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Solving Environmental Problems: Knowledge and Coordination in Collaborative Search

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Recent innovation and strategy research emphasizes the importance of firm's search for external knowledge to improve innovation performance. We focus on such search strategies within the domain of sustainable innovation in which problems are inherently complex and the relevant knowledge is widely dispersed. Hence, firms need to collaborate. We shed new light on collaborative search strategies led by firms in general and for solving environmental problems in particular. Both topics are largely absent in the extant open innovation literature. Using data from the European Seventh Framework Program for Research and Technological Development (FP7), our results indicate that the problem-solving potential of a search strategy increases with the diversity of existing knowledge of the partners in a consortium and with the experience of the partners involved. Moreover, we identify a substantial negative effect from involving partners in a search consortium who collaborate for the first time. Our findings have implications for both the literature on firms' search and the creation of sustainable innovation.

Introduction

Firms are increasingly challenged to generate sustainable innovations that provide economic returns and simultaneously have positive effects by solving environmental or societal problems (Ketata et al., 2015). Such challenges are often beyond the expertise of individual firms and require collaboration with outside partners to jointly develop promising solutions. Prior research has frequently documented the benefits of integrating external knowledge into firms' innovation processes (e.g., Garriga et al., 2013; Laursen and Salter, 2006; Leiponen and Helfat, 2010). Connecting with external sources of knowledge, such as universities, customers, or suppliers, allows firms to access contextually different knowledge that they can recombine with internal knowledge to improve their innovation outcomes (Chesbrough, 2003).

Firms develop search strategies that target external knowledge sources in order to find solutions to a problem they are facing (Katila and Ahuja, 2002). When problems are complex, a search strategy is likely to involve relationships with several external partners at the same time in order to collaboratively solve a problem. However, the particularities of collaborative search strategies have received little attention so far in extant research (exceptions include the simulation studies of Knudsen and Srikanth, 2014). We develop a theoretical understanding of problemistic search that takes into account the fact that the search is collaborative in nature. We argue that each partner in a consortium contributes knowledge to potential solutions from its particular domain, while the problem-solving potential of the overall search strategy depends on how well these contributions can be integrated (Knudsen and Srikanth, 2014). In that sense, search strategies do not only differ with respect to the diversity of knowledge provided by external sources but also how well these sources and their contributions can be coordinated.

We predict that both the prior knowledge of partners involved in a search strategy and their experience with coordination in collaborative search will positively influence the problem-solving potential of the search strategy. Moreover, we argue that the problem-solving potential of a search consortium decreases if it includes partners who participate for the first time.

The empirical context of our paper is the domain of sustainable innovation. More specifically, we focus on solving environmental problems — one of the core elements of the sustainability agenda (Ketata et al., 2015; Siegel, 2009). Innovation activities that target environmental problems are different from solving other innovation related problems for two main reasons. First, environmental problems are typically complex and the knowledge to solve them is dispersed. In fact, many sustainable innovations are systemic in nature and they originate from complex sets of knowledge that require the involvement of diverse groups of actors (Hall and Vredenburg, 2003). Second, environmental problems are rarely formulated by the firm devising a search strategy but rather by the external setting the firm is operating in. This includes stakeholders,

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NGOs, and society more generally, which demand solutions to the problems they have defined in a discursive way (Devinney, 2009). Both complexity and the limited ability to define the problem at hand make coordination within a search strategy a particularly salient issue (Felin and Zenger, 2014).

Testing our hypotheses requires a research design in which many firms search for comparable solutions to environmental problems by assembling search consortia of different partners. We have the unique opportunity to study such a setting by accessing all 731 firm-led project applications submitted to 25 different collaborative topic calls in the environmental area of the European Commission's Seventh Framework Program for Research and Technological Development (FP7), a research funding program that ran during the period of 2007–2013 with a total budget of more than 50 billion Euros, of which 1.89 billion Euros were allocated to the environmental area. Individual project grants can reach budgets of several million Euros and the grant application process requires significant investments by the applicants. Hence, the effort is significant and there is a potentially high payoff in terms of funding obtained to execute the proposed solution. Grant applications are submitted through consortia of partners and receive a quality score based on standardized criteria from multiple independent experts. This provides us with a unique dependent variable to measure the problem-solving potential of a search strategy, which is exogenous to the firm and comparable across applications within the same topic area.

Our research contributes to the literature in three ways. First, by emphasizing the coordination effort required in search consortia, we look both theoretically and empirically at an understudied area in the literature on external knowledge search (e.g., Laursen and Salter, 2006, Leiponen and Helfat, 2010). On the one hand, prior literature treats external search, at least implicitly, as independent, bilateral arrangements, controlled by a focal firm that seeks to solve a problem. We suggest that this assumption is too narrow and biases the results. Instead, search strategies are oftentimes multilateral in nature. As a consequence, coordination among the partners involved becomes a crucial factor, currently absent in most models of knowledge search. Research that focuses on collaborative search is often limited to simulation studies (Knudsen and Srikanth, 2014). On the other hand, prior literature largely ignores the fact that the partners involved in a search consortium differ with regard to not only the knowledge they can provide but also the collaborative experience they bring into the consortium. We suggest that the distribution of both knowledge and experience among the partners matters for the problem-solving potential of a search strategy.

Second, by focusing on the problem-solving potential of a search strategy we are able to observe the likelihood with which a search strategy will be successful. Prior research has typically looked at the outcomes of a firm's search strategy, for example, the number of patents or innovative products generated subsequently or the sales achieved with such new products (Katila and Ahuja, 2002; Laursen and Salter, 2006; Rosenkopf and Nerkar, 2001). These outcomes, however, are hard to trace back to a firm's original search strategy since they easily confound searching with finding. The latter is likely to be only a narrow snapshot of the search strategies that were originally developed. Instead, the problem-solving potential isolates the likely effectiveness of a search strategy. What is more, it reflects the more likely scenario within firms in which different search strategies compete for resources to be enacted. We have the unique opportunity to also observe the less successful strategies while previous studies fail to distinguish innovative firms which have searched but not found.

Third, our research provides direct implications for management practice in the area of sustainable innovation. While the problems in this area are typically formulated outside the firm's boundaries and are thus beyond the firm's control, management does have the opportunity to configure and manage a search consortium that is likely to solve the formulated problem. In that regard, our research suggests that coordination experience is important and that a consortium benefits from the accumulated experience of the partners in order to tackle the complexities of sustainable innovation.

The remainder of this paper is structured as follows. The following section describes the theoretical background and derives a set of hypotheses. Data, measures, and the empirical model are outlined in the subsequent section followed by the results. Subsequently, we discuss these results and draw conclusions. The final section addresses the limitations of our research and implications for future research.

Theory and hypotheses

Problemistic search for sustainable innovation

Within the model of problemistic search firms develop search strategies to find solutions for a problem they are facing (Katila and Ahuja, 2002). Accordingly, we investigate search strategies at the problem level rather than at the aggregated firm level. This allows us to develop theory to match the nature of sustainable innovation, which often requires search strategies that differ from the overall search strategy formulated at the firm level (Ketata et al., 2015). We will develop theoretical predictions for why certain search strategies have a higher potential to solve sustainable innovation problems than others. We will explain these differences in the problem-solving potential of different search strategies based on both the accumulated knowledge of a search consortium and how well the consortium partners and their knowledge can be coordinated. The latter factor is largely ignored in existing search theory but is especially relevant for sustainable innovation because of its inherent complexities and the dispersion of relevant knowledge. We start out by defining central constructs and mechanisms.

Firms develop search strategies by defining a set of technologies or technological areas (Katila and Ahuja, 2002) and/or knowledge sources (Laursen and Salter, 2006) that can provide a solution to a problem. Firms have been found to benefit

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from including external knowledge sources, such as universities, for two primary reasons. First, firms can find more novel and hence unique solutions if they combine existing firm knowledge with outside expertise (Rosenkopf and Nerkar, 2001). Second, access to external knowledge enables firms to increase the speed with which they can find solutions because they do not have to develop all relevant knowledge internally (Fleming and Sorenson, 2004).

While many empirical studies find that search strategies that include external knowledge sources increase the innovation performance of firms, there is also consistent evidence that firms struggle with extracting the maximum value of their search strategies, i.e., they search too narrowly or too broadly (for a recent review see Laursen, 2012). Existing theoretical explanations center on the nature of the knowledge encompassed in a search strategy. Katila and Ahuja (2002) suggest that firms will increasingly exhaust the valuable pools of external knowledge and search strategies may therefore suffer from decreasing returns. Laursen and Salter (2006) emphasize the costs of screening external knowledge from various sources vis-à-vis its benefits. They conclude that the screening costs can outweigh the advantages of a search strategy.

We define collaborative search by drawing on the search model of Laursen and Salter (2006), who describe a firm's search strategy as encompassing several external organizations, e.g., suppliers, universities, and customers. We will refer to the group of organizations involved in a collaborative search strategy as a firm's search consortium. Furthermore, we assume that all partners of a search consortium suggest potential solutions to the overall problem that the consortium wants to solve. However, the consortium will eventually formulate only a single search strategy. This implies that the search strategy of the consortium is the outcome of communication and coordination processes within the consortium in which the partners identify, screen and integrate the potential solutions provided by each partner (Knudsen and Srikanth, 2014). We further assume that a resource controlling authority which has solicited search strategies to a particular problem in the first place compares and ranks search consortia based on the problem-solving potential of their respective search strategies.

Our model deviates from existing theoretical models of knowledge search by going beyond the dimension of knowledge diversity and the need for screening of the searching firm. Instead, we envision a search process in which the firm is not a unitary actor that merely collects knowledge from various sources. We suggest a model of collaborative search in which the problem-solving potential of the overall search strategy depends at least partially on the interaction of partners within a search consortium (Knudsen and Srikanth, 2014). The following section will outline our hypotheses.

Hypotheses

Unique knowledge is among a firm's most valuable assets for achieving competitive advantage (Grant, 1996; Liebeskind, 1996). The open innovation perspective has highlighted that unique knowledge is not only a result of a firm's own internal research and development (R&D) activities but can also stem from external sources (Chesbrough, 2003). The recombination of internal and external knowledge has been shown to improve a firm's innovation performance (e.g., Grimpe and Kaiser, 2010; Laursen and Salter, 2006). At the same time, knowledge that the firm possesses performs an important function in determining its absorptive capacity (Cohen and Levinthal, 1989, 1990). The idea behind absorptive capacity is that external sources of knowledge need to be identified, activated, and managed for successful integration into the firm's innovation process (Todorova and Durisin, 2007). In that sense, absorptive capacity provides firms with a richer set of diverse knowledge, allowing them more options for solving problems and reacting to change in the environment. As a result, firms may predict future developments more accurately (Cohen and Levinthal, 1994) and refocus their knowledge base through iterative learning processes (Szulanski, 1996; Zahra and George, 2002).

While this line of research implicitly adopts the perspective of a firm searching for knowledge from an external source on a bilateral basis, we can transfer the reasoning on firms' knowledge and absorptive capacity into a model of collaborative search. In the following, we will therefore suggest that the problem-solving potential of a collaborative search strategy will increase with the diversity of accumulated knowledge of the partners in a consortium for two main reasons. First, the diversity of knowledge in a search consortium increases the chance that partners can recombine existing knowledge elements in a way that solves the problem. Knowledge stocks from different organizations within a search consortium allow novel knowledge combinations through collaborative search, which will then be more distant, spanning various organizational boundaries (Rosenkopf and Nerkar, 2001). Second, the absorptive capacity argument suggests that firms benefit from prior related knowledge when identifying, assimilating and exploiting external knowledge (Cohen and Levinthal, 1989). While each individual firm may be bound by its own prior knowledge when searching for external knowledge, a consortium of firms can overcome this limitation. Firms with increasingly diverse prior related knowledge will be more likely to explore potential solutions from a variety of fields. Consequently the pool of potential solutions to a problem within the search consortium becomes broader and more diverse, compared to a situation in which all firms in a consortium draw from the same pool of existing knowledge to guide their search. As a consequence, consortia with diverse pools of prior knowledge are more likely to access and assimilate knowledge that can be found beyond the individual partners.[1] As a result, our first hypothesis reads as follows:

[1] Prior literature has frequently made a distinction between search breadth and depth (e.g., Laursen and Salter, 2006). Our context is characterized by a rather high degree of search depth, i.e. intensive collaboration with selected partners. For that reason, we focus our arguments on the diversity of knowledge, i.e. on search breadth.

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Hypothesis 1. The problem-solving potential of a collaborative search strategy increases with the diversity of existing knowledge of the partners.

While each knowledge source provides potential solutions from its particular domain, our next hypothesis will argue that the problem-solving potential of the overall search strategy depends on how well these solutions can be integrated (Knudsen and Srikanth, 2014). The ability to effectively coordinate partners within a search consortium is therefore separate from the diversity of knowledge that the partners provide. Coordination within a search consortium typically refers to communicating potential solutions, setting priorities for particularly promising ones, and assimilating various solutions so that they form a conclusive search strategy. This is all the more important the higher the complexity of the problem to solve and the lower the ability to actually define the problem (Felin and Zenger, 2014).

Problems in the area of sustainable innovation are likely to be more complex because they require the involvement of diverse groups of actors (Hall and Vredenburg, 2003). Ketata et al. (2015) show that sustainable innovation benefits more from a broader involvement of knowledge sources such as suppliers or customers, which in turn need to be coordinated. We therefore argue that the problem-solving potential of a consortium's search strategy depends on how well it can be coordinated internally. Coordination avoids confusion among partners by providing directions and setting priorities (Knudsen and Srikanth, 2014).

Since collaborative search requires decision making across partners, coordination contributes to defining a shared language, criteria, and decision rules with respect to the combination of knowledge elements, which should eventually improve the understanding of the problem and the solution potential. In that sense, coordination prevents the search strategy from becoming too narrow (Knudsen and Srikanth, 2014) or too broad (Laursen and Salter, 2006). Powell et al. (1996) find that firms do not just acquire knowledge when collaborating with other firms but that they also develop capabilities to function within a context that spans firm boundaries. Love et al. (2014) extend this argument to the search context and show that the effectiveness of firms' search strategies increases if firms search repeatedly. They explain this improvement in a firm's search with the creation of routines and management systems for coordinating the search. We combine these theoretical arguments by arguing that all partners in a search consortium will benefit from such experience effects of engaging repeatedly in the formulation of search strategies. We argue that communication and coordination costs decrease with the experience of the partners involved in collaborative search. The greater their experience, the better the partners are presumably able to draw on effective tools and vocabularies, making the assimilation of partner knowledge more efficient. As a result, experience also decreases the degree to which management attention is required for coordination efforts (Ocasio, 1997) since experience is likely to generate routines that facilitate collaboration.

Relatedly, having experience in the formulation of collaborative search strategies will likely also benefit the overall structuring, content and configuration of partners involved. These management skills of the firm leading the search consortium and the partners develop through experience and represent a separate mechanism, independent of the benefits that experience has for coordination. Since search consortia require resources in order to implement the devised search strategy, partners involved in a consortium have an interest in structuring and describing the search strategy in a way that is clear and convincing to both internal and external providers of resources and funding. As a result, not only will the perception of the problem-solving potential increase, but a clear and convincing search strategy will also have positive repercussions for the partners involved. They will benefit from a more structured approach and will find it easier to identify key requirements and common objectives while the search strategy is being implemented. Taking the two mechanisms together, our second hypothesis reads as follows:

Hypothesis 2. The problem-solving potential of a collaborative search strategy increases with the combined collaborative experience of the partners.

Inherent in our elaborations on collaborative experience is the notion that a search consortium creates an inter-organizational context in which potential solutions are identified, evaluated and integrated. Rules and procedures for how to operate efficiently within this context are rarely codified. As a consequence, relevant capabilities need to be developed in practice over time (Powell et al., 1996). Following this logic, we explore the particular situation of consortium partners which participate for the first time, i.e. have no collaborative experience. We develop a line of reasoning that draws a distinction between an overall absence of experience and the otherwise gradually accumulated level of experience laid out in Hypothesis 2.

There are two primary reasons for why collaboration rules in a search consortium cannot be sufficiently laid out in handbooks, contracts or manuals. First, the nature of the content underlying the inter-organizational agreement to search for solutions to a problem within a consortium is necessarily novel, untested and fluid. Partners can hardly foresee ex-ante which search strategy will emerge and which particular resources are required to provide it. Hence, every contractual agreement or manual is necessarily abstract and incomplete. Second, contractual agreements capture necessarily only a fraction of the actual exchanges between partners in inter-firm research activities (Powell et al., 1996). Relevant interactions between organizations for new knowledge occur mostly through inter-personal exchange among scientists and engineers from various organizations. Large parts of their exchanges produce a shared knowledge which is tacit in nature since it requires personal interaction (Agrawal, 2006).

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Given the absence of codified rules and manuals, partners without prior collaborative experience are likely to increase the costs for communication and coordination within a search consortium because they are necessarily ill-prepared for the particular context. Contributions of such first-time search partners are more likely to be misaligned with shared language conventions and procedures of a consortium. This makes their contributions harder to absorb and evaluate for the rest of the consortium. Similarly, first-time search partners are more likely to be a source of conflict within a consortium because they are less likely to understand the full set of mechanisms through which a consortium can deal with diverging priorities and incentives. Moreover, considerable investments are required in order to prepare the organization for the collaborative effort (including the hiring of specialized personnel for project management and accounting, provisions against unintended knowledge leakage, etc.) that consume and re-direct management attention (Ocasio, 1997) that cannot be dedicated to solving the actual problem. We hypothesize that the sum of these effects will have a detrimental effect on the problem-solving potential of the search strategy of the consortium as a whole:

Hypothesis 3. The problem-solving potential of a collaborative search strategy decreases with the share of partners who participate in a search consortium for the first time.

Data and methods

Data

We test our theoretical predictions by using collaborative search strategies of firms formulated as grant applications for project research. This approach differs from existing research, which has captured knowledge search strategies by relying on three primary types of data sources: patent statistics (e.g., Katila and Ahuja, 2002), firm alliance data (e.g., Rosenkopf and Almeida, 2003), and innovation surveys (e.g., Laursen and Salter, 2006). All of these data sources have in common that they capture search strategies in which firms have actually found knowledge. These approaches assume, at least implicitly, that (a) what the firm was searching for and what it found were identical, (b) that the firm engaged exclusively in the successful search strategy, and (c) that no external firm factors exist that systematically influence finding but not searching. We argue that these assumptions are too narrow. We observe search processes in which firms devise multiple search strategies and compete for funding to execute them on the basis of their problem solving potential. Firms can improve the formulation of their search strategies because the search process is under their control. The subsequent finding stage, though, may be subject to a multitude of outside factors.

We investigate search strategies and their problem solving potential in a setting in which firms formulate search strategies for comparable problems by assembling consortia, i.e., engaging in collaborative search for comparable problems. We utilize data on joint applications for funding submitted to the environmental area of the European Commission's Seventh Framework Program (FP7) between 2007 and 2013. The program is sizable, with 1.89 billion Euros designated to solving problems that directly relate to sustainable innovation. The explicit goal of the program is to solicit potential solutions related to challenges caused by the increasing pressure on the environment with a commercial target of developing environmental technologies to create growth and business opportunities globally.[2] Applicants submit proposals to a distinct call put forth by the European Commission, each representing specific and complex environmental problems. In Appendix 1 we provide examples of calls which are part of our empirical setting, which target the development of new technology for transforming waste to useable resources, and monitoring and management of water and flood risks respectively. All environmental calls can be found on the European Commission's Cordis website in the "Cooperation" section.[3]

Successful applicants receive funding to cover part of the project costs, amounting to several million Euros, making the rewards of investing time and effort into the joint development of a search strategy highly attractive. Within our dataset all calls are directed at environmental challenges. These calls provide an abstract description of the problem, which is supposed to be solved, and the respective goals. Examples of the calls included in our analysis are requests for proposals to develop technologies that improve the safety of buildings in case of flooding, proposals that address the adaption of water supply systems to cope with climate change, or the development of green infrastructure or organic materials. Firms and other organizations collaboratively develop search strategies within a particular call. The call also describes the application and evaluation procedures.

We believe that funding applications within FP7 are suitable to study the theoretical predictions of our hypotheses for several reasons. The FP7 explicitly aims at facilitating collaborative research projects that seek to develop novel solutions and technologies and not just apply existing knowledge to new problems. In that sense, FP7-funded projects resemble very closely firm-funded collaborative research activities, particularly because a firm's R&D also needs to secure internal funding that will only be released if projects promise to actually solve problems that the firm experiences in its innovation

[2] Detailed information is available on the website of the European Commission's Seventh Framework Program: www.ec.europa.eu/research/fp7.
[3] http://cordis.europa.eu/fp7.

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activities. Our data emerge from the application stage, which provides a unique view on the formation and configuration of the search consortium that otherwise cannot be easily observed. Hence, we argue that grant applications, provided that the funding program is actually geared toward technological novelty like FP7, may very well complement existing types of data sources to study organizational search strategies.

We restrict our sample to project proposals from private firms because their search strategies are at the core of our theoretical logic. Each of these firms assembles a project consortium of various partners, e.g., universities, which will contribute to the search strategy. The resulting sample consists of 731 search strategies from all search consortia led by private firms, each submitted to one of 25 different calls, which are analyzed to estimate the effects of knowledge and experience on problem solving potential.

We add data on successful applications in the Sixth EU Framework Program to our data on the FP7. This extends our measure of experience to cover activities in these programs in the period from 2002 to 2013. The data on applications, experience and expert evaluations are combined with register data from Bureau van Dijk's Orbis database, which provides patent information on the participants.

Dependent variable

We use experts' ratings of the proposed search strategies as our dependent variable to analyze the influence of knowledge and experience on the problem-solving potential of collaborative search. To evaluate proposals, the European Commission appoints three to five independent experts on the basis of their level of expertise within the specific proposal area. Each expert prepares an individual evaluation before the team of experts assigned to a specific proposal convenes in Brussels to reach a consensus on the potential of the proposal. This process is led by a representative from the European Commission and overseen by an additional expert to ensure an unbiased process that considers the input of each individual expert. A score ranging from 0 to 100 reflects the final evaluation of the problem-solving potential of a proposal.

Three overall criteria are evaluated in assigning these scores: First, the technological and scientific excellence of the proposal is evaluated based on whether it contains a sound concept with high-quality objectives, whether the methodology is effective and the extent to which the proposed solution moves beyond the state-of-the-art. Second, the quality and efficiency of the implementation and management are evaluated, which consider the structures and procedures for execution, the competences of the participants related to carrying out their individual tasks, the quality of the consortium and whether the requisite resources are made available by the participants. Third, the impact of the solution is evaluated based on the potential and exploitation of the commercial results and dissemination of the scientific outputs. This provides us with a unique dependent variable to capture the problem-solving potential of a firm's problemistic search.[4]

Ex-ante measures provide unique opportunities to study the front-end of innovation (Salter et al., 2015) by isolating the mechanisms influencing the problem-solving potential of a search strategy without the risk of confounding it with effects originating from the finding stage. As such, our measure responds to the call for an increasing focus on early-stage innovation activities (Kijkuit and van den Ende, 2010). The process of assigning scores consists of initial individual evaluation by the experts and subsequent consensus creation. By relying on multiple independent experts the likelihood of biased perceptions of the solution potential is reduced, as is the risk of individuals overlooking important caveats in the proposals. The presence of a representative of the European Commission and of an additional expert to lead the consensus building increases the reliability of the measure by ensuring that all valid and relevant aspects are heard and considered in the final score. Our dependent variable "problem solving potential" thereby captures the experts' rating of both approved and rejected applications, reflected by a score between 0 and 100.

Explanatory variables

Knowledge diversity

Following prior literature in the field (Katila and Ahuja, 2002; Rosenkopf and Nerkar, 2001), we use patents assigned by the European Patent Office to the organizations involved in a search consortium to construct our measure knowledge diversity. Patents are a widely used measure of knowledge because the patent application process is costly and patent offices require a degree of novelty ("inventive step") for a patent to be granted (Encaoua et al., 2006). Patents are therefore valid representations of knowledge following a shared quality standard across organizations.

[4] Prior research has frequently made a distinction between more radical and incremental innovations (e.g., Laursen and Salter, 2006). In our context, solutions to problems sought within FP7 are unlikely to be incremental. In fact, FP7 explicitly facilitates joint technology development and basic research that not least due to competitive reasons has to be distant from actual application. The problem-solving potential hence focuses on problems that are rather radical.

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We calculate the diversity of a search consortium's existing knowledge by counting the number of different patent classes (IPC) in which the partners of a search consortium have patented. Technology classifications of patents are assigned by patent offices and grouped according to their respective bodies of knowledge and technologies. We measure the patent portfolios of the partners at the aggregate organization level, meaning that for a firm with multiple business units or divisions we count the aggregate number of patents at the level of the overall organization. Ideally, we would register patents at department, unit or team levels. However, given the diversity of organizations in our empirical setting, this is not systematically possible. Consