

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

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

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

451 If stakeholders do not agree on the underlying biophysical limits within a trade-off, they are  
452 unlikely to reach agreement when it comes to determining how the trade-off should be  
453 managed as divergent stakeholder perceptions act as a major barrier to collaboration  
454 (Porrás *et al.* 2018). Estimating PPFs for contentious trade-offs could therefore provide a  
455 mechanism to improve stakeholder understanding of ecosystem functioning. Researchers  
456 could play a leading role here as actors to promote stakeholder cooperation and knowledge  
457 sharing, aid implementation of innovative land management practice, and advise the farming

458 community on the environmental and socio-economic consequences from unsustainable  
459 agricultural practices (Schröter *et al.* 2015). This is supported by our findings that the  
460 Catchment Scientists responded not only most similarly within their group but their  
461 responses also corresponded closely to the mean from all stakeholders, which may indicate  
462 more precise and balanced insights into the socio-ecological system, reflecting their role as  
463 outside observers, seeking unbiased, objective descriptions of reality (Rose & Parsons  
464 2015). Catchment Scientists were also the only group not to differ in where their utility  
465 function was placed by the other three stakeholder groups, which again perhaps reflects on  
466 their impartiality.

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

480 In our study participants had to estimate the potential impacts of increased agricultural  
481 intensity on WFD ecological status for their entire catchments. This contributed a large  
482 amount of uncertainty to their judgement, which is likely why we did not see any differences  
483 between catchments. This may be addressed in future studies, however, by estimating PPFs  
484 within a study catchment using spatially explicit models such as InVEST (Integrate Valuation

485 of Ecosystem Services and Trade-offs) or SWAT (Soil and Water Assessment Tool; Cord *et*  
486 *al.* 2017). Given that measures we used in our application of the methodology were relatively  
487 broad and incorporated a number of ecosystem services, differences in stakeholder  
488 perception of these may have influenced the results as well. When interpreting the results it  
489 is important to remember that the stakeholder responses incorporated their cultural values,  
490 as well as their perception of the socio-economics of the trade-off and their views on the  
491 institutional specificities of their own and the other stakeholder groups. Incorporating expert  
492 judgements can deliver benefits to ecosystem service assessments; however, it may be  
493 difficult to disentangle such perceived judgements from the underlying socio-ecological  
494 processes. Although expert judgements are more liable to biases than other techniques due  
495 to tendencies such as overconfidence and anchoring (Mach *et al.* 2017), they may also  
496 assess trade-offs and uncertainties in ways that are not otherwise possible and can provide  
497 logical arguments to support their judgements (Singh *et al.* 2017). Expert knowledge may  
498 also provide time-integrated assessments, as opposed to momentary snapshots and can  
499 interpolate or extrapolate when ecosystem services may not be measured directly (i.e.  
500 Martin *et al.* 2012). Making use of a ‘thought experiment’, such as that used in our  
501 methodology, can extract stakeholder experience and acquired instinct to capture  
502 estimations which could not have been measured in the field.

503 There were also clear differences between Farm Advisors and Environmental Regulators in  
504 estimating utility functions. Farm Advisors scored utility functions toward lower agricultural  
505 intensity for their own, together with the other groupings; whereas the Environmental  
506 Regulators perceived all stakeholder groups to prefer higher agricultural intensity than the  
507 mean results suggested. Given the natural potential of these two groups for conflict due to  
508 their competing priorities, this misconception, or lack of understanding of the opposing  
509 group’s interests may further exacerbate tensions (Petersen-Perlman *et al.* 2017). These  
510 differences are likely due to the nature of their professions, for example, environmental  
511 regulators are driven by EU legislation to avoid declines in ecological status of water bodies,

512 while a priority for farm advisors is often the financial viability of agricultural systems. This is  
513 an important point because respondents were asked to participate as professionals and not  
514 as individuals, though it is difficult to ascertain whether personal preference could ultimately  
515 influence their choice (Nordén *et al.* 2017). This is particularly true when ecosystem service  
516 interactions are antagonistic, which might lead to tensions and inconsistencies in  
517 professional judgements and personal views (Barnaud *et al.* 2018).

518 If land management policies continue to increasingly focus on providing multiple ecosystem  
519 services, farmers may end up as the main 'losers' due to reduced provisioning services,  
520 exacerbating conflicts between farmers and regulators (Kovács *et al.* 2015). Adapting the  
521 approach used in one-to-one interviews here for the context of a group discussion may  
522 therefore present an opportunity for stakeholders to articulate their utility functions and allow  
523 different organisations to improve their mutual understanding of each other's priorities and  
524 conflicting goals in a non-confrontational and abstract setting (Cebrián-Piqueras *et al.* 2017).

525 Reducing bias in how stakeholders view their catchments could positively affect the  
526 capability of people to cooperate effectively and may, in turn, help to highlight 'win-win'  
527 opportunities in land and water management (Vallet *et al.* 2018). Although unprompted,  
528 when discussing PPFs and utility functions at the start of the exercise, a number of Farm  
529 Advisors, Environmental Regulators and Catchment Scientists mentioned that their work  
530 aims to change the shape of the PPF in their catchment to allow for higher agricultural  
531 intensity without compromising ecological status. The difference in the placement of utility  
532 functions on the threshold PPF illustrates this as utility functions shifted towards higher  
533 agricultural intensity without compromising ecological status. This presents a potential win-  
534 win opportunity, particularly between Farm Advisors and Environmental Managers to  
535 improve their utility functions by shifting the PPF through land-based management  
536 techniques, such as expansion of riparian buffer zones and agro-forestry, and increased  
537 production of legumes (Howe *et al.* 2014).

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

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

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

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

585

586

## 587 **5. Conclusion**

588 This study shows the importance of participatory trade-off analysis due to the differences in  
589 how stakeholders prioritise trade-off preferences arising from ecosystem service  
590 interactions. Valuing stakeholder knowledge as a form of expert data and integrating this into

591 participatory decision-making processes for land and water management thus contributes  
592 considerable value beyond traditional approaches to ecosystem service assessments. Our  
593 results suggest that to achieve sustainable management of socio-ecological systems it is  
594 insufficient to focus on optimising ecosystem service trade-offs alone, as this fails to capture  
595 the social dimensions associated with end-user interactions when balancing the often  
596 competing demands of different stakeholder groups. Using participatory trade-off analysis  
597 can therefore reveal potential sources of conflict and/or synergies between stakeholder  
598 groups. In turn, approaches like this can support interdisciplinary research to better our  
599 understanding of the socio-ecological complexity of catchment systems and the  
600 management of ecosystem service interactions to deliver multiple benefits for stakeholders  
601 with differing environmental management remits.

602

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607

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