



HAL
open science

Ecological research and environmental management: We need different interfaces based on different knowledge types

Frédéric Gosselin, T. Cordonnier, Isabelle Bilger, M. Jappiot, C. Chauvin, Marion Gosselin

► **To cite this version:**

Frédéric Gosselin, T. Cordonnier, Isabelle Bilger, M. Jappiot, C. Chauvin, et al.. Ecological research and environmental management: We need different interfaces based on different knowledge types. *Journal of Environmental Management*, 2018, 218, pp.388-401. <10.1016/j.jenvman.2018.04.025>. <hal-02499888>

HAL Id: hal-02499888

<https://hal.science/hal-02499888v1>

Submitted on 5 Mar 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

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

3

4 Frédéric Gosselin^{1*}; Thomas Cordonnier²; Isabelle Bilger¹; Marielle Jappiot³; Christophe
5 Chauvin²; Marion Gosselin¹

6 ¹Irstea, UR EFNO, Domaine des Barres, 45290 Nogent-sur-Vernisson, France.

7 ²Université Grenoble Alpes, Irstea, UR LESSEM, 2 rue de la Papeterie, BP76, 38402 Saint-
8 Martin-d'Hères cedex, France.

9 ³Irstea, UR RECOVER/EMR, 3275 Route de Cézanne, CS 40061, 13182 Aix-en-Provence
10 cedex 5, France

11

12 *Corresponding author:

13 e-mail: frederic.gosselin@irstea.fr

14 Fax: 00 33 238 95 03 44, Tel: 00 33 238 95 03 58

15

16 **Published in Journal of Environmental Management 2018, Vol. 218,**

17 **pp.388-401**

18 **(doi: 10.1016/j.jenvman.2018.04.025).**

19 **Available at**

20 **<https://www.sciencedirect.com/science/article/pii/S0301479718304018>**

21

18

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*¹— 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:

¹ 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 m² 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

812 **Acknowledgments**

813 This article comes from discussions initiated in the RESINE project (French Ministry of
814 Ecology BGF Program 2005-2010, Grant #CV05000150) and developed under the
815 SEDYVIN research theme (Irstea). Some ideas and examples also come from the experience
816 of the authors, who belong to different collaborative groups involving researchers and
817 managers: GIS-Coopérative de données sur la croissance des peuplements forestiers, GIP
818 Ecofor, Conseil Scientifique BGF (Biodiversité et Gestion Forestière), CST ONB, CST

819 EFESE, Zone Atelier Alpes, Groupe Recherche des Réserves MAB. We thank Patrick
820 Blandin, Nigel Yoccoz, Claude Millier, Isabelle Arpin and Victoria Moore for valuable
821 comments on first drafts of the manuscript, three anonymous reviewers for their patient help
822 on improving the manuscript despite ontological differences, and Glen McCulley (ATT) for
823 English-language editing.

824

825 Appendix SM1. Supplementary Material related to this article can be found in
826 <https://doi.org/10.1016/j.jenvman.2018.04.025>.

827

828 **References:**

829 Banobi, J.A., Branch, T.A., Hilborn, R., 2011. Do rebuttals affect future science? *Ecosphere*
830 2, 1-11.

831 Barot, S., Abbadie, L., Couvet, D., Hobbs, R.J., Lavorel, S., Mace, G.M., Le Roux, X., 2015.
832 Evolving away from the linear model of research: A response to Courchamp et al. *Trends in*
833 *Ecology and Evolution* 30, 368-370.

834 Beatty, J., 1995. The evolutionary contingency thesis, in: Wolters, G., Lennox, J.G.,
835 McLaughlin, P. (Eds.), *Concepts, Theories, and Rationality in the Biological Sciences: The*
836 *Second Pittsburgh-Konstanz Colloquium in the Philosophy of Science*, University of
837 Pittsburgh, October 1-4, 1993. University of Pittsburgh Press, Pittsburgh, pp. 45-81.

838 Beck, M.W., 1997. Inference and generality in ecology: Current problems and an
839 experimental solution. *Oikos* 78, 265-273.

840 Belovsky, G.E., Botkin, D.B., Crowl, T.A., Cummins, K.W., Franklin, J.F., Hunter Jr., M.L.,
841 Joern, A., Lindenmayer, D.B., MacMahon, J.A., Margules, C.R., Scott, J.M., 2004. Ten
842 suggestions to strengthen the science of ecology. *BioScience* 54, 345-351.

843 Bestelmeyer, B.T., Miller, J.R., Wiens, J.A., 2003. Applying species diversity theory to land
844 management. *Ecological Applications* 13, 1750-1761.

845 Bi, H., 2001. The self-thinning surface. *Forest Science* 47, 361-370.

846 Bissonette, J.A., Storch, I., 2002. Fragmentation: Is the message clear? *Conservation Ecology*
847 6, 14.

848 Bormann, B. T., Martin, J.R., Wagner, G.F.H., Wood, G.W., Algeria, J., Cunningham, P. G.,
849 Brookes, M.H., Friesema, P., Berg, J., Henshaw, J. R., 1999, Adaptive management, in:
850 Sexton, W. T, Malk, A. J., Szaro, R. C., Johnson, N. C. (Eds.), *Ecological stewardship. A*
851 *common reference for ecosystem management*. Elsevier, Oxford, England, pp. 505-534.

852 Bouget, C., Lassauce, A., Jonsell, M., 2012. Effects of fuelwood harvesting on biodiversity –
853 a review focused on the situation in Europe. *Canadian Journal of Forest Research* 42, 1421-
854 1432.

855 Bouleau, N., 1999. *Philosophies des mathématiques et de la modélisation, Du chercheur à*
856 *l'ingénieur*, L'Harmattan, Paris, France.

857 Bunnell, F.L., Huggard, D.J., 1999. Biodiversity across spatial and temporal scales: problems
858 and opportunities. *Forest Ecology and Management* 115, 113-126.

859 Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jager, J.,
860 Mitchell, R.B., 2003. Knowledge systems for sustainable development. *Proceedings of the*
861 *National Academy of Sciences of the United States of America* 100, 8086-8091.
862 <https://doi.org/> Jul 8.

863 Castedo-Dorado, F., Crecente-Campo, F., Álvarez-Álvarez, P., Barrio-Anta, M., 2009.
864 Development of a stand density management diagram for radiata pine stands including
865 assessment of stand stability. *Forestry* 82, 1-16.

866 Charru, M., Seynave, I., Morneau, F., Rivoire, M., Bontemps, J.D., 2012. Significant
867 differences and curvilinearity in the self-thinning relationships of 11 temperate tree species
868 assessed from forest inventory data. *Annals of Forest Science* 69, 195-205.

869 Cordonnier, T., Gosselin, F., Bouget, C., Brézard, J.-M. , Allain, R., 2009. Gestion adaptative
870 ou gestion expérimentale du bois mort, des vieux arbres et des arbres à cavités : exercice de
871 prospective. *Rendez-Vous Techniques* 25-26, 34-37.

872 Courchamp, F., Dunne, J.A., Le Maho, Y., May, R.M., Thébaud, C., Hochberg, M.E., 2015.
873 Fundamental ecology is fundamental. *Trends in Ecology and Evolution* 30, 9-16.

874 Courtney, S. P., Blakesley, J. A., Bigley, R. E., Cody, M. L., Dumbacher, J. P., Fleischer, R.
875 C., Franklin, A. B., Franklin, J. F., Gutiérrez, R. J., Marzluff, J. M., Sztukowski. L., 2004.
876 Scientific evaluation of the status of the Northern Spotted Owl. Sustainable Ecosystem
877 Institute, Portland, Oregon.

878 Dayton, P.K., 2003. The importance of the natural sciences to conservation: (An American
879 Society of Naturalists Symposium Paper). *American Naturalist* 162, 1-13.
880 <https://doi.org/10.1086/376572>.

881 Di Stefano, J., 2001. Power analysis and sustainable forest management. *Forest Ecology and*
882 *Management* 154, 141-153.

883 Dorren, L., Berger, F., 2006. Balancing tradition and technology to sustain rockfall-protection
884 forests in the Alps. *Forest Snow and Landscape Research* 80, 87-98.

885 Dovers, S.R., Norton, T.W., Handmer, J.W., 1996. Uncertainty, ecology, sustainability and
886 policy. *Biodiversity and Conservation* 5, 1143-1167.

887 Driscoll, D.A., Lindenmayer, D.B., 2011. Framework to improve the application of theory in
888 ecology and conservation. *Ecological Monographs* 82, 129-147.

889 Duncan, S.L., Thompson, J.R., 2006. Forest plans and ad hoc scientist groups in the 1990s:
890 Coping with the forest service viability clause. *Forest Policy and Economics* 9, 32-41.

891 Fahrig, L., 2017a. Ecological responses to habitat fragmentation per se. *Annual Review of*
892 *Ecology Evolution and Systematics* 48, 1-23.

893 Fahrig, L., 2017b. Forty years of bias in habitat fragmentation research, in: P. Kareiva,
894 Marvier, M., Silliman, B. (Eds.), *Effective conservation science: data not dogma*. Oxford
895 University Press, Oxford, UK, pp. 32-38.

896 Failing, L., Gregory, R. Higgins, P., 2013. Science, uncertainty, and values in ecological
897 restoration: A case study in structured decision-making and adaptive management.
898 *Restoration Ecology* 21, 422-430.

899 Fazey, I., Fazey, J.A., Fazey, D.M.A., 2005. Learning more effectively from experience.
900 *Ecology and Society* 10, art. 4.

901 Fazey, I., Fazey, J.A., Salisbury, J.G., Lindenmayer, D.B., Dovers, S., 2006. The nature and
902 role of experiential knowledge for environmental conservation. *Environmental Conservation*
903 33, 1-10.

904 Fox, J. 2011. Zombie ideas in ecology. *Oikos Blog*.
905 <https://oikosjournal.wordpress.com/2011/06/17/zombie-ideas-in-ecology/> (accessed 17
906 January 2018).

907 Giuggiola, A., Bugmann, H., Zingg, A., Dobbertin, M., Rigling, A., 2013. Reduction of stand
908 density increases drought resistance in xeric Scots pine forests. *Forest Ecology and*
909 *Management* 310, 827-835.

910 Gosselin, F., 2009. Management on the basis of the best scientific data or integration of
911 ecological research within management? Lessons learned from the northern spotted owl saga
912 on the connection between research and management in conservation biology. *Biodiversity*
913 *and Conservation* 18, 777-793.

914 Gosselin, F., 2011. From ecology to ecological engineering: mainly through theory and
915 concepts? *Procedia Environmental Sciences* 9, 60-63.

916 Gosselin, M., Valadon, A., Bergès, L., Dumas, Y., Gosselin, F., Baltzinger, C., Archaux, F.,
917 2006. Prise en compte de la biodiversité dans la gestion forestière : état des connaissances et
918 recommandations. Rapport de convention Cemagref-ONF, Cemagref, Nogent-sur-Vernisson.

919 Graham, A.C., Kruger, L.E., 2002. Research in adaptive management working relations and
920 the research process. USDA Forest Service Pacific Northwest Research Station, Research
921 Paper.

922 Graham, I.D., Logan, J., Harrison, M.B., Straus, S.E., Tetroe, J., Caswell, W., Robinson, N.,
923 2006. Lost in knowledge translation: time for a map? *The Journal of Continuing Education in*
924 *the Health Professions* 26, 13-24.

925 Gray, A.N., 2000. Adaptive ecosystem management in the Pacific Northwest: a case study
926 from coastal Oregon. *Conservation Ecology* 4, 6.

927 Gregory, R., Ohlson, D., Arvai, J., 2006. Deconstructing adaptive management: Criteria for
928 applications to environmental management. *Ecological Applications* 16, 2411-2425.

929 Gregory, R., Failing, L., Harstone, M., Long, G., McDaneils, T., Ohlson, D., 2012. *Structured*
930 *Decision Making. A Practical Guide to Environmental Management.* Wiley-Blackwell.

931 Haila, Y., 2002. A conceptual genealogy of fragmentation research: From island
932 biogeography to landscape ecology. *Ecological Applications* 12, 321-334.

933 Hall, C.A., 1988. An assessment of several of the historically most influential theoretical
934 models used in ecology and of the data provided in their support. *Ecological Modelling* 43, 5-
935 31.

936 Haller, B.C., 2014. Theoretical and empirical perspectives in ecology and evolution: A
937 survey. *BioScience* 64, 907-916.

938 Hansson, L., 2003. Why ecology fails at application: should we consider variability more
939 than regularity? *Oikos* 100, 624-627.

940 Harrison, S., 1991. Local extinction in a metapopulation context – an empirical evaluation.
941 *Biological Journal of the Linnean Society* 42, 73-88.

942 Harrison, S., 1994, Metapopulations and conservation, in: P. J. Edwards, May, R. M., Webbs,
943 N. R. (Eds.), *Large-scale ecology and conservation biology*. Blackwell, Oxford (UK), pp.
944 111-128.

945 Hart, D.D., Calhoun, A.J., 2010. Rethinking the role of ecological research in the sustainable
946 management of freshwater ecosystems. *Freshwater Biology* 55, 258-269.

947 Hecht, A., Parkin, M.J., 2001. Improving peer review of listings and recovery plans under the
948 Endangered Species Act. *Conservation Biology* 15, 1269-1273.

949 Higgs, A.J., 1981. Island biogeography theory and nature reserve design. *Journal of*
950 *Biogeography* 8, 117-124.

951 Hilborn, R., Walters, C.J., 1981. Pitfalls of environmental baseline and process studies.
952 *Environmental Impact Assessment Review* 2, 265-278.

953 Howes, M., Wortley, L., Potts, R., Dedekorkut-Howes, A., Serrao-Neumann, S., Davidson,
954 J., Smith, T., Nunn, P., 2017. Environmental sustainability: A case of policy implementation
955 failure? *Sustainability* 9, art. 165.

956 Hulme, P.E., 2014. Bridging the knowing-doing gap: Know-who, know-what, know-why,
957 know-how and know-when. *Journal of Applied Ecology* 51, 1131-1136.

958 Hurlbert, S.H., 1984. Pseudoreplication and the design of ecological field experiments.
959 *Ecological Monographs* 54, 187-211.

