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Review

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

Frédéric Gosselin [a,*], Thomas Cordonnier [b], Isabelle Bilger [a], Marielle Jappiot [c], Christophe Chauvin [b], Marion Gosselin [a]

[a] Irstea, UR EFNO, Domaine des Barres, 45290, Nogent-sur-Vernisson, France
[b] Université Grenoble Alpes, Irstea, UR LESSEM, 2 rue de la Papeterie, BP76, 38402, Saint-Martin-d'Hères Cedex, France
[c] Irstea, UR RECOVER/EMR, 3275 Route de Cézanne, CS 40061, 13182, Aix-en-Provence Cedex 5, France

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ABSTRACT

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

(i) explicitizing the link between three categories of ecological research and the type of research–management interface they are associated with. We first evaluate three types of unidirectional interfaces and recommend a new kind of interface – called the Research-Within-Management interface (RWM).
(ii) suggesting that adaptive management and structured decision-making can integrate all these different angles and serve as meta-interfaces in their relation to research.
(iii) distinguishing explanatory knowledge from empirical knowledge, and contending that explanatory knowledge is not necessarily the most important output for the research-management interface today.
(iv) highlighting that experiential ecological knowledge—including the expertise and experience of managers, citizens and scientists—is another primary knowledge input in environmental decision-making that should not be systematically downplayed.

We point out the complementarities as well as the specificities and limitations of the different types of ecological research, ecological knowledge and research–management interfaces, which is of major importance for environmental management and research policies.

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* Corresponding author.
E-mail address: frederic.gosselin@irstea.fr (F. Gosselin).

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1. Introduction

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

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

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

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

(P2) Other authors consider that not all types of interfaces between research and management (see Table 1) provide efficient links between ecological results and management practices. In what follows, we define an interface as both "the place at which independent and often unrelated systems meet and act on or communicate with each other", which is close to the notion of boundary, and "the means by which interaction or communication is achieved at an interface" (Merriam-Webster's Collegiate Dictionary, 10th Edition), which is related to the notion of boundary work. The notions of interface and boundary naturally emerge as soon as we recognize that research and management are very different in many regards (e.g. evaluation systems, risks involved, temporal horizon, public scrutiny and opinion) (Cash et al., 2003). Cash et al. (2003) insisted that conscientious work needs to be done at the boundary between research and decision making, while Roux et al. (2006), Van Kerkhoff and Lebel (2006), and Hart and Calhoun (2010) stressed that classical unidirectional interfaces from research to management are not sufficient to appropriately integrate scientific knowledge into environmental management.

(P3) Focusing on the research side of the interface, Underwood (1995) believes that recognizing four different categories of ecological research would enhance interactions between ecological research and management decisions (see Table 1 and Fig. 2). Category 1 research (R1) is either "directed to the needs of management" or refers to existing results from ecological research that managers may find useful to "evaluate problems, validate the questions and formulate models of the system being managed"

[1] A star *flags the first occurrence of words that we define in the Glossary found in Supplementary Material Appendix A.

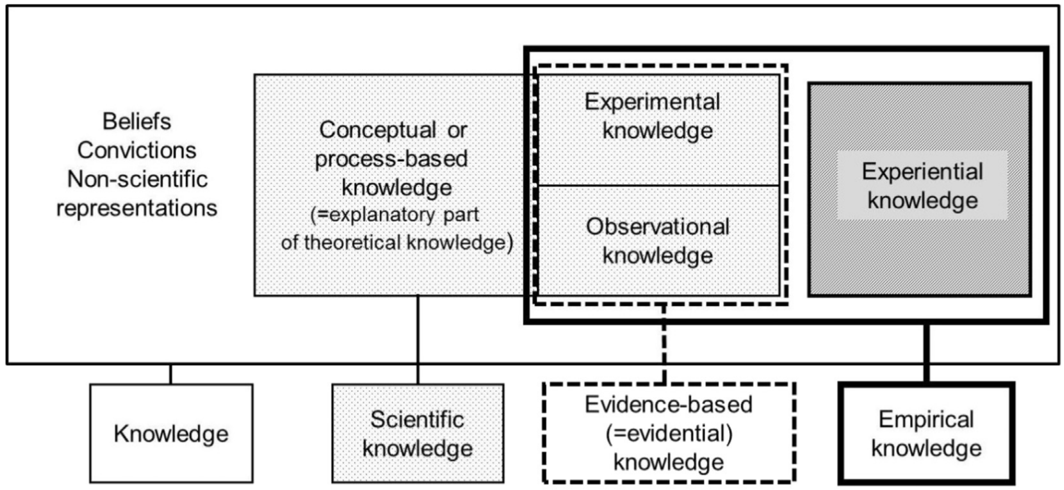

Fig. 1. Relative positions of the different types of ecological knowledge and representations as defined and discussed in this paper. This figure illustrates some of the definitions in the text and in Appendix A.

