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1 **Ecological research and environmental management: we need different**  
2 **interfaces based on different knowledge types**

3

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22

23 **Abstract**

24 The role of ecological science in environmental management has been discussed by many  
25 authors who recognize that there is a persistent gap between ecological science and  
26 environmental management. Here we develop theory through different perspectives based on  
27 knowledge types, research categories and research–management interface types, which we  
28 combine into a common framework. To draw out insights for bridging this gap, we build our  
29 case by:

30 1– explicitizing the link between three categories of ecological research and the type  
31 of research–management interface they are associated with. We first evaluate three types of  
32 unidirectional interfaces and recommend a new kind of interface – called the Research-  
33 Within-Management interface (RWM).

34 2– suggesting that adaptive management and structured decision-making can integrate  
35 all these different angles and serve as meta-interfaces in their relation to research.

36 3– distinguishing explanatory knowledge from empirical knowledge, and contending  
37 that explanatory knowledge is not necessarily the most important output for the research-  
38 management interface today.

39 4– highlighting that experiential ecological knowledge—including the expertise and  
40 experience of managers, citizens and scientists—is another primary knowledge input in  
41 environmental decision-making that should not be systematically downplayed  
42 We point out the complementarities as well as the specificities and limitations of the different  
43 types of ecological research, ecological knowledge and research–management interfaces,  
44 which is of major importance for environmental management and research policies.

45

46 **Keywords**

- 47 environmental management; management-integrated research; monitoring; adaptive
- 48 management; ecological knowledge; research–management boundary.

49 **1. Introduction**

50 The role of ecological science in environmental management\*<sup>1</sup>— hereafter also referred to as  
51 ‘management’— has been discussed by many authors who recognize that there is a persistent  
52 gap between the two (Hart and Calhoun, 2010; Hulme, 2014; Underwood, 1995, 1998; Van  
53 Kerkhoff and Lebel 2006). These authors stress that ecological scientific knowledge\* is not  
54 sufficiently taken into account in environmental management (Bestelmeyer et al. 2003;  
55 Murphy and Noon, 1991; Sutherland et al., 2004; Underwood, 1995). This gap leads to  
56 situations where despite scientific advances, we still often fail to manage natural ecosystems  
57 in a sustainable way (Bunnell and Huggard, 1999; Howes et al., 2017; Ludwig, 2001; Ludwig  
58 et al., 1993; Prendergast et al., 1999). The gap is also manifest when environmental  
59 managers\*— also referred to hereafter as ‘managers’— from around the world call for more  
60 useful information (Cash et al., 2003; McNie, 2007).

61 Several reasons may explain this situation. First, scientific knowledge is not the only factor in  
62 decision-making. Many decisions are affected by values, belief systems or political issues  
63 unrelated to scientific knowledge (Gregory et al., 2012; Hart and Calhoun, 2010; Ludwig,  
64 2001; Ludwig et al., 1993, Walters, 2007). Furthermore, environmental management is not  
65 usually based on ecology-first decisions (Ludwig et al., 1993; Young et al., 2014): the  
66 economic and social aspects of sustainability often outweigh the ecological ones (Dovers et  
67 al., 1996). Lastly, the ecological basis for sustainable management remains weak due to the  
68 fact that interactions between ecological research and environmental managers are not as  
69 effective as they might be (Bunnell and Huggard, 1999; Dovers et al., 1996).

70 The literature has advanced four proposals—from contrasting points of view—to provide a  
71 better account of ecological science in management:

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<sup>1</sup> A star \*flags the first occurrence of words that we define in the Glossary found in Supplementary Material Appendix SM1.

72 (P1) Some authors stress that the a priori (or explanatory) credibility\* of a scientific  
73 result, judged on the coherence and appeal of its concepts\* and mechanisms\*, is not  
74 sufficient for environmental management and would be better supplemented by empirical  
75 knowledge\* (see Graham et al., 2006; Hulme, 2014; Roux et al., 2006), which is knowledge  
76 based on observation or analysis of real data, i.e. data observed in the field or in field-or-lab  
77 experiments (cf. Figure 1). Empirical knowledge includes both evidential (or evidence-based)  
78 knowledge\*, generated by empirical scientific research, and experiential knowledge\*,  
79 resulting from ordinary experience or “isolated” random observations without any relation to  
80 any predetermined hypothesis or theory\*. In what follows, we define a theory as a system of  
81 conceptual constructs that organizes and explains the observable phenomena in a stated  
82 domain of interest (Pickett et al., 2007) and puts forward potentially falsifiable predictions  
83 (Driscoll and Lindenmayer, 2011). A theory therefore incorporates not only an explanatory  
84 part but also an empirical part that has two components: (i) the observable phenomena that  
85 helped frame the theory through induction and (ii) unsuccessful attempts to refute the theory,  
86 which constitutes its evidential base. The credibility of a scientific result or theory  
87 (Watanabe, 1975) can be broken down into *a priori* explanatory credibility, based on “extra-  
88 evidential”, “a-rational” factors (aesthetics, theoretical coherence...) and *a posteriori*  
89 evidential credibility. Although Watanabe (1975) developed the notion of credibility within a  
90 probabilistic and academic framework, it remains valuable outside these frameworks, in  
91 particular regarding the application of scientific knowledge.

92 (P2) Other authors consider that not all types of interfaces between research and  
93 management (see Table 1) provide efficient links between ecological results and management  
94 practices. In what follows, we define an interface as both “the place at which independent and  
95 often unrelated systems meet and act on or communicate with each other”, which is close to  
96 the notion of boundary, and “the means by which interaction or communication is achieved at

97 an interface” (Merriam-Webster’s Collegiate Dictionary, 10th Edition), which is related to  
98 the notion of boundary work. The notions of interface and boundary naturally emerge as soon  
99 as we recognize that research and management are very different in many regards (e.g.  
100 evaluation systems, risks involved, temporal horizon, public scrutiny and opinion) (Cash et  
101 al., 2003). Cash et al. (2003) insisted that conscientious work needs to be done at the  
102 boundary between research and decision making, while Roux et al. (2006), Van Kerkhoff and  
103 Lebel (2006), and Hart and Calhoun (2010) stressed that classical unidirectional interfaces  
104 from research to management are not sufficient to appropriately integrate scientific  
105 knowledge into environmental management.

106 (P3) Focusing on the research side of the interface, Underwood (1995) believes that  
107 recognizing four different categories of ecological research would enhance interactions  
108 between ecological research and management decisions (see Table 1 and Figure 2). Category  
109 1 research (R1) is either “directed to the needs of management” or refers to existing results  
110 from ecological research that managers may find useful to “evaluate problems, validate the  
111 questions and formulate models of the system being managed” (Underwood, 1995, Figure 11,  
112 p.234). Category 2 research (R2) is mobilized within management, when management  
113 practices become relevant hypotheses that need to be tested rather than proven “solutions”. If  
114 these management hypotheses fail, Category 3 research (R3) aims to develop new ecological  
115 knowledge in order to explain the management failure observed. Category 4 research (R4) is  
116 “managerial”, and carries two strands: 1) ecologists analyze *a posteriori* how the ecological  
117 information is used by managers to reach their decisions; and 2) social scientists investigate  
118 how the management decision process works.

119 (P4) Some authors have insisted that comprehensive management frameworks such as  
120 adaptive management (Bormann et al., 1999; McNie, 2007; Rist et al., 2013a, 2013b; Stankey  
121 et al., 2005; Walters and Holling 1990) or structured decision-making (Failing et al., 2013;

122 Gregory et al., 2012) are key to a better connection between ecological research and  
123 environmental management, as they can orchestrate different research categories and  
124 research–management interfaces in a structured way around a given management problem.

125         Although partly connected, these four proposals (P1 to P4) have never, to our  
126 knowledge, been considered simultaneously. In this paper, we link them by asking the  
127 following questions: How do research-management interfaces (P2) integrate the different  
128 types of ecological knowledge (P1), research categories (P3) and practice? What viable meta-  
129 interface mobilizes multiple interface types (P4)? We answer these questions from the  
130 position of ecological scientists—referred to hereafter as ‘ecologists’ or ‘researchers’—who  
131 are concerned with appropriate use of ecological knowledge for environmental management.  
132 Answering these research questions has led us to propose a new, bidirectional interface type  
133 which we call the Research-Within-Management interface (RWM).

134         Proposals P1 to P4 deal with different but complementary ingredients of research–  
135 management interactions, so linking them within a coherent framework may valuably  
136 improve the uptake of ecological knowledge (both scientific and non-scientific) in  
137 environmental management. We propose three main ways to establish this link:

138         (i) In sections 2 to 3, we explicitly connect Underwood’s first three categories of  
139 ecological research R1 to R3 (P3) with different types of research–management interfaces  
140 (P1; see Table 1, Figure 2): R1 with the transfer-and-translate interface\*, R3 with the user-  
141 push interface\*. For R2, we introduce the RWM interface type to distinguish real integrated  
142 R2 projects, where the variable to be tested is the management practice itself, from R1  
143 projects, where the variable to be tested, though linked to management, is not a management  
144 practice. R4 (“managerial ecological research”) will not be developed in this paper because it  
145 is positioned at a higher level of integration involving social science that we do not  
146 extensively address here. Our position—centered on the interface between *ecological*



147 research and management—enables us to keep a sharper focus in terms of the types of  
148 knowledge involved, both scientific and experiential.

149 (ii) In section 4, we show how adaptive management, and more generally structured  
150 decision-making, can be considered *in their relationship with research* as meta-interfaces (P4  
151 and P1) since they can mobilize all the above-mentioned interface types during different  
152 phases of the management process.

153 (iii) Finally, in sections 2 and 5, we discuss the importance of the various types of  
154 scientific and non-scientific ecological knowledge (P2) as inputs for the interface types (P1)  
155 (see Figure 2). We especially consider the value of including experiential ecological  
156 knowledge, encompassing managers', citizens' and scientists' expertise. We also question the  
157 role evidential knowledge and explanatory knowledge play in Underwood's categories, and  
158 discuss their respective strengths for management.

159

## 160 **2. Assessment of unidirectional interface types**

161 Managers readily use ecological results, mainly of R1 type, in two types of research–  
162 management interfaces defined by Van Kerkhoff and Lebel (2006), called trickle-down\*  
163 (TD) and transfer-and-translate\* (TT), both of which are unidirectional, i.e. from research to  
164 management. TD often applies scientific knowledge based on a blind confidence in scientific  
165 credibility. In particular, TD does not differentiate between explanatory credibility and  
166 evidential credibility, and implicitly favors the former for its appeal and flexibility (cf. *infra*).  
167 We will also see that TT pays more attention to the evidential credibility of knowledge.  
168 Lastly, when managers do not find suitable scientific knowledge, they can ask research to  
169 produce new knowledge: this is done through another kind of unidirectional interface type  
170 called 'user-push'.

171

172 **2.1 The trickle-down interface and Category-1 research: A straightforward but**  
173 **oversimplistic interface type**

174 In TD, also known as the linear model in ecology (Barot et al., 2015; Pielke, 2007),  
175 the application of scientific knowledge to environmental management is mostly  
176 straightforward: when researchers produce research, users\* can adopt it without further effort  
177 from the research community (Figure 3a). This case corresponds to Strategy 1 ecological  
178 research *sensu* Hart and Calhoun (2010), where ecological research is conducted with  
179 minimal attention to users' needs or decision-making processes. There is no real interaction  
180 in this case, as researchers publish for academic peers only, independently of topics of  
181 interest to users, while users are left to consult the available academic publications. In this  
182 respect, in TD, there is no real need to distinguish Underwood's R1 from other types of  
183 ecological research results (see Table 1): managers will use some of the research published  
184 regardless of whether or not it is specifically directed to them, and there is no need to  
185 evaluate or translate the results in terms of applicability.

186

187 **2.1.1 Why the trickle-down interface is so popular**

188 The first reason TD is so popular is that new theories clearly provide managers with  
189 fresh perspectives and frameworks to better handle their daily management concerns. If  
190 correctly framed and well defined (Driscoll and Lindenmayer, 2011), theories can effectively  
191 help managers organize the information they learn through different case studies or  
192 experiments (Belovsky et al., 2004).

193 Second, TD is popular because of the way ecology promotes, presents and evaluates its  
194 results. Data confirming ecologically "fashionable" theories are likely to be more published  
195 and cited than data contradicting such theories (Fahrig, 2017b; Hall, 1988, Fahrig 2017b),  
196 which leads to the well-known publication bias in meta-analyses (Rothstein et al., 2005).

197 Furthermore, even if rebuttals are published, they do not strongly affect how we consider and  
198 cite the original results (Banobi et al., 2011). In the same vein, ecology often favors theories  
199 with good explanatory credibility (Pickett et al., 2007) rather than good evidential credibility  
200 (Mouquet et al., 2015; Peters, 1991; Rigler, 1982). Both approaches are inherent to the  
201 scientific process (Rigler, 1982), but in ecology we might too often consider explanatory  
202 theories to be the only ones worthy of interest. The emphasis on explanatory credibility ahead  
203 of predictive power and evidential credibility, together with an artificially homogeneous  
204 record of publications and citations, promotes a simplistic view of research results. This may  
205 in turn favor a simplistic view of knowledge transfer, making TD appear suitable.

206 A third reason comes from the management sphere itself: managers and decision-makers are  
207 very keen to have simple tools or models, sometimes even to the detriment of more rigorous  
208 tools. Their demand for flagship species, keystone species, efficient corridors and threshold  
209 values is strong—and may pressure researchers into trying to rapidly fulfill this demand  
210 (Simberloff, 1998, 1999). Furthermore, if scientific results are worded with managers’  
211 favorite concepts, they will more easily end up in the management sphere, even if they are  
212 not essentially relevant to the ecological system being managed. The irony is that the  
213 concepts behind these often-used management tools have typically been defined by ecologists  
214 themselves, often with limited empirical grounds.

215 A fourth reason TD is so popular is the lack of an in-depth analysis of the salience\* of  
216 scientific results, which Cash et al. (2003) defined as the relevance of the result to the needs  
217 of managers or decision-makers. Managers may often think that scientific results are salient  
218 only because the wording and proposed mechanisms related to the results—based on their  
219 explanatory credibility—appears relevant to the case at hand. As we will see, it takes much  
220 more work to qualify the true salience of scientific results.

221

## 222 **2.1.2 Limitations of directly using ecological results in the trickle-down interface**

223         Some authors have insisted on the limitations of directly using ecological theories in  
224 environmental management (Driscoll and Lindenmayer, 2011; Shrader-Frechette and McCoy,  
225 1994; Simberloff and Abele, 1976). First, theories used in environmental management are  
226 sometimes based on very weak evidence. For example, the notion that habitat fragmentation  
227 *per se* has negative impacts on biodiversity has dominated the narratives of biodiversity  
228 scientists and environmental managers for decades, yet a recent review by Fahrig (2017a)  
229 found evidence to the contrary: fragmentation *per se* was actually positive for biodiversity on  
230 the whole. Hall (1988) gave another example: even though classic theoretical population  
231 models (the logistic, Lotka-Volterra and Ricker models) are not supported by datasets from  
232 populations in the wild, they are still routinely used by wildlife and wild fisheries managers.  
233 These are examples of zombie ideas in ecology, i.e. ideas that should be dead but are still  
234 alive in the minds of scientists or managers despite evidence to the contrary (Fahrig, 2017b;  
235 Fox, 2011). Ecology is not the only discipline where zombie ideas can be found: there are  
236 similar examples in applications of physics to engineering (Bouleau, 1999).

237         Second, theories may be misused when applied outside their domain of validity. Indeed, there  
238 may be a significant difference between the conditions or hypotheses under which they were  
239 developed and evaluated and the varied, complex environments within which they are  
240 subsequently applied (Beck 1997; Bissonette and Storch, 2002; Bunnell and Huggard, 1999;  
241 Haila, 2002; Harrison, 1994; Schulte et al., 2006). A good example is when one variable has  
242 extreme levels in a scientific experiment, e.g. in predator or competitor density studies  
243 (Belovsky et al., 2004; Schulte et al., 2006). Another example is the concept of keystone  
244 species (Beck, 1997; Simberloff, 1998), where the theory was generalized from a few small-  
245 scale experiments, although further tests strongly limited the generalizability of the concept.  
246         Similarly, despite the intellectual pull of the notion, fully-functioning metapopulations in

247 their strictest sense are not the rule (Harrison, 1991; Smith and Green, 2005), and applying  
248 metapopulation theory—such as to guide a biodiversity conservation strategy in the absence  
249 of further data—would be misleading (e.g. Harrison, 1994). The same is true for island  
250 biogeography theory (Haila, 2002). These examples illustrate that lacking a clear delimitation  
251 of the validity of a theory, or assuming its domain of validity is the same in the academic  
252 sphere as in management contexts, often leads to problems. Using Cash et al.’s (2003) words,  
253 it means that too often, the credibility of scientific results is insufficiently distinguished from  
254 the true salience of those results.

255 Third, environmental management often uses TD to apply only one limited theory in broad-  
256 scope cases that necessitate mobilizing several theories (Mitchell 2005). Furthermore, this  
257 preferred theory is often the one dominating the scientific sphere at the time. This was more  
258 or less the case for the Habitats Directive in Europe (92/43/EEC) and the U.S. Endangered  
259 Species Act (ESA), where very strong emphasis was placed on the role played by habitat  
260 quality or quantity in determining levels of biodiversity. Simberloff (2004) and Driscoll and  
261 Lindenmayer (2011) explained why we cannot expect the general application of only one  
262 single ecological theory to yield good results in environmental management: with the process  
263 of evolution involved, few if any general laws can be defined in ecology (see the evolutionary  
264 contingency thesis of Beatty, 1995; Lawton, 1999; Mayr, 2004). Adopting Cash et al.  
265 (2003)’s terminology, such applications may lack scientific legitimacy\* as they fail to  
266 account for the plurality of scientific theories.

267 Fourth, the link between theory and application in management is sometimes based on  
268 an inadequate deductive construct. According to Simberloff (1983), this was the case for the  
269 IUCN considerations on reserves design in 1980: “the main recommendation advocated in the  
270 name of the theory—single large rather than clusters of small ones [refuges]—is not a  
271 consequence of the theory”, since application requires a host of additional, context-specific

272 parameters (proportion of species in common between reserves, slope of species–area curve,  
273 scale of the reserve; Higgs, 1981; Simberloff and Abele, 1976).

274         The above discussion shows the limitations of direct application of ecological theories  
275 to environmental management in TD, which ultimately proves an inefficient interface type  
276 for solving environmental or societal problems (Hart and Calhoun, 2010). Indeed, TD is  
277 based on an idealistic and unrealistic conception of science (Jasanoff, 1997, 2008). A second  
278 view of the interface between scientific knowledge and management, i.e. the transfer-and-  
279 translate (TT) interface (Van Kerkhoff and Lebel, 2006), partly compensates for these  
280 shortcomings.

281

## 282 **2.2. The transfer-and-translate (TT) interface and category-1 research: A more** 283 **balanced intermediate unidirectional interface type**

284         In TT, scientists make a concerted effort to transfer their results in a comprehensible  
285 way, while managers test the relevance of these results for management and then translate  
286 them into coherent management practices. TT stems from the transfer-of-technology model  
287 and recognizes that published scientific results need transferors and translators to be  
288 efficiently applied (Van Kerkhoff and Lebel, 2006). TT has been implemented in agriculture,  
289 for example, with extension officers playing the role of translators at the interface between  
290 scientific knowledge and the farmer.

291         TT is still a unidirectional interface: the knowledge moves one way, from research to  
292 management, with a research-push\* driving force on one side and a user-pull \* driving force  
293 on the other (cf. Figure 3b and Table 1), which means the associated category of ecological  
294 research is R1. Research and management are still only weakly integrated in this interface  
295 type, as are scientific and experiential knowledge. However, TT does make a first step

296 towards interaction, as transferors and translators consult, adapt and translate scientific  
297 publications with the users' needs in mind.

298 The literature has discussed various types of knowledge transfer and translation (e.g.  
299 Johnson, 2005). Here we look at TT along the lines of Graham et al. (2006), who  
300 distinguished between a knowledge creation cycle and an action cycle. These two cycles are  
301 closely linked to the research-push and user-pull driving forces (see Table 1). As they  
302 progress through these two cycles, four main steps act as successive sieves for scientific  
303 knowledge.

304

### 305 **2.2.1 Academic transferors on the research-push side of the interface**

306 The first two steps in knowledge transfer occur when results are published for an  
307 academic audience (Graham et al., 2006). The first step—shared with TD—involves the  
308 academic publication of individual results, while the second step consists in knowledge  
309 synthesis, typically checking the published evidence for or against a theory, through meta-  
310 analyses or literature reviews (e.g. Fahrig, 2017a). Both can be broadcasted by research  
311 institutions through newsletters, websites, or even mass media where there is no specific  
312 target audience as the sole aim is to promote awareness of the results (Johnson, 2005).

313 The third step of knowledge transfer is more targeted to a specific audience and uses  
314 what Graham et al. (2006) call third-generation scientific knowledge. This corresponds to the  
315 dissemination phase of knowledge transfer in Johnson (2005). A typical example is when  
316 researchers write and present summaries of the state-of-the-art research, typically in the form  
317 of best-practice guides. Such knowledge overviews are often carried out at the request of  
318 managers. Another example is when managers ask researchers to assess which scientific  
319 knowledge is most useful and applicable for the case at hand (Underwood, 1995). External  
320 scientific review adds further depth and rigor to the process (Hecht and Parkin, 2001;

321 Smallwood et al., 1999; Underwood, 1995). For instance, ecologists were actively involved  
322 in the case of the Northern spotted owl in Northwestern USA, either as scientific experts in  
323 ad-hoc scientific groups or as reviewers through professional scientific academic societies  
324 (Duncan and Thompson 2006; Gosselin, 2009; Murphy and Noon, 1991).

325

### 326 **2.2.2 Translators on the user-pull side of the interface**

327 The fourth step is Graham et al.'s action cycle where specific means are devised to  
328 check whether the selected ecological result operates in the local context and at the scale of  
329 the management system. Indeed, classical evidence-based methods, including meta-analyses,  
330 often estimate a “mean” response over several ecological studies performed in different  
331 conditions, which means they often suffer a lack of contextualization as numerous additional  
332 hypotheses are generally required before applying a general result to specific cases.

333 As an illustration, in the case of the spotted owl, an early option was to manage the forested  
334 landscape to provide corridors for the Northern spotted owl to disperse more easily among  
335 habitat patches. However, with the help of scientific advisory groups, this option was  
336 discarded because empirical results from radio-tracked dispersing spotted owls showed that  
337 they did not use the “corridor” structures intensively. Instead, the “matrix”—the whole  
338 landscape extending between potential spotted-owl territories—had to be managed to provide  
339 an effective dispersal habitat (Courtney et al., 2004).

340 Shrader-Frechette and McCoy (1994) give further examples of such complex verification  
341 processes when applying island biogeography theory to specific cases. Driscoll and  
342 Lindenmayer (2011) also give examples of specific cases where general theories have  
343 successfully been applied, provided they were first checked in the specific context at hand. In  
344 agriculture, this role is played by agronomic trials that are carried out by professionals with a  
345 strong emphasis on evidence gathering.



346 The final steps in Graham et al.'s (2006) TT scheme include identifying the barriers to using  
347 the knowledge, intervening to facilitate use of the knowledge, and monitoring actual  
348 knowledge use. These steps mostly involve management translators, but potentially also  
349 social scientists and, more rarely, ecologists as well.

350

### 351 **2.3. The user-push interface and R3 ecological research**

352 So far, we have discussed two types of unidirectional research-to-management interface (TD  
353 and TT associated to R1). A third, complementary type of unidirectional interface is the  
354 “user-push interface” (see Figure 3c). Here, the users commission research on topics they are  
355 interested in, with a more or less well-defined predetermined objective in mind. Some forms  
356 of user-push interfaces are already partly active in TT (see section 2.2), such as when  
357 managers ask scientists to summarize the state of the knowledge, typically through a meta-  
358 analysis.

359 Another type of user-push interface is associated with what Underwood (1995, 1998) defined  
360 as the third category of ecological research (R3): new fundamental\* and strategic research  
361 designed to develop new mechanistic theories\* when earlier managerial decisions and actions  
362 have failed. In this case, it is managers who instigate the research: they recognize that  
363 management has failed—even though they may have taken existing scientific knowledge into  
364 account—and they want to understand why.

365 In a more general user-push interface setting, managers may ask researchers to produce  
366 knowledge that will inform their future management, such as when they launch calls for  
367 tenders in applied research. In France, several research programs have stressed the need for  
368 research that can ultimately be readily used by environmental managers: involving managers  
369 in the research projects is highly appreciated and is taken into account during the selection  
370 process. Moreover, some of these programs include one or several events (e.g. meetings) or

371 outputs (e.g. books) designed to speed the transfer of research results to the management  
372 sphere. This is an example of a boundary-spanning institution created to enhance effective  
373 scientific advice in environmental management, as recommended by Cash et al. (2003).  
374 In addition to calls for research projects, some research can be programmed through specific  
375 agreements between a research institute and a management organization. For instance, the  
376 French National Forestry Service (ONF) has had a years-long partnership with (the French  
377 National Research Institute of Science and Technology for Environment and Agriculture  
378 (Irstea) to rebuild its policy on biodiversity preservation in public forests (Gosselin et al.,  
379 2006). Similarly, several members of the French Forest Health Department (DSF) are hosted  
380 within INRA research laboratories to boost research/management interactions.

381 User-programmed research is likely to increase the salience of the research for those users  
382 (Hart and Calhoun, 2010), which should enable research where the underlying questions are  
383 partly formulated from managers' questions or needs, as advised by Bunnell and Huggard  
384 (1999).

385 However, user-programmed research, though welcome, does not come without risks: it could  
386 constrain research to the currently perceived needs of managers, thus preventing researchers  
387 from stepping back to ask new questions. It is therefore important to develop confidence  
388 between end-users and researchers, and to plan applied research not only on currently  
389 identifiable questions but also on non-dominant questions. Scientists are currently under  
390 increasing pressure at regional, national and international levels to make applied research  
391 move towards market-valued innovation, especially when training future researchers,  
392 responding to calls for tender, or developing general guidelines for research. This kind of  
393 user-push interface could completely shift the nature of the research being performed, and  
394 possibly jeopardize non-merchantable scientific knowledge.

395

## 396 **2.4 Comparing unidirectional interface types**

397           The examples given in section 2.3 illustrate how the user-push interface type is  
398 currently active and multifaceted. It is complementary to the other interfaces, all the more so  
399 as the difference between R1 and R3 arises more from the interface type they are related to  
400 than from the type of ecological knowledge produced. For R1, the interface (research-push or  
401 user-pull) focuses on research results, and is placed *after* the research process, in contrast to  
402 R3 which is characterized by a user-push interface acting from the *outset of the research*.

403           In sections 2.1 and 2.2, we saw that R1 results can vary in nature and may not always  
404 be appropriate for management decisions. The most frequent mistake stems from TD and  
405 consists in applying one single theory directly to management without robust testing of  
406 whether or not it is adequate for the case at hand. TT is preferable, since potentially useful  
407 ecological results are gradually filtered before being applied. This shift from TD to TT is  
408 grounded in the notion that for scientific results to find use in management, it is not enough to  
409 be credible—they also need to be salient, i.e. relevant to the needs of users (Cash et al.,  
410 2003). We found that the explanatory credibility of scientific results may make them appear  
411 salient to managers, due to the wording used and the potentially appealing mechanisms put  
412 forward. However, what is important to actually evaluate the salience of scientific results is  
413 evidential rather than explanatory credibility. More precisely, what is needed is a specific  
414 kind of evidential credibility, one that is oriented towards users' needs, and which may not be  
415 the same as that used to develop the knowledge in the academic sphere.

416           However, in TD and TT, contrary to the recommendations of Hart and Calhoun (2010) and  
417 Hulme (2014), most of the knowledge is produced within and for the research sphere, without  
418 considering *a priori* whether it will be useful for or transferable to managers. Researchers  
419 will screen pre-existing scientific results for those that could be transferable to specific  
420 management objectives. Some results may get selected and transferred and even end up

421 providing an adequate response to certain management issues, but more by chance than by  
422 design. In TT, there is no assurance that existing scientific knowledge contains appropriate  
423 information for transfer. Although the user-push interface diminishes this drawback,  
424 interaction with managers remains limited in all three unidirectional interfaces.

425

### 426 **3. Developing a bidirectional interface: research-within-management interface (RWM)**

427 This section presents a new type of research–management interface, that we call research-  
428 within-management (RWM), based on strong research–management interactions and on  
429 bidirectional flows of knowledge. RWM is an exchange interface\* where researchers and  
430 managers work together, pushing and pulling knowledge to define research questions and  
431 conduct ecological research relevant to their mutual skills and needs (Johnson, 2005; Roux et  
432 al., 2006). RWM is directly related to Underwood’s R2 (see Table 1) and involves both  
433 scientific and experiential ecological knowledge (see Figure 1). It differs significantly from  
434 TD and TT in that managers and researchers interact throughout the implementation,  
435 monitoring and evaluation of the management strategies to co-produce a common set of case-  
436 specific scientific and experiential knowledge (Figure 4). Below, we present RWM and its  
437 link with R2, looking at when and why it holds relevance. We argue that RWM complements  
438 other classic interface types well and should be pursued in the future to help diversify and  
439 strengthen interaction processes between management and research spheres.

440

#### 441 **3.1 R2 and RWM**

442 Underwood (1995) defines R2 as “applied environmental research aimed at specific tests of  
443 the results of decisions made by managers by treating these decisions as testable hypotheses”.  
444 The goal is to address key issues identified by managers (e.g. dead wood management or  
445 green tree retention in forest cuts) or, in some cases, by pressure groups or even society as a

446 whole. In order to guarantee its management-integrated signature, R2 follows three main  
447 principles (Underwood 1995, 1998): (i) it specifically studies management options by  
448 considering them as explicit testable hypotheses; (ii) it relies on experiments or structured  
449 observations at spatial and temporal scales corresponding to the scale at which environmental  
450 management is applied; and (iii) its research designs take into account the variability of the  
451 ecological conditions found in the managed areas.

452 The first principle mentioned above is essential: investigation targets management practices  
453 themselves, rather than more proximal ecological factors, as experimental treatments or  
454 observational units. Take the example of deadwood management in temperate and boreal  
455 forests (Bouget et al., 2012). While R1 would quantify the relationships between deadwood  
456 metrics (volume, diversity) and biodiversity metrics, R2 would test the effect of different  
457 deadwood management scenarios (e.g. retention of snags and large logs; creation of high  
458 stumps) on these metrics based on *a priori* hypotheses about the relative performances of  
459 these scenarios and the associated mechanisms (Cordonnier et al., 2009). With this approach,  
460 management options can advantageously integrate economic and technical constraints, and  
461 this improves the transferability of the results to management. Managers sometimes prefer to  
462 test a single management option that they assume is optimal for their objectives. Such an  
463 approach can still be included in R2 if it respects the second principle concerning scale and  
464 the third principle concerning ecological conditions. Consequently, targeted monitoring  
465 (Nichols and Williams, 2006) of the expected outcomes of a management option falls under  
466 the scope of R2.

467 The second and third principles of R2 call for multi-site experiments or structured  
468 observations which compare management alternatives in different ecological conditions.  
469 Multi-site experiments or structured observations usually increase the level of inference of  
470 the results and provide opportunities for unexpected output, both of which in turn stimulate

471 interactions between scientists and managers (Sit and Taylor, 1998). This kind of approach  
472 has been adopted in forest ecosystems in France to test different stand density regimes for  
473 several tree species at different sites. A specific collaborative research network (GIS Coop:  
474 Scientific Interest Group Cooperative for data on forest tree and stand growth; Seynave *et al.*,  
475 2018) involving both forest managers and forest scientists has been set up to manage and  
476 monitor these long-term experiments. From inception, the aim of these experiments has been  
477 twofold: 1) to improve silvicultural results (stand growth, tree growth and wood quality) for  
478 managers, and 2) to improve future forest growth models for both managers and researchers.  
479 Finally, as R2 explicitly considers management options, it mobilizes non-scientific data such  
480 as descriptive information on natural resources used for forest management, and even  
481 experiential knowledge (Dorren and Berger, 2006; Ogden and Innes, 2009).

482 R2 is typically associated with RWM because it is management-oriented and bases its  
483 questioning on hypotheses made within the management framework. R2 thus calls for this  
484 new RWM interface that promotes fruitful collaboration between researchers and managers.

485

### 486 **3.2 When should RWM and R2 be considered?**

487 RWM and the associated R2 share several features that facilitate knowledge sharing between  
488 researchers and managers, the most obvious one being that management practices are  
489 analyzed as experimental treatments or explanatory variables. However, there are questions  
490 remaining over the real efficiency of the approach and the conditions in which it proves more  
491 relevant than other types of research and other types of research–management interface.

492 Ludwig *et al.* (1993) proposed that “actions that are robust to uncertainties” and “actions that  
493 are informative” should be favored. The latter case appears to justify choosing RWM when  
494 there is a strong structural uncertainty (Regan *et al.*, 2002) about the managed system. Strong  
495 uncertainty usually arises when two phenomena co-occur: (i) existing theories do not provide

496 quantitative predictions or matured hypotheses about the relationship between the  
497 management practices and the ecosystem properties, and (ii) the management practices are  
498 too recent to draw feedback from past experience. This case can be illustrated in the context  
499 of ecosystem adaptation to climate change. A current management recommendation in  
500 forestry is to reduce stand density to improve tree water balance and stand resistance to  
501 drought (Linder, 2000). Although models and field studies exist (e.g. Giuggiola et al., 2013),  
502 there are few general guidelines enabling managers to target stand densities that increase  
503 stand health and maintain high wood productivity. More experiments are needed to clarify the  
504 appropriate density levels for different species in different ecological situations, and RWM is  
505 well geared to that purpose.

506 RWM should also be applied in ecological contexts where theoretical hypotheses are  
507 available but evidence-based results are rare. In a way, this is much like a validation process  
508 that checks the robustness of an ecological theory's output within a management context –  
509 here, RWM becomes an extension of TT (cf. section 2.2). A clear example is the self-  
510 thinning line in plant ecology, which is known to depend on both species (Charru et al., 2012)  
511 and ecological situation (Bi, 2001). As the self-thinning line has now been integrated into  
512 management guidelines for certain species through stand density diagrams (Castedo-Dorado  
513 et al., 2009) and growth models (Le Moguédec and Dhôte, 2012), forest managers and  
514 researchers now want calibrated relationships and applications for other species, site  
515 conditions and stand types (e.g. mixed forests; Long and Vacchiano, 2014), which entails  
516 carrying out further observational studies and new experiments. RWM becomes effective  
517 when these experiments include management scenarios that contrast stand densities and stand  
518 structures, and thus mobilize both scientific and experiential knowledge.

519 RWM should also be selected rather than more classical unidirectional interfaces when  
520 management practices are very specific. Examples include the short- and long-term impacts

521 of mechanized wood harvesting on forest soil compaction and soil functioning, or fuelwood  
522 extraction, which may involve whole tree removal (Thiffault et al., 2011). RWM is also  
523 valuable when the available research results deal with variables that are not directly targeted  
524 by management practices, as in the case of deadwood management in temperate and boreal  
525 forest ecosystems. The amount of deadwood depends on stand productivity, but also on  
526 different management practices such as deadwood removal, hollow tree retention and leaving  
527 logging remnants (Lee et al., 1997). It is quite a challenge to unravel the direct impact of such  
528 management practices on deadwood quantity and quality, two major indicators of saproxylic  
529 species diversity (Bouget et al., 2012). Here again, experiments controlling for management  
530 practices may help test the efficiency of these practices in producing various deadwood  
531 structures.

532 Finally, RWM should be considered when available research results are not directly  
533 transferable to environmental management due to a mismatch in scales (Bunnell and  
534 Huggard, 1999; Schulte et al., 2006). This issue arises in numerous cases, as the scientific  
535 approach is precisely to reduce the spatial and temporal scale of a problem in order to  
536 simplify it and increase the statistical power of the study. Here again, deadwood management  
537 is a relevant example. Studies dealing with deadwood–biodiversity relationships use  
538 measurements taken at a plot size of 300 m<sup>2</sup> to 1 ha (Okland et al., 1996), whereas  
539 management recommendations are usually applied at a unit level of several hectares, or even  
540 at a forest level of several thousand hectares. This discrepancy has implications for  
541 biodiversity, since scale appears to influence the effect of deadwood volume on biodiversity  
542 (Okland et al., 1996).

543



### 544 3.3 Limitations of R2 and RWM

545 The main limitation concerns the spatial scale of R2 studies, which is usually broader than for  
546 standard scientific studies. Addressing the management scale requires large *in situ*  
547 experimental and observational units (Renken et al., 2004; Walters and Holling, 1990).  
548 Moreover, to reach an acceptable level of generality, the experiments or structured  
549 monitoring used in RWM must be replicated in different ecological conditions. These  
550 technical constraints have been outlined by several authors (e.g. Peterson and Anderson,  
551 2009; Seymour et al., 2006). In some circumstances, R2 can be conducted at a scale smaller  
552 than the usual management scale, provided that management issues are still addressed. For  
553 instance, small but highly replicated experiments on regeneration operations in forestry  
554 would suffice to gain valuable operational results applicable at management-unit level.  
555 A second limitation, closely related to the first, is that R2 experimental units are often quite  
556 large, which makes local replication difficult, thus limiting statistical power. A higher  
557 experimental residual error due to variations in management practices and unpredictable  
558 disturbance events (i.e. windstorms in forests) can accentuate this limitation (Hurlbert, 1984).  
559 This raises the question of what type of statistical analysis to use in such experiments. One  
560 option in classic frequentist approaches is to increase the p-value for hypothesis testing in  
561 linear models (Di Stefano, 2001). Unreplicated experiments can mobilize other approaches  
562 such as Bayesian statistics and decision analysis (Sit and Taylor, 1998). Enhanced impact  
563 designs could also be considered (Schwarz, 1998).  
564 A third limitation is embedded in the RWM itself. Close interaction between researchers and  
565 managers may complicate the execution of experiments by involving different partners with  
566 different prerogatives and cultures. Experimental approaches may necessitate modifying or  
567 controlling management practices, or conversely, management practices may put constraints  
568 on scientific observations and planning. Institutional support is required to establish lasting

569 partnerships between the research and management spheres, but institutions can be weakened  
570 by factors such as structural reforms, financial problems or changes in priorities (Gray, 2000).  
571 To overcome these limitations, RWM usually mobilizes a high level of resources, which can  
572 be a major constraint at some institutions or in some economies. In these cases, it might be  
573 possible, as suggested by Rist et al. (2013b) for adaptive management, to reduce the cost of  
574 RWM by addressing only a subpart of the research question or management issue being  
575 tackled.

576

#### 577 **4. Meta-interface frameworks: adaptive management and structured decision making**

578 Adaptive management (AM) is “an approach to managing complex natural systems  
579 that builds on learning—based on common sense, experience, experimentation, and  
580 monitoring—by adjusting practices based on what was learned” (Bormann et al., 1999). As  
581 AM mobilizes different research–management interfaces at different steps in its adaptive  
582 cycle, it can prove an effective meta-interface framework in relation to research. In this  
583 regard, AM does not necessarily put to use all of the interface types mentioned earlier, but it  
584 can implement one or more of them depending on the management phase, complexity and  
585 collaborative nature of the AM project considered. From this perspective, AM can serve to  
586 intensify interactions between ecological research and environmental management.  
587 AM projects can take different forms, from tests of simple practices in small management  
588 units (e.g. fertilization trials) to large, complex experiments carried out at catchment or  
589 landscape scale (Gregory et al., 2006). AM is usually represented by an adaptive cycle with a  
590 sequence of different phases related to scheduling, implementation and evaluation processes.  
591 After defining objectives and desired outcomes, AM defines management scenarios by  
592 combining and sharing knowledge. AM cycles usually start with an in-depth analysis of the  
593 question addressed and a comprehensive overview of the state-of-the-art, which may enroll

594 TT as well as R1 (cf. section 2.2). During this phase, and depending on the level of  
595 uncertainty (Gregory et al., 2006), researchers and managers interact to identify key issues,  
596 build models, and define the main hypotheses through a collaborative (Graham and Kruger,  
597 2002) or even a participatory approach (Stringer et al. 2006). Given our limited  
598 understanding of the complex components and operating rules in ecosystems (Hilborn and  
599 Walters, 1981; Underwood, 1998), management options are generally identified and selected  
600 based on *a priori* assumptions of how the system functions and how it could respond to  
601 management practices. The hypothesis framing phase requires scientific knowledge and  
602 methodology to specify potential ecosystem responses (both structural and functional) to  
603 management practices (Underwood, 1995) and try to link these practices with potentially  
604 multiple theories (Nichols et al., 2015). However, the experiential knowledge of managers is  
605 equally essential to avoid pitfalls, help define the range of relevant practices, and help  
606 identify the mechanisms at work.

607 The next phase of AM includes management implementation, monitoring and evaluation.  
608 This phase comes quite close—at least for the ecological part of the management plan—to  
609 RWM and R2 (see section 3), as it involves updating the degree of evidence of alternative  
610 theories that have been deemed related to the management practice (Nichols et al., 2015).  
611 Moreover, in its most developed form, AM integrates many of the points that Underwood  
612 (1995) highlighted for R2. For instance, active AM is based on using ecological experimental  
613 procedures to test the hypotheses made by managerial agencies and evaluate the effects of  
614 different management options (Stankey et al., 2005). However, AM has a broader scope than  
615 R2. It aims not only to assess the effects of management but also to learn about the  
616 management process itself through double-loop learning (Stankey et al., 2005), which is not a  
617 primary goal for R2. Authors' opinions vary (Medema et al., 2008), but AM can involve  
618 many stakeholders (managers and citizens) and promote inter-disciplinarity. This means that

619 AM can potentially integrate Underwood (1995)'s R4 research ("managerial ecological  
620 research"), which is not a prerequisite for R2.

621 Finally, the learning feedback loop can bring about new R3 through an internalized user-push  
622 interface (see section 2.3). This process happens when management options do not meet the  
623 objectives and are considered as failures. Management failure in cases where RWM and R2  
624 have been applied can also indicate that current theories or previous evidence-based studies  
625 are unable to explain the phenomena encountered; this situation then calls for further R3. The  
626 feedback loops from R2 to R3 and R1, through their associated interfaces (RWM, user-push  
627 and TT), are essential pathways that can result in another adaptive cycle, or even a new AM  
628 project.

629 As a meta-interface framework, AM is potentially broader and more complex than the  
630 individual interfaces discussed above, but it may prove harder and riskier to apply, since AM  
631 projects may need long-term institutional support (capacity, willingness, leadership; Walters,  
632 2007) and involve complex interactions between stakeholders (Medema et al., 2008). AM can  
633 impel a highly active bidirectional flow of scientific and experiential knowledge during  
634 hypothesis framing, selection of management options, implementation of experiments or  
635 structured observations, and evaluation of results. However, AM has been criticized by  
636 several authors on grounds that it is too "science-oriented" and too static, and thus less  
637 pragmatic than approaches focusing on the decision process itself (Gregory et al., 2012).

638 The upshot is that structured decision-making (SDM) is usually considered a more realistic  
639 way of conducting a project dealing with environmental management issues (Gregory et al.,  
640 2012). SDM is "a prescriptive approach to environmental decision-making that facilitates  
641 better choices based both on theories of rational choice and the judgmental limitations of  
642 decision-makers and stakeholders" (Failing et al., 2013). Beyond applied ecology, SDM  
643 involves decision and cognitive sciences, recognizes the importance of values in decision-

644 making, and advocates specific analytical methods to address complex environmental issues.  
645 It is based on a succession of critical steps that deal with the way the problem is framed, how  
646 relevant options are defined, and how trade-offs are analyzed. Although the learning process  
647 and the research–management interface are mentioned in SDM, they appear to be less  
648 fundamental than in the AM framework: the ultimate goal of SDM is to enable managers to  
649 make decisions in a temporal scale that is compatible with management planning. Overall,  
650 SDM appears closer to Underwood’s R4 which analyzes how managers and ecologists make  
651 decisions. Nevertheless, we propose that SDM can occasionally transform itself into an AM  
652 process when uncertainty, lack of knowledge and learning are found to be limiting factors in  
653 the management process. Alternatively, AM projects could benefit from being implemented  
654 inside a SDM process (Failing et al., 2013).

655

## 656 **5. The roles of experiential and fundamental ecological knowledge**

657 Now that we have looked at the relationships between categories of applied ecological  
658 research, types of research–management interfaces and their links with adaptive management  
659 and structured decision-making, we can complete Figure 1 by analyzing the role of the  
660 different kinds of ecological knowledge at these interfaces. We propose that knowledge  
661 produced by applied ecological research should be well connected with other forms of  
662 knowledge—i.e. experiential knowledge and fundamental ecological knowledge—to deliver  
663 more appropriate knowledge to managers (e.g. in the transfer-and-translate interface).

664

### 665 **5.1. Importance of experiential knowledge**

666 There is no escaping the fact that scientific ecological knowledge does have limits when it  
667 comes to management applications. In addition, management projects can usefully employ  
668 other non-scientific sources of ecological knowledge: Roux et al. (2006) identified various

669 sources of relevant knowledge outside the scientific sphere, namely among policymakers,  
670 managers, naturalists, or broader societal communities. Here, experiential knowledge plays a  
671 central role. There are several different categories of experiential knowledge: first of all,  
672 knowledge of natural history; second, the experiential knowledge that scientists use to draw  
673 analogies with similar contexts previously investigated in the framework of case studies  
674 (Simberloff, 2004); and third, the experiential knowledge of managers when they draw  
675 judgments on the feasibility of a management plan (see sections 3 and 5). The following  
676 discussion focuses mainly on natural history, which we think is a cornerstone.

677 We will treat natural history as an art or a craft rather than a science (Peters, 1991; Weiner,  
678 1995), although many scientists have considerable natural history knowledge and can use it  
679 as a form of pre-theoretical knowledge, e.g. as a source of scientifically testable hypotheses.

680 Ecology and natural history share a common subject, and ecologists themselves recognize  
681 that “there is much knowledge in the art of natural history” (Weiner, 1995; see also Hansson,  
682 2003). Empirical ecology—especially the study of natural patterns – could even be called  
683 “quantitative natural history”, following Weiner (1995) who goes on to state that “one of the  
684 goals of ecological science is to transform this intuitive knowledge into scientific knowledge,  
685 and thus enable us to extend it”. Natural history, either alone or combined with scientific  
686 ecological knowledge, can help choose which ecological scientific results or theories are  
687 useful in a given management situation (Dayton, 2003, Fazey et al., 2005, 2006). Both  
688 Weiner (1995) and Hansson (2003) assert that experiential ecological knowledge is the best  
689 source of ecological knowledge for managers today, but it is not always mentioned in the  
690 literature linking ecological research and management, such as Underwood (1995),  
691 Bestelmeyer et al. (2003) and Courchamp et al. (2015).

692         To better valorize experiential knowledge, we need to change the vision of knowledge  
693 transfer. The relatively inefficient traditional vision considers a unidirectional flow of

694 scientific knowledge from researchers (as the only knowledge-producers) to managers or  
695 policymakers (as mere knowledge-consumers) (see section 2). Our vision is that experiential  
696 knowledge, whatever its origin, should at least have a more explicit place in this transfer  
697 interface, and should complement R1 results as a useful knowledge source for devising  
698 management options. Roux et al. (2006; see also Hulme, 2014) promoted a more thorough  
699 vision that consists in an effective bidirectional flow of knowledge, like the RWM we  
700 propose in section 3, taking into account all types of knowledge and enabling new knowledge  
701 to be shared and co-constructed .

702         However, for knowledge to be efficiently shared between communities, there are  
703 cultural barriers to overcome. Sharing knowledge that has already been explicitly  
704 formulated—like scientific information—is relatively easy, even though doing so generally  
705 requires translation (see section 2.2 and Cash et al., 2003). However, a large—and crucial—  
706 part of experiential knowledge is tacit knowledge (Roux et al., 2006), a hidden part of  
707 knowledge that is personal and difficult to formalize. Sharing tacit knowledge requires  
708 spending time in face-to-face interactions. This is a first step towards formulating tacit  
709 knowledge in a more explicit way, through efforts to explain things to other communities.  
710 Boundary structures between research and management can do this: Cash et al. (2003) give  
711 the example of the International Maize and Wheat Improvement Center which allowed  
712 traditional farmers to convert their tacit knowledge into information useful to crop breeders.  
713 RWM and AM (cf. sections 3 and 4) both offer a suitable forum to do this, by defining shared  
714 hypotheses and testing new management schemes partly based on tacit knowledge of  
715 different types (natural history, managerial, and so on). In addition to producing new  
716 scientific knowledge inside the action cycle, R2 and RWM should therefore recognize—and  
717 even foster (Fazey et al., 2005) —concurrent planned, or unplanned, development of  
718 experiential knowledge. This recognition should bring about better dialog, and could better

719 integrate both types of knowledge within the management sphere, and in turn improve the  
720 acceptance of research results (Graham et al., 2006; Hulme 2014; Roux et al., 2006).

721

## 722 **5.2 Importance of fundamental knowledge**

723 Applied ecological research also needs to be closely linked with fundamental ecology.

724 This is acknowledged in Figure 2, where fundamental research is mostly hosted in “Other  
725 academic research”, a category that strongly interacts with the different categories of applied  
726 ecological research. Fundamental ecological research—whose aim is “primarily to acquire  
727 new knowledge of the underlying foundations of phenomena and observable facts without  
728 any particular application in view” (Courchamp et al. 2015, p.10)—enables scientists to  
729 explore situations or processes that cannot be investigated inside the management process.

730 Fundamental research also helps reformulate questions, potentially through new concepts or  
731 formalisms (Romesburg, 1981; Pickett et al., 2007). It leaves a door open to new knowledge  
732 on ecological processes, which could help us understand what is going on in managed  
733 ecosystems, or help devise new practices to be tested.

734 This statement might puzzle the careful reader of section 2, where we stressed the limitations  
735 of explanatory ecological knowledge and the utility of empirical ecological knowledge for the  
736 research–management interface. Our point was not to say that empirical knowledge should  
737 prevail over explanatory knowledge but simply that it should have its recognized place, both  
738 inside ecological research and at the ecological research–environmental management  
739 interface. As we made clear in section 2, we are somewhat skeptical that fundamental  
740 research results alone can efficiently orient management in general.

741 Ecology would do well to reconcile the explanatory and empirical perspectives, and to couple  
742 the two more effectively (Haller 2014; Hansson, 2003; Marquet et al., 2014; Weiner, 1995).

743 Indeed, in ecology, we seem to neglect the gap between theoretical development and the first



744 tests or applications in management. Instead of the “physics envy” they often manifest  
745 (Gosselin, 2011; Simberloff, 2004), ecologists should perhaps develop a stronger affiliation  
746 with “clinical envy”—e.g. by mimicking the successive phases I, II, III and IV in drug  
747 development trials (e.g. [Kuhlman, 1997](#)). This mirrors the tension between ecologists and  
748 agronomists, as summarized by Paul and Robertson (1989): “ecologists tend to view  
749 agronomists as strict empiricists, and agronomists tend to view ecologists as overly  
750 theoretical purveyors of the obvious”.

751

## 752 **6. Conclusion**

753 This paper is, to our knowledge, the first attempt to narrow the gap between  
754 ecological science and environmental management by combining three perspectives: (i) the  
755 different categories of ecological research useful for environmental management, *sensu*  
756 Underwood (1995); (ii) the different interfaces between research and management; (iii) the  
757 different types of ecological knowledge useful for environmental management. After first  
758 evaluating the trickle-down (TD) interface, we identified three types of interfaces connected  
759 to Underwood’s research categories (R1, R2, R3) and described their limitations and  
760 usefulness: (i) the transfer-and-translate (TT) interface is related to the most classic type of  
761 applied ecological research (R1); (ii) the user-push interface initiated by users’ questions is  
762 related to Underwood’s R3; and (iii) the bidirectional Research-within-Management (RWM)  
763 interface is a new R2-related interface type characterized by co-monitoring and co-analysis  
764 of environmental management results. We further highlight the fruitful contributions of  
765 adaptive management (AM), a framework that can integrate all the different interfaces except  
766 TD, according to management phase, context, degree of knowledge and level of uncertainty.  
767 The different interfaces can be seen as concrete examples of boundary structures between  
768 research and decision-making or management, as called for by Cash et al. (2003). They

769 embed some of Cash's boundary functions—especially translation (TT, RWM) and  
770 communication (RWM) —but we agree that mediation, when deep disagreements between  
771 researchers and managers exist, should also be promoted.

772 We also highlighted the existence of different sources of ecological knowledge, whether  
773 scientific or experiential, explanatory or empirical. We stress that empirical knowledge, both  
774 experiential and evidential, should be given a more central place in research–management  
775 interfaces, to help counteract a persistent tendency to directly apply academically fashionable  
776 mechanisms and concepts to environmental management. The salience of scientific results  
777 was shown to relate more to empirical credibility—gauged with managers' needs in mind—  
778 than to explanatory credibility. We also believe that applied ecological research should be  
779 better connected to other forms of knowledge, to improve not only its scientific value and  
780 credibility but also its practical usefulness or salience and legitimacy.

781 We point out the complementarities as well as the specificities and limitations of the different  
782 research categories and related interface types, which is of major importance for  
783 environmental management and research policies. First, this leads us to recognize the  
784 legitimacy and usefulness of the different types of interfaces and research, all of which  
785 participate in the flow of knowledge between research and management, although in different  
786 conditions and with different intensities. R1 and TT occur at the end of the knowledge  
787 creation cycle and the beginning of the action cycle, whereas R3 and the user-push interface  
788 are active at the beginning of the knowledge-creation cycle and at the end of the action cycle.

789 Second, RWM integrates the R2-type scientific knowledge creation cycle within the action  
790 cycle itself. Third, our analysis clearly distinguishes the research types that induce an  
791 obviously limiting unidirectional flow of knowledge (e.g. R1) from those (e.g. R2) that favor  
792 a bidirectional flow of knowledge between research and management. Although this idea is  
793 not entirely new, we have tried to better specify the conditions where these different research

794 types might be relevant. We think that R2 and RWM in particular should be encouraged,  
795 since they are currently underdeveloped in some fields; it is important to gain more  
796 experience with R2 and RWM to better assess their potential relative to R1, R3 and related  
797 interfaces. Finally, an interesting perspective would be to develop research programs or  
798 projects that articulate, in a structured manner, different research categories and interfaces  
799 around the same management issue. In line with Rist et al. (2013b)'s analysis, we think that  
800 AM projects are well geared for this purpose, while at the same time reducing uncertainties  
801 on the effects of management on ecosystem structure and functioning.

802 Our paper may help ecologists realize that scientific ecological knowledge is necessary, but  
803 not sufficient, to address environmental management issues. Ecologists should be able to  
804 improve the applicability of their research through better interaction with managers and by  
805 working towards a more management-integrated research. Furthermore, our paper may help  
806 policymakers and funders effectively balance different categories of research for use by  
807 environmental managers, and serve for better evaluation of public policies and management  
808 strategies, even when they are based on scientific theories. Managers are encouraged to  
809 interact more closely with scientists through a diversity of interfaces, which would better  
810 equip them to use the research results provided.

811

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827

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<b>Interface type</b>	<b>Knowledge source</b>	<b>Flow of knowledge</b>	<b>Driving forces of knowledge at research/management interfaces</b>	<b>Types of knowledge</b>	<b>Underwood (1995)'s categories of ecological research</b>
Trickle-down	Researchers	Unidirectional	None	Explanatory scientific Evidential scientific	All published ecological research
Transfer-and-translate	Researchers	Unidirectional	Research-push User-pull	Explanatory scientific Evidential scientific	R1 (Available research that will be used by managers whether it is specifically directed to them or not)
User-push	Researchers with managers at the onset	Unidirectional	User-push	Explanatory scientific Evidential scientific	R3 (Research initiated by former management decision failures)
Research-Within-Management	Researchers & managers	Bidirectional	Research-push Research-pull User-push User-pull	Explanatory scientific Evidential scientific Experiential	R2 (Research aimed to specifically evaluate the results of decisions made by managers by treating these decisions as testable hypotheses)

Table 1: Summary of the connections between the types of research–management interfaces, categories of ecological research, and types of knowledge involved.



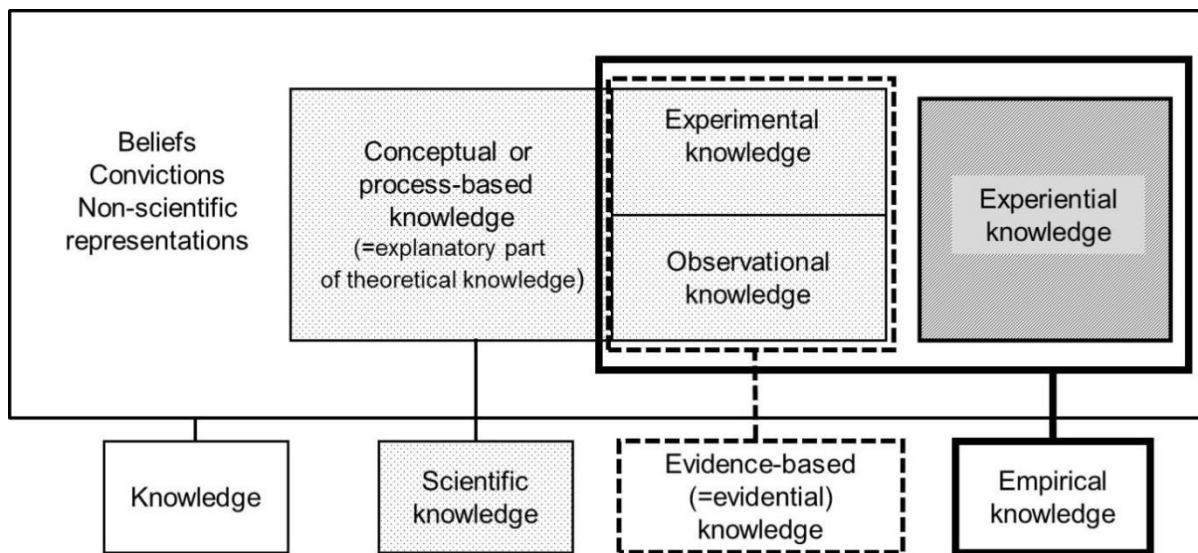


Figure 1. Relative positions of the different types of ecological knowledge and representations as defined and discussed in this paper. This figure illustrates some of the definitions in the text and in Appendix SM1.

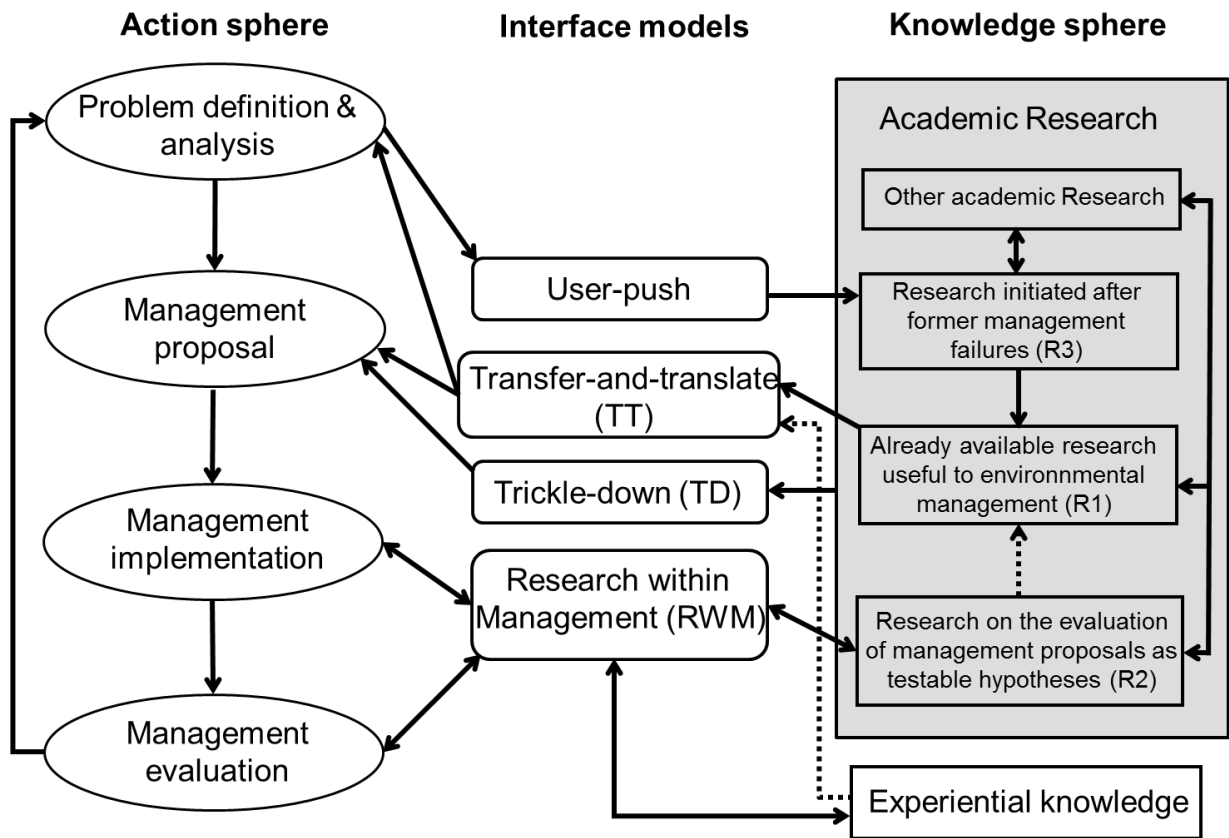


Figure 2. Relationships between the knowledge sphere and the action sphere according to the first three categories of ecological research useful for management (R1, R2, R3) identified by Underwood (1995) and the four types of interfaces discussed in this paper. For ease of graphical representation, the interfaces are not presented in the same order as in the paper. Solid arrows indicate usual direct links. Dotted arrows indicate welcome but currently under-recognized or under-developed links.

Figure 3a:

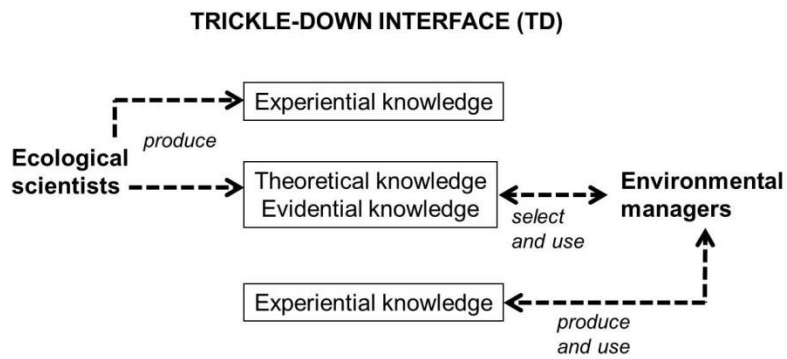


Figure 3b:

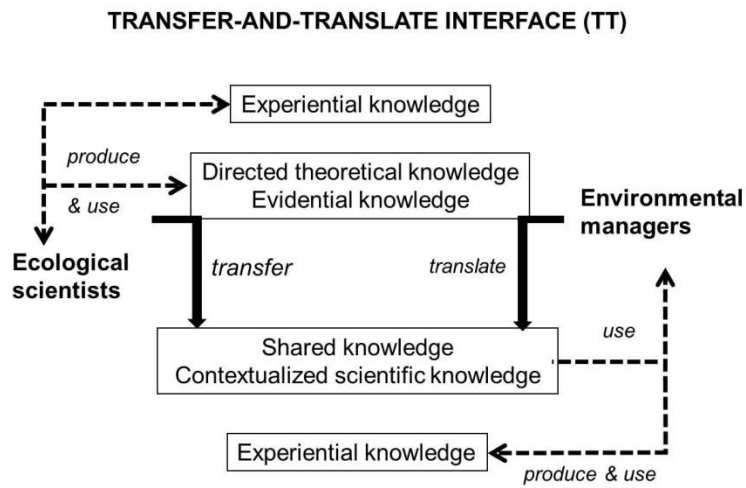


Figure 3c:

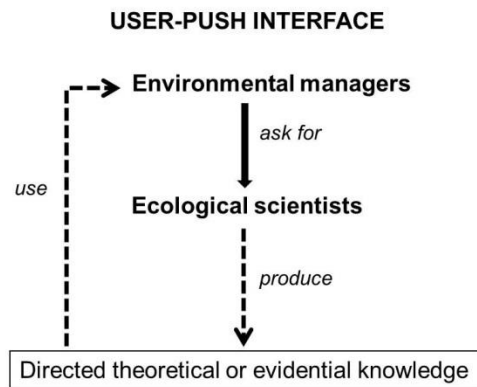


Figure 3. Schematic representation of the three unidirectional interfaces discussed in section 2: trickle-down (TD; Figure 3a), transfer-and-translate (TT; Figure 3b) and user-push (Figure 3c). This figure shows the links (arrows) between actors and types of knowledge. Boxes represent the different types of knowledge used or produced. Solid arrows indicate links activated specifically by the interface while dotted arrows indicate links unrelated to the interface.

## RESEARCH WITHIN MANAGEMENT INTERFACE (RWM)

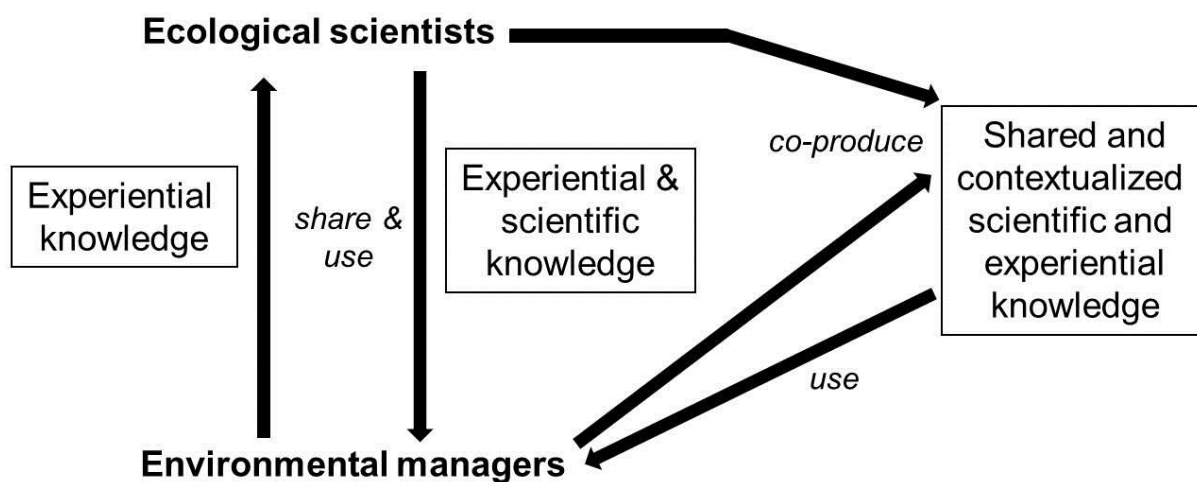


Figure 4. Schematic representation of the Research-within-Management type of research–management interface, showing the links (arrows) between actors and types of knowledge. Boxes represent the different types of knowledge used or produced. In contrast with the unidirectional interfaces in Figure 3, this type of interface activates all the potential links (solid arrows).