960 Jasanoff, S., 1997, *Science at the bar*, Harvard University Press, Harvard.

961 Jasanoff, S., 2008. Speaking honestly to power. *American Scientist* 96, 3.

962 Johnson, L.S., 2005. From knowledge transfer to knowledge translation: Applying research to
963 practice. *Occupational Therapy Now* 7, 11-14.

964 Kuhlmann, J., 1997. Drug research: From the idea to the product. *International Journal of*
965 *Clinical Pharmacology and Therapeutics* 35, 541-552.

966 Lawton, J.H., 1999. Are there general laws in ecology? *Oikos* 84, 177-192.

967 Le Moguédec, G., Dhôte, J.-F., 2012. Fagacées: a tree-centered growth and yield model for
968 sessile oak (*Quercus petraea* L.) and common beech (*Fagus sylvatica* L.). *Annals of Forest*
969 *Science* 69, 257-269.

970 Lee, P.C., Crites, S., Nietfeld, M., Van Nguyen, H., Stelfox, J.B., 1997. Characteristics and
971 origins of deadwood material in aspen-dominated boreal forests. *Ecological Applications* 7,
972 691-701.

973 Linder, M., 2000. Developing adaptive forest management strategies to cope with climate
974 change. *Tree Physiology* 20, 299-307.

975 Long, J., Vacchiano, G., 2014. A comprehensive framework of forest stand property–density
976 relationships: perspectives for plant population ecology and forest management. *Annals of*
977 *Forest Science* 71, 325-335.

978 Ludwig, D., 2001. The era of management is over. *Ecosystems* 4, 758-764.

979 Ludwig, D., Hilborn, R., Walters, C., 1993. Uncertainty, resource exploitation, and
980 conservation: lessons from history. *Science* 260, 17-18.

981 McNie, E., 2007. Reconciling the supply of scientific information with user demands: an
982 analysis of the problem and review of the literature. *Environmental Science and Policy* 10,
983 17-38.

984 Marquet, P. A., Allen, A. P., Brown, J. H., Dunne, J. A., Enquist, B. J., Gillooly, J. F.,
985 Gowaty, P. A., Green, J. L., Harte, J., Hubbell, S. P., O'Dwyer, J., Okie, J. G., Ostling, A.,
986 Ritchie, M., Storch, D., West, G. B., 2014. On theory in ecology. *BioScience* 64, 701-710.

987 Mayr, E. 2004. What makes biology unique? Considerations on the autonomy of a scientific
988 discipline, Cambridge University Press, Cambridge.

989 Medema, W., McIntosh, B.S., Jeffrey, P.J., 2008. From premise to practice: A critical
990 assessment of integrated water resources management and adaptive management approaches
991 in the water sector. *Ecology and Society* 13, art. 29.

992 Mitchell, S.C., 2005. How useful is the concept of habitat? A critique. *Oikos* 110, 634-638.

993 Mouquet, N., Lagadeuc, Y., Devictor, V., Doyen, L., Duputié, A., Eveillard, D., Faure, D.,
994 Garnier, E., Gimenez, O., Huneman, P., Jabot, F., Jarne, P., Joly, D., Julliard, R., Kéfi, S.,
995 Kergoat, G.J., Lavorel, S., Le Gall, L., Meslin, L., Morand, S., 2015. Predictive ecology in a
996 changing world. *Journal of Applied Ecology* 52, 1293-1310.

997 Murphy, D.D., Noon, B.R., 1991. Coping with uncertainty in wildlife biology. *Journal of*
998 *Wildlife Management* 55, 773-782.

999 Nichols, J.D., Williams, B.K., 2006. Monitoring for conservation. *Trends in Ecology and*
1000 *Evolution* 21, 668-673.

1001 Nichols, J.D., Johnson, F.A., Williams, B.K., Boomer, G.S., 2015. On formally integrating
1002 science and policy: Walking the walk. *Journal of Applied Ecology* 52, 539-543.

1003 Ogden, A.E., Innes, J.L., 2009. Application of structured decision making to an assessment of
1004 climate change vulnerabilities and adaptation options for sustainable forest management.
1005 *Ecology and Society* 14, 11.

1006 Okland, B., Bakke, A., Hagvar, S., Kvamme, T., 1996. What factors influence the diversity of
1007 saproxylic beetles? A multiscaled study from a spruce forest in southern Norway.
1008 *Biodiversity and Conservation* 5, 75-100.

1009 Paul, E.A., Robertson, G.P., 1989. Ecology and the agricultural sciences: A false dichotomy?
1010 *Ecology* 70, 1594-1597.

1011 Peters, R. H., 1991. *A critique for ecology*, Cambridge University Press, Cambridge.

1012 Peterson, C.E., Anderson, P.D., 2009. Large-scale interdisciplinary experiments inform
1013 current and future forestry management options in the U.S. Pacific Northwest. *Forest*
1014 *Ecology and Management* 258, 409-414.