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

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)

(Underwood, 1995, Figure 11, p.234). Category 2 research (R2) is mobilized within management, when management practices become relevant hypotheses that need to be tested rather than proven "solutions". If these management hypotheses fail, Category 3 research (R3) aims to develop new ecological knowledge in order to explain the management failure observed. Category 4 research (R4) is "managerial", and carries two strands: 1) ecologists analyze *a posteriori* how the ecological information is used by managers to reach their decisions; and 2) social scientists investigate how the management decision process works.

(P4) Some authors have insisted that comprehensive management frameworks such as adaptive management (Bormann et al., 1999; McNie, 2007; Rist et al., 2013a, 2013b; Stankey et al., 2005; Walters and Holling, 1990) or structured decision-making (Failing et al., 2013; Gregory et al., 2012) are key to a better connection between ecological research and environmental management, as they can orchestrate different research categories and research–management interfaces in a structured way around a given management problem.

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

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

(i) In sections 2–3, we explicitly connect Underwood's first three categories of ecological research R1 to R3 (P3) with different types of research–management interfaces (P1; see Table 1, Fig. 2): R1 with the transfer-and-translate interface*,

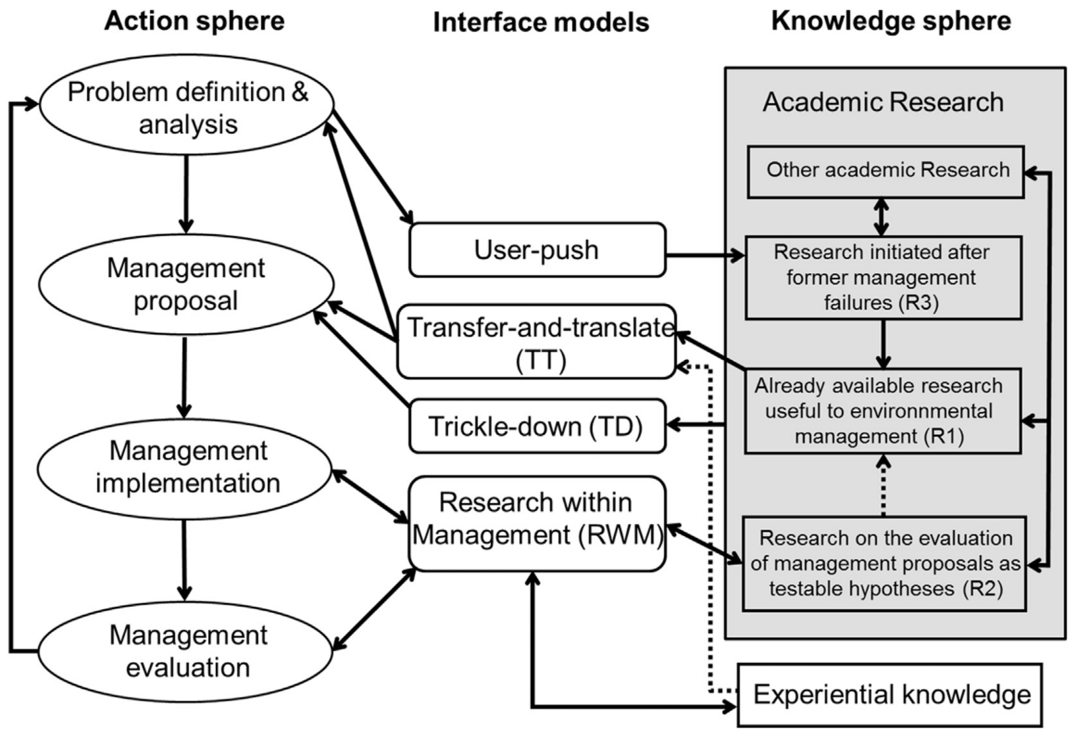

Fig. 2. Relationships between the knowledge sphere and the action sphere according to the first three categories of ecological research useful for management (R1, R2 & R3) identified by Underwood (1995) and the four types of interfaces discussed in this paper. For ease of graphical representation, the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

R3 with the user-push interface*. For R2, we introduce the RWM interface type to distinguish real integrated R2 projects, where the variable to be tested is the management practice itself, from R1 projects, where the variable to be tested, though linked to management, is not a management practice. R4 ("managerial ecological research") will not be developed in this paper because it is positioned at a higher level of integration involving social science that we do not extensively address here. Our position—centered on the interface between *ecological* research and management—enables us to keep a sharper focus in terms of the types of knowledge involved, both scientific and experiential.

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

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

2. Assessment of unidirectional interface types

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

2.1. The trickle-down interface and Category-1 research: a straightforward but oversimplistic interface type

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

2.1.1. Why the trickle-down interface is so popular

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

Second, TD is popular because of the way ecology promotes, presents and evaluates its results. Data confirming ecologically “fashionable” theories are likely to be more published and cited than data contradicting such theories (Fahrig, 2017b; Hall, 1988; Fahrig, 2017b), which leads to the well-known publication bias in meta-analyses (Rothstein et al., 2005). Furthermore, even if rebuttals are published, they do not strongly affect how we consider and cite the original results (Banobi et al., 2011). In the same vein, ecology often favors theories with good explanatory credibility (Pickett et al., 2007) rather than good evidential credibility (Mouquet et al., 2015; Peters, 1991; Rigler, 1982). Both approaches are inherent to the scientific process (Rigler, 1982), but in ecology we might too often consider explanatory theories to be the only ones worthy of interest. The emphasis on explanatory credibility ahead of predictive power and evidential credibility, together with an artificially homogeneous record of publications and citations, promotes a simplistic view of research results. This may in turn favor a simplistic view of knowledge transfer, making TD appear suitable.

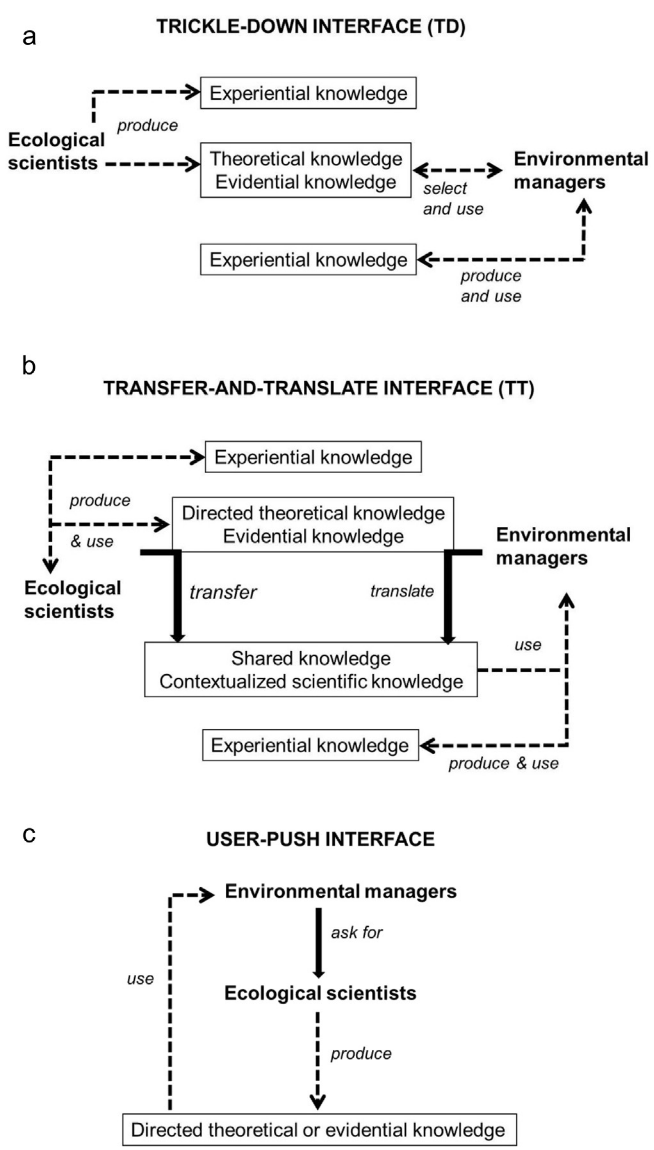

Fig. 3. Schematic representation of the three unidirectional interfaces discussed in section 2: trickle-down (TD; Fig. 3a), transfer-and-translate (TT; Fig. 3b) and user-push (Fig. 3c). This figure shows the links (arrows) between actors and types of knowledge. Boxes represent the different types of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

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

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

2.1.2. Limitations of directly using ecological results in the trickle-down interface

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

Second, theories may be misused when applied outside their domain of validity. Indeed, there may be a significant difference between the conditions or hypotheses under which they were developed and evaluated and the varied, complex environments within which they are subsequently applied (Beck, 1997; Bissonette and Storch, 2002; Bunnell and Huggard, 1999; Haila, 2002; Harrison, 1994; Schulte et al., 2006). A good example is when one variable has extreme levels in a scientific experiment, e.g. in predator or competitor density studies (Belovsky et al., 2004; Schulte et al., 2006). Another example is the concept of keystone species (Beck, 1997; Simberloff, 1998), where the theory was generalized from a few small-scale experiments, although further tests strongly limited the generalizability of the concept. Similarly, despite the intellectual pull of the notion, fully-functioning metapopulations in their strictest sense are not the rule (Harrison, 1991; Smith and Green, 2005), and applying metapopulation theory—such as to guide a biodiversity conservation strategy in the absence of further data—would be misleading (e.g. Harrison, 1994). The same is true for island biogeography theory (Haila, 2002). These examples illustrate that lacking a clear delimitation of the validity of a theory, or assuming its domain of validity is the same in the academic sphere as in management contexts, often leads to problems. Using Cash et al.'s (2003) words, it means that too often, the credibility of scientific results is insufficiently distinguished from the true salience of those results.

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

Fourth, the link between theory and application in management is sometimes based on an inadequate deductive construct. According to Simberloff (1983), this was the case for the IUCN considerations on reserves design in 1980: "the main recommendation advocated in the name of the theory—single large rather than clusters of small ones [refuges]—is not a consequence of the theory", since application requires a host of additional, context-specific parameters (proportion of species in common between reserves, slope of species–area curve, scale of the reserve; Higgs, 1981; Simberloff and Abele, 1976).

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

2.2. The transfer-and-translate (TT) interface and category-1 research: a more balanced intermediate unidirectional interface type

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

TT is still a unidirectional interface: the knowledge moves one way, from research to management, with a research-push* driving force on one side and a user-pull * driving force on the other (cf. Fig. 3b and Table 1), which means the associated category of ecological research is R1. Research and management are still only weakly integrated in this interface type, as are scientific and experiential knowledge. However, TT does make a first step towards interaction, as transferors and translators consult, adapt and translate scientific publications with the users' needs in mind.

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

2.2.1. Academic transferors on the research-push side of the interface

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

The third step of knowledge transfer is more targeted to a specific audience and uses what Graham et al. (2006) call third-generation scientific knowledge. This corresponds to the dissemination phase of knowledge transfer in Johnson (2005). A typical example is when researchers write and present summaries of the state-of-the-art research, typically in the form of best-practice guides. Such knowledge overviews are often carried out at the request of managers. Another example is when managers ask researchers to assess which scientific knowledge is most useful and applicable for the case at hand (Underwood, 1995). External scientific review adds further depth and rigor to the process (Hecht and Parkin, 2001; Smallwood et al., 1999; Underwood, 1995). For instance, ecologists were actively involved in the case of the Northern spotted owl in Northwestern USA, either as scientific experts in ad-hoc scientific groups or as reviewers through professional scientific academic societies (Duncan and Thompson, 2006; Gosselin, 2009; Murphy and Noon, 1991).

2.2.2. Translators on the user-pull side of the interface

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

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

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

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

2.3. The user-push interface and R3 ecological research

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

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

In a more general user-push interface setting, managers may ask researchers to produce knowledge that will inform their future management, such as when they launch calls for tenders in applied research. In France, several research programs have stressed the need for research that can ultimately be readily used by environmental managers: involving managers in the research projects is highly appreciated and is taken into account during the selection process. Moreover, some of these programs include one or several events (e.g. meetings) or outputs (e.g. books) designed to speed the transfer of research results to the management sphere. This is an example of a boundary-spanning institution created to enhance effective scientific advice in environmental management, as recommended by Cash et al. (2003).

In addition to calls for research projects, some research can be programmed through specific agreements between a research institute and a management organization. For instance, the French National Forestry Service (ONF) has had a years-long partnership with the French National Research Institute of Science and Technology for Environment and Agriculture (Irstea) to rebuild its policy on biodiversity preservation in public forests (Gosselin et al., 2006). Similarly, several members of the French Forest Health Department (DSF) are hosted within INRA research laboratories to boost research/management interactions.

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

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

2.4. Comparing unidirectional interface types

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

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

However, in TD and TT, contrary to the recommendations of Hart and Calhoun (2010) and Hulme (2014), most of the knowledge is produced within and for the research sphere, without considering *a priori* whether it will be useful for or transferable to managers. Researchers will screen pre-existing scientific results for those that could be transferable to specific management objectives. Some results may get selected and transferred and even end up providing an adequate response to certain management issues, but more by chance than by design. In TT, there is no assurance that existing scientific knowledge contains appropriate information for transfer. Although the user-push interface diminishes this drawback, interaction with managers remains limited in all three unidirectional interfaces.

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

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

3.1. R2 and RWM

Underwood (1995) defines R2 as "applied environmental research aimed at specific tests of the results of decisions made by managers by treating these decisions as testable hypotheses". The goal is to address key issues identified by managers (e.g. dead wood management or green tree retention in forest cuts) or, in some cases, by pressure groups or even society as a whole. In order to guarantee its management-integrated signature, R2 follows three main principles (Underwood, 1995, 1998): (i) it specifically studies management options by considering them as explicit testable hypotheses; (ii) it relies on experiments or structured observations at spatial and temporal scales corresponding to the scale at which environmental management is applied; and (iii) its research designs take into account the variability of the ecological conditions found in the managed areas.

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

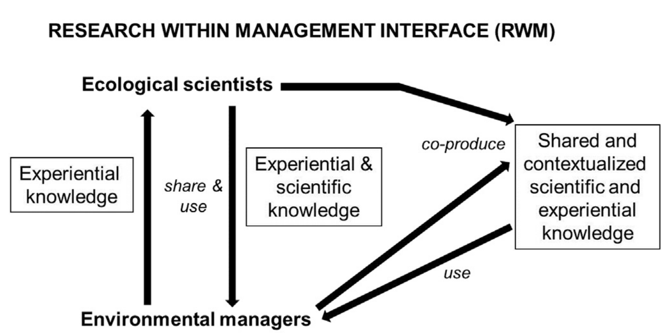

Fig. 4. Schematic representation of the Research-within-Management type of research—management interface, showing the links (arrows) between actors and types of knowledge. Boxes represent the different types of knowledge used or produced. In contrast with the unidirectional interfaces in Fig. 3, this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

outcomes of a management option falls under the scope of R2.

The second and third principles of R2 call for multi-site experiments or structured observations which compare management alternatives in different ecological conditions. Multi-site experiments or structured observations usually increase the level of inference of the results and provide opportunities for unexpected output, both of which in turn stimulate interactions between scientists and managers (Sit and Taylor, 1998). This kind of approach has been adopted in forest ecosystems in France to test different stand density regimes for several tree species at different sites. A specific collaborative research network (GIS Coop: Scientific Interest Group Cooperative for data on forest tree and stand growth; Seynave et al., 2018) involving both forest managers and forest scientists has been set up to manage and monitor these long-term experiments. From inception, the aim of these experiments has been twofold: 1) to improve silvicultural results (stand growth, tree growth and wood quality) for managers, and 2) to improve future forest growth models for both managers and researchers. Finally, as R2 explicitly considers management options, it mobilizes non-scientific data such as descriptive information on natural resources used for forest management, and even experiential knowledge (Dorren and Berger, 2006; Ogden and Innes, 2009).

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

3.2. When should RWM and R2 be considered?

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

Ludwig et al. (1993) proposed that "actions that are robust to uncertainties" and "actions that are informative" should be favored. The latter case appears to justify choosing RWM when there is a strong structural uncertainty (Regan et al., 2002) about the managed system. Strong uncertainty usually arises when two phenomena co-occur: (i) existing theories do not provide quantitative predictions or matured hypotheses about the relationship between the management practices and the ecosystem properties, and (ii) the management practices are too recent to draw feedback from past experience. This case can be illustrated in the context of ecosystem adaptation to climate change. A current management recommendation in forestry is to reduce stand density to improve tree water balance and stand resistance to drought (Linder, 2000). Although models and field studies exist (e.g. Giuggiola et al., 2013), there are few general guidelines enabling managers to target stand densities that increase stand health and maintain high wood productivity. More experiments are needed to clarify the appropriate density levels for different species in different ecological situations, and RWM is well geared to that purpose.

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

RWM should also be selected rather than more classical unidirectional interfaces when management practices are very specific. Examples include the short- and long-term impacts of mechanized wood harvesting on forest soil compaction and soil functioning, or fuelwood extraction, which may involve whole tree removal (Thiffault et al., 2011). RWM is also valuable when the available research results deal with variables that are not directly targeted by management practices, as in the case of deadwood management in temperate and boreal forest ecosystems. The amount of deadwood depends on stand productivity, but also on different management practices such as deadwood removal, hollow tree retention and leaving logging remnants (Lee et al., 1997). It is quite a challenge to unravel the direct impact of such management practices on deadwood quantity and quality, two major indicators of saproxylic species diversity (Bouget et al., 2012). Here again, experiments controlling for management practices may help test the efficiency of these practices in producing various deadwood structures.

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

3.3. *Limitations of R2 and RWM*

The main limitation concerns the spatial scale of R2 studies, which is usually broader than for standard scientific studies. Addressing the management scale requires large *in situ* experimental and observational units (Renken et al., 2004; Walters and Holling, 1990). Moreover, to reach an acceptable level of generality, the experiments or structured monitoring used in RWM must be replicated in different ecological conditions. These technical constraints have been outlined by several authors (e.g. Peterson and Anderson, 2009; Seymour et al., 2006). In some circumstances, R2 can be conducted at a scale smaller than the usual management scale, provided that management issues are still addressed. For instance, small but highly replicated experiments on regeneration operations in forestry would suffice to gain valuable operational results applicable at management-unit level.

A second limitation, closely related to the first, is that R2 experimental units are often quite large, which makes local replication difficult, thus limiting statistical power. A higher experimental residual error due to variations in management practices and unpredictable disturbance events (i.e. windstorms in forests) can accentuate this limitation (Hurlbert, 1984). This raises the question of what type of statistical analysis to use in such experiments. One option in classic frequentist approaches is to increase the p-value for hypothesis testing in linear models (Di Stefano, 2001). Unreplicated experiments can mobilize other approaches such as Bayesian statistics and decision analysis (Sit and Taylor, 1998). Enhanced impact designs could also be considered (Schwarz, 1998).

A third limitation is embedded in the RWM itself. Close interaction between researchers and managers may complicate the execution of experiments by involving different partners with different prerogatives and cultures. Experimental approaches may necessitate modifying or controlling management practices, or conversely, management practices may put constraints on scientific observations and planning. Institutional support is required to establish lasting partnerships between the research and management spheres, but institutions can be weakened by factors such as structural reforms, financial problems or changes in priorities (Gray, 2000).

To overcome these limitations, RWM usually mobilizes a high level of resources, which can be a major constraint at some institutions or in some economies. In these cases, it might be possible, as suggested by Rist et al. (2013b) for adaptive management, to reduce the cost of RWM by addressing only a subpart of the research question or management issue being tackled.

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

Adaptive management (AM) is “an approach to managing complex natural systems that builds on learning—based on common sense, experience, experimentation, and monitoring—by adjusting practices based on what was learned” (Bormann et al., 1999). As AM mobilizes different research–management interfaces at different steps in its adaptive cycle, it can prove an effective meta-interface framework in relation to research. In this regard, AM does not necessarily put to use all of the interface types mentioned earlier, but it can implement one or more of them depending on the management phase, complexity and collaborative nature of the AM project considered. From this perspective, AM can serve to intensify interactions between ecological research and environmental management.

AM projects can take different forms, from tests of simple practices in small management units (e.g. fertilization trials) to large, complex experiments carried out at catchment or landscape scale (Gregory et al., 2006). AM is usually represented by an adaptive cycle with a sequence of different phases related to scheduling, implementation and evaluation processes.

After defining objectives and desired outcomes, AM defines management scenarios by combining and sharing knowledge. AM cycles usually start with an in-depth analysis of the question addressed and a comprehensive overview of the state-of-the-art, which may enroll TT as well as R1 (cf. section 2.2). During this phase, and depending on the level of uncertainty (Gregory et al., 2006), researchers and managers interact to identify key issues, build models, and define the main hypotheses through a collaborative (Graham and Kruger, 2002) or even a participatory approach (Stringer et al., 2006). Given our limited understanding of the complex components and operating rules in ecosystems (Hilborn and Walters, 1981; Underwood, 1998), management options are generally identified and selected based on *a priori* assumptions of how the system functions and how it could respond to management practices. The hypothesis framing phase requires scientific knowledge and methodology to specify potential ecosystem responses (both structural and functional) to management practices (Underwood, 1995) and try to link these practices with potentially multiple theories (Nichols et al., 2015). However, the experiential knowledge of managers is equally essential to avoid pitfalls, help define the range of relevant practices, and help identify the mechanisms at work.

The next phase of AM includes management implementation, monitoring and evaluation. This phase comes quite close—at least for the ecological part of the management plan—to RWM and R2 (see section 3), as it involves updating the degree of evidence of alternative theories that have been deemed related to the management practice (Nichols et al., 2015). Moreover, in its most developed form, AM integrates many of the points that Underwood (1995) highlighted for R2. For instance, active AM is based on using ecological experimental procedures to test the hypotheses made by managerial agencies and evaluate the effects of different management options (Stankey et al., 2005). However, AM has a broader scope than R2. It aims not only to assess the effects of management but also to learn about the management process itself through double-loop learning (Stankey et al., 2005), which is not a primary goal for R2. Authors' opinions vary (Medema et al., 2008), but AM can involve many stakeholders (managers and citizens) and promote inter-disciplinarity. This means that AM can potentially integrate Underwood (1995)'s R4 research ("managerial ecological research"), which is not a prerequisite for R2.

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

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

The upshot is that structured decision-making (SDM) is usually considered a more realistic way of conducting a project dealing with environmental management issues (Gregory et al., 2012). SDM is "a prescriptive approach to environmental decision-making that facilitates better choices based both on theories of rational choice and the judgmental limitations of decision-makers and stakeholders" (Failing et al., 2013). Beyond applied ecology, SDM involves decision and cognitive sciences, recognizes the importance of values in decision-making, and advocates specific analytical methods to address complex environmental issues. It is based on a succession of critical steps that deal with the way the problem is framed, how relevant options are defined, and how trade-offs are analyzed. Although the learning process and the research–management interface are mentioned in SDM, they appear to be less fundamental than in the AM framework: the ultimate goal of SDM is to enable managers to make decisions in a temporal scale that is compatible with management planning. Overall, SDM appears closer to Underwood's R4 which analyzes how managers and ecologists make decisions. Nevertheless, we propose that SDM can occasionally transform itself into an AM process when uncertainty, lack of knowledge and learning are found to be limiting factors in the management process. Alternatively, AM projects could benefit from being implemented inside a SDM process (Failing et al., 2013).

5. The roles of experiential and fundamental ecological knowledge

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

5.1. Importance of experiential knowledge

There is no escaping the fact that scientific ecological knowledge does have limits when it comes to management applications. In addition, management projects can usefully employ other non-scientific sources of ecological knowledge: Roux et al. (2006) identified various sources of relevant knowledge outside the scientific sphere, namely among policymakers, managers, naturalists, or broader societal communities. Here, experiential knowledge plays a central role. There are several different categories of experiential knowledge: first of all, knowledge of natural history; second, the experiential knowledge that scientists use to draw analogies with similar contexts previously investigated in the framework of case studies (Simberloff, 2004); and third, the experiential knowledge of managers when they draw judgments on the feasibility of a management plan (see sections 3 and 5). The following discussion focuses mainly on natural history, which we think is a cornerstone.

We will treat natural history as an art or a craft rather than a science (Peters, 1991; Weiner, 1995), although many scientists have considerable natural history knowledge and can use it as a form of pre-theoretical knowledge, e.g. as a source of scientifically testable hypotheses. Ecology and natural history share a common subject, and ecologists themselves recognize that "there is much knowledge in the art of natural history" (Weiner, 1995; see also Hansson, 2003). Empirical ecology—especially the study of natural patterns – could even be called "quantitative natural history", following Weiner (1995) who goes on to state that "one of the goals of ecological science is to transform this intuitive knowledge into scientific knowledge, and thus enable us to extend it". Natural history, either alone or combined with scientific ecological knowledge, can help choose which ecological scientific results or theories are useful in a given management situation (Dayton, 2003, Fazey et al., 2005, 2006). Both Weiner (1995) and Hansson (2003) assert that experiential ecological knowledge is the best source of ecological knowledge for managers today, but it is not always mentioned in the literature linking ecological research and management, such as Underwood (1995), Bestelmeyer et al. (2003) and Courchamp et al. (2015).

To better valorize experiential knowledge, we need to change the vision of knowledge transfer. The relatively inefficient traditional vision considers a unidirectional flow of scientific knowledge from researchers (as the only knowledge-producers) to managers or policymakers (as mere knowledge-consumers) (see section 2).

Our vision is that experiential knowledge, whatever its origin, should at least have a more explicit place in this transfer interface, and should complement R1 results as a useful knowledge source for devising management options. Roux et al. (2006; see also Hulme, 2014) promoted a more thorough vision that consists in an effective bidirectional flow of knowledge, like the RWM we propose in section 3, taking into account all types of knowledge and enabling new knowledge to be shared and co-constructed.

However, for knowledge to be efficiently shared between communities, there are cultural barriers to overcome. Sharing knowledge that has already been explicitly formulated—like scientific information—is relatively easy, even though doing so generally requires translation (see section 2.2 and Cash et al., 2003). However, a large—and crucial—part of experiential knowledge is tacit knowledge (Roux et al., 2006), a hidden part of knowledge that is personal and difficult to formalize. Sharing tacit knowledge requires spending time in face-to-face interactions. This is a first step towards formulating tacit knowledge in a more explicit way, through efforts to explain things to other communities. Boundary structures between research and management can do this: Cash et al. (2003) give the example of the International Maize and Wheat Improvement Center which allowed traditional farmers to convert their tacit knowledge into information useful to crop breeders. RWM and AM (cf. sections 3 and 4) both offer a suitable forum to do this, by defining shared hypotheses and testing new management schemes partly based on tacit knowledge of different types (natural history, managerial, and so on). In addition to producing new scientific knowledge inside the action cycle, R2 and RWM should therefore recognize—and even foster (Fazey et al., 2005) —concurrent planned, or unplanned, development of experiential knowledge. This recognition should bring about better dialog, and could better integrate both types of knowledge within the management sphere, and in turn improve the acceptance of research results (Graham et al., 2006; Hulme, 2014; Roux et al., 2006).

5.2. Importance of fundamental knowledge

Applied ecological research also needs to be closely linked with fundamental ecology. This is acknowledged in Fig. 2, where fundamental research is mostly hosted in “Other academic research”, a category that strongly interacts with the different categories of applied ecological research. Fundamental ecological research—whose aim is “primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts without any particular application in view” (Courchamp et al., 2015, p.10)—enables scientists to explore situations or processes that cannot be investigated inside the management process. Fundamental research also helps reformulate questions, potentially through new concepts or formalisms (Romesburg, 1981; Pickett et al., 2007). It leaves a door open to new knowledge on ecological processes, which could help us understand what is going on in managed ecosystems, or help devise new practices to be tested.

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

Ecology would do well to reconcile the explanatory and empirical perspectives, and to couple the two more effectively (Haller, 2014; Hansson, 2003; Marquet et al., 2014; Weiner, 1995). Indeed, in ecology, we seem to neglect the gap between theoretical development and the first tests or applications in management. Instead of the “physics envy” they often manifest (Gosselin, 2011; Simberloff, 2004), ecologists should perhaps develop a stronger affiliation with “clinical envy”—e.g. by mimicking the successive phases I, II, III and IV in drug development trials (e.g.Kuhlman, 1997). This mirrors the tension between ecologists and agronomists, as summarized by Paul and Robertson (1989): “ecologists tend to view agronomists as strict empiricists, and agronomists tend to view ecologists as overly theoretical purveyors of the obvious”.

6. Conclusion

This paper is, to our knowledge, the first attempt to narrow the gap between ecological science and environmental management by combining three perspectives: (i) the different categories of ecological research useful for environmental management, *sensu* Underwood (1995); (ii) the different interfaces between research and management; (iii) the different types of ecological knowledge useful for environmental management. After first evaluating the trickle-down (TD) interface, we identified three types of interfaces connected to Underwood's research categories (R1, R2, R3) and described their limitations and usefulness: (i) the transfer-and-translate (TT) interface is related to the most classic type of applied ecological research (R1); (ii) the user-push interface initiated by users' questions is related to Underwood's R3; and (iii) the bidirectional Research-within-Management (RWM) interface is a new R2-related interface type characterized by co-monitoring and co-analysis of environmental management results. We further highlight the fruitful contributions of adaptive management (AM), a framework that can integrate all the different interfaces except TD, according to management phase, context, degree of knowledge and level of uncertainty.

The different interfaces can be seen as concrete examples of boundary structures between research and decision-making or management, as called for by Cash et al. (2003). They embed some of Cash's boundary functions—especially translation (TT, RWM) and communication (RWM) —but we agree that mediation, when deep disagreements between researchers and managers exist, should also be promoted.

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

We point out the complementarities as well as the specificities and limitations of the different research categories and related interface types, which is of major importance for environmental management and research policies. First, this leads us to recognize the legitimacy and usefulness of the different types of interfaces and research, all of which participate in the flow of knowledge between research and management, although in different conditions and with different intensities. R1 and TT occur at the end of the knowledge creation cycle and the beginning of the action cycle, whereas R3 and the user-push interface are active at the beginning of the knowledge-creation cycle and at the end of the action cycle. Second, RWM integrates the R2-type scientific knowledge creation cycle within the action cycle itself. Third, our analysis clearly distinguishes the research types that induce an obviously limiting unidirectional flow of knowledge (e.g. R1) from those (e.g. R2) that favor a bidirectional flow of knowledge between research and management. Although this idea is not entirely new, we have tried to better specify the conditions where these different research types might be relevant. We think that R2 and RWM in particular should be encouraged, since they are currently underdeveloped in some fields; it is important to gain more experience with R2 and RWM to better assess their potential relative to R1, R3 and related interfaces. Finally, an interesting perspective would be to develop research programs or projects that articulate, in a structured manner, different research categories and interfaces around the same management issue. In line with Rist et al. (2013b)'s analysis, we think that AM projects are well geared for this purpose, while at the same time reducing uncertainties on the effects of management on ecosystem structure and functioning.

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

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Appendix A. Supplementary material

Supplementary material related to this article can be found at https://doi.org/10.1016/j.jenvman.2018.04.025.

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