1015 Pickett, S. T., AKolasa, J., Jones, C. G., 2007. *Ecological understanding: The nature of the*
1016 *theory and the theory of nature*, Academic Press, San Diego.

1017 Pielke, R. A., 2007, *The honest broker: making sense of science in policy and politics*,
1018 Cambridge University Press, Cambridge.

1019 Prendergast, J.R., Quinn, R.M., Lawton, J.H., 1999. The gaps between theory and practice in
1020 selecting nature reserves. *Conservation Biology* 13, 484-492.

1021 Regan, H.M., Colyvan, M., Burgman, M.A., 2002. A taxonomy and treatment of uncertainty
1022 for ecology and conservation biology. *Ecological Applications* 12, 618-628.

1023 Renken, R.B., Gram, W.K., Fantz, D.K., Richter, S.C., Miller, T.J, Ricke, K.B., Russell, B.,
1024 Wang, X., 2004. Effects of forest management on amphibians and reptiles in Missouri Ozark
1025 forests. *Conservation Biology* 18, 174-188.

1026 Rigler, F. H. 1982. Recognition of the possible: an advantage of empiricism in ecology.
1027 *Canadian Journal of Fisheries and Aquatic Sciences* 39, 1323-1331.

1028 Rist, L., Campbell, B.M., Frost, P., 2013a. Adaptive management: Where are we now?
1029 *Environmental Conservation* 40, 5-18.

1030 Rist, L., Felton, A., Samuelsson, L., Sandström, C., Rosvall, O., 2013b. A new paradigm for
1031 adaptive management. *Ecology and Society* 18, 4.

1032 Romesburg, H.C., 1981. Wildlife science: gaining reliable knowledge. *Journal of Wildlife*
1033 *Management* 45, 293-313.

1034 Rothstein, H., Sutton, A., Borenstein, M., 2005. *Publication Bias in Meta-Analysis*, in:
1035 Rothstein, H., Sutton, A., Borenstein, M. (Eds), *Publication Bias in Meta-Analysis:*
1036 *Prevention, Assessment and Adjustments*, Wiley & Sons, Chichester, England, pp. 2-8

1037 Roux, D.J., Rogers, K.H., Biggs, H.C., Ashton, P.J., Sergeant, A., 2006. Bridging the
1038 science-management divide: Moving from unidirectional knowledge transfer to knowledge
1039 interfacing and sharing. *Ecology and Society* 11, art.4.

1040 Schulte, L.A., Mitchell, R.J., Hunter, M.L., Franklin, J.R., McIntyre, R.K., Palik, B.J., 2006.
1041 Evaluating the conceptual tools for forest biodiversity conservation and their implementation
1042 in the US. *Forest Ecology and Management* 232, 1-11.

1043 Schwarz, C.J., 1998. Studies of uncontrolled events, in: Taylor, V. S. (Ed.), *Statistical*
1044 *methods for adaptive management studies*. *Land Management Handbook*, Ministry of Forest
1045 Resources, Victoria (British Columbia), pp. 19-39.

1046 Seymour, R., Guldin, J., Marshall, D., Palik, D., 2006. Large-scale, long-term silvicultural
1047 experiments in the United States: historical overview and contemporary examples.
1048 *Allgemeine Forst und Jagdzeitung* 177, 104-112.

1049 Seynave, I., Bailly, A., Balandier, P., Bontemps, J.-D., Cailly, P., Cordonnier, T., Deleuze,
1050 C., Dhôte, J-F., Ginisty, C., Lebourgeois, F., Merzeau, D., Paillassa, E., Perret, S., Richter,
1051 C., Meredieu, C. 2018. GIS Coop: Networks of silvicultural trials for supporting forest
1052 management under changing environment. *Annals of Forest Science* 77, 48.

1053 Shrader-Frechette, K.S., McCoy, E.D., 1994. What ecology can do for environmental
1054 management. *Journal of Environmental Management* 41, 293-307.

1055 Simberloff, D. 1983. Competition theory, hypothesis-testing, and other community ecological
1056 buzzwords. *American Naturalist* 122, 626-635.

1057 Simberloff, D., 1998. Flagships, umbrellas, and keystones: Is single-species management
1058 passé in the landscape era? *Biological Conservation* 83, 247-257.

1059 Simberloff, D., 1999. The role of science in the preservation of forest biodiversity. *Forest*
1060 *Ecology and Management* 115, 101-111.

1061 Simberloff, D., 2004. Community ecology: Is it time to move on? (An American Society of
1062 Naturalists presidential address). *American Naturalist* 163, 787-799.

1063 Simberloff, D., Abele, L., 1976. Island biogeography theory and conservation practice.
1064 *Science* 191, 285-286.

1065 Sit, V., Taylor B. (Eds.), 1998. Statistical methods for adaptive management studies. *Land*
1066 *Management Handbook No.42*. Ministry of Forest Resources, Victoria (British Columbia).

1067 Smallwood, K.S., Beyea, J., Morrison, M.L., 1999. Using the best scientific data for
1068 endangered species conservation. *Environmental Management* 24, 421-435.

1069 Smith, M.A., Green, D.M., 2005. Dispersal and the metapopulation paradigm in amphibian
1070 ecology and conservation: are all amphibian populations metapopulations? *Ecography* 28,
1071 110-128.

1072 Stankey, G. H., Clark, R. N., Bormann, B. T., 2005. Adaptive management of natural
1073 resources: theory, concepts and management institutions. PNW-GTR-654, USDA Forest
1074 Service, Pacific Northwest Research Station, Portland, Oregon.

1075 Stringer, L.C., Dougill, A.J., Fraser, E., Hubacek, K., Prell, C., Reed, M., 2006. Unpacking
1076 “participation” in the adaptive management of social–ecological systems: a critical review.
1077 *Ecology and Society* 11, art.39.

1078 Sutherland, W.J., Pullin, A.S., Dolman, P.M., Knight, T.M., 2004. The need for evidence-
1079 based conservation. *Trends in Ecology and Evolution* 19, 305-308.

1080 Thiffault, E., Hannam, K.D., Paré, D., Titus, B.D., Hazlett, P.W., Maynard, D.G., Brais, S.,
1081 2011. Effects of forest biomass harvesting on soil productivity in boreal and temperate forests
1082 - A review. *Environmental Reviews* 19, 278-309.

1083 Underwood, A.J., 1995. Ecological research and (and research into) environmental
1084 management. *Ecological Applications* 5, 232-247.

1085 Underwood, A.J., 1998. Relationships between ecological research and environmental
1086 management. *Landscape and Urban Planning* 40, 123-130.

1087 Van Kerkhoff, L., Lebel, L., 2006. Linking knowledge and action for sustainable
1088 development. *Annual Review of Environment and Resources* 31, 445-477.

1089 Walters, C.J., 2007. Is adaptive management helping to solve fisheries problems? *Ambio* 36,
1090 304-307.

1091 Walters, C.J., Holling, C.S., 1990. Large-scale management experiments and learning by
1092 doing. *Ecology* 71, 2060-2068.

1093 Watanabe, S., 1975. Needed: a historico-dynamical view of theory change. *Synthese* 32, 113-
1094 134.

1095 Weiner, J., 1995. On the practice of ecology. *Journal of Ecology* 83, 153-158.

1096 Young, J.C., Waylen, K., Sarkki, S., Albon, S., Bainbridge, I., Balian, E., Davidson, J.,
1097 Edwards, D., Fairley, R., Margerison, C., McCracken, D., Owen, R., Quine, C.P., Stewart-
1098 Roper, C., Thompson, D., Tinch, R., Van den Hove, S., Watt, A., 2014. Improving the
1099 science-policy dialogue to meet the challenges of biodiversity conservation: having
1100 conversations rather than talking at one-another. *Biodiversity and Conservation* 23, 387-404.

Interface type	Knowledge source	Flow of knowledge	Driving forces of knowledge at research/management interfaces	Types of knowledge	Underwood (1995)'s categories of ecological research
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.

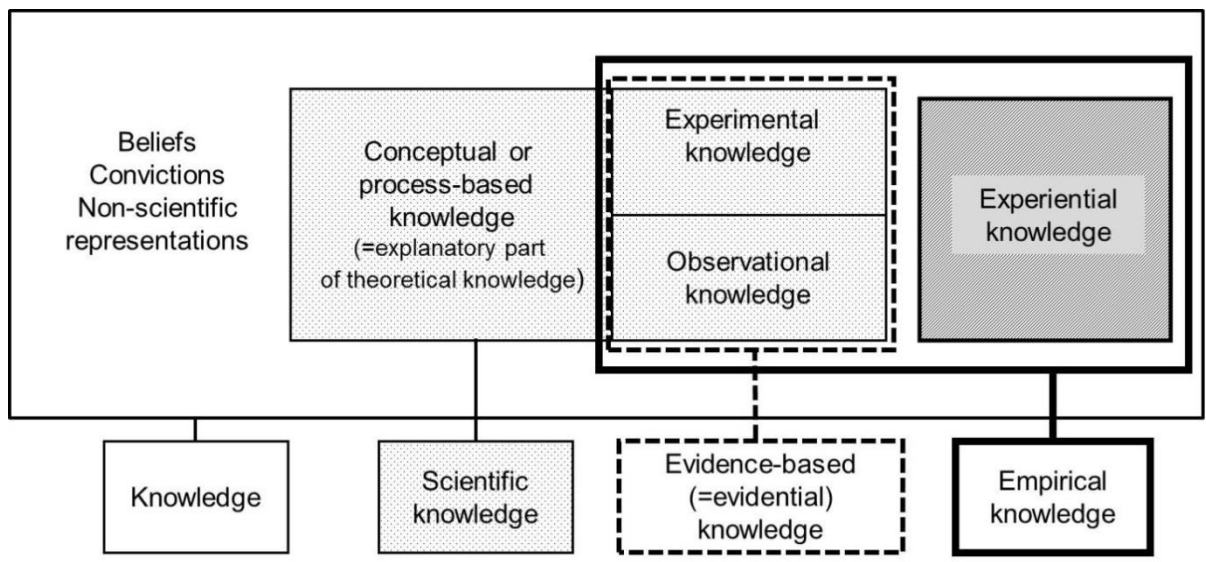


Figure 1. Relative positions of the different types of ecological knowledge and representations as defined and discussed in this paper. This figure illustrates some of the definitions in the text and in Appendix SM1.

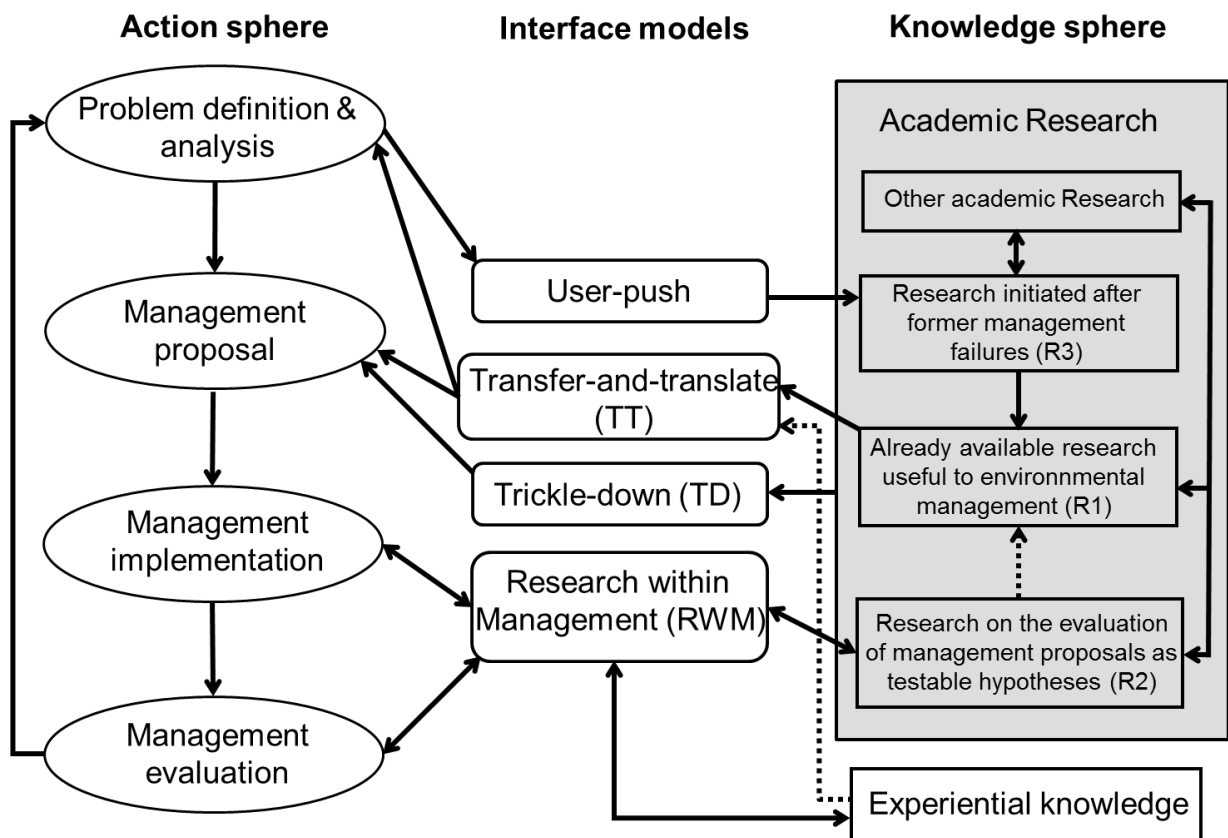


Figure 2. Relationships between the knowledge sphere and the action sphere according to the first three categories of ecological research useful for management (R1, R2, R3) identified by Underwood (1995) and the four types of interfaces discussed in this paper. For ease of graphical representation, the 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:

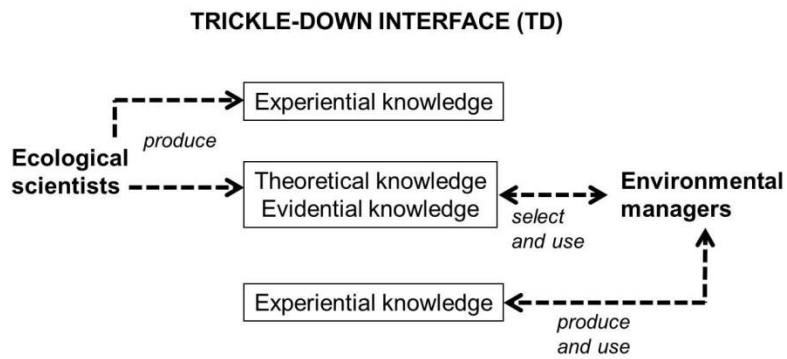


Figure 3b:

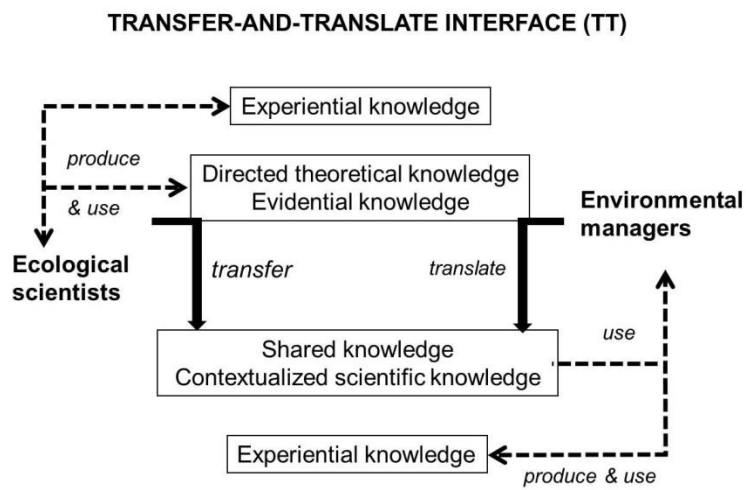


Figure 3c:

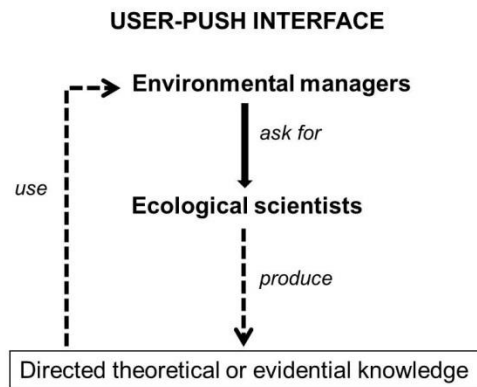


Figure 3. Schematic representation of the three unidirectional interfaces discussed in section 2: trickle-down (TD; Figure 3a), transfer-and-translate (TT; Figure 3b) and user-push (Figure 3c). This figure shows the links (arrows) between actors and types of knowledge. Boxes represent the different types 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)

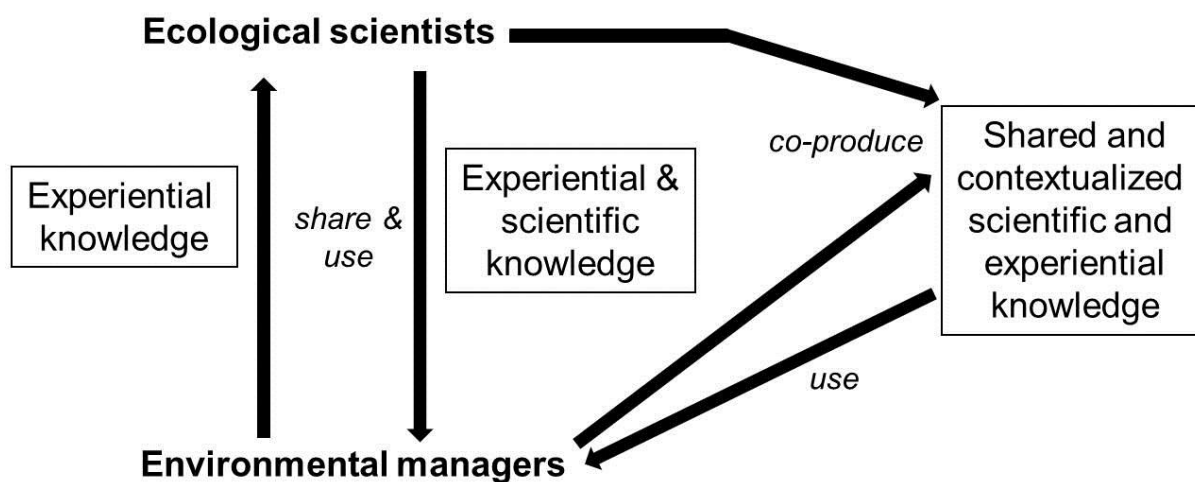


Figure 4. Schematic representation of the Research-within-Management type of research–management interface, showing the links (arrows) between actors and types of knowledge. Boxes represent the different types of knowledge used or produced. In contrast with the unidirectional interfaces in Figure 3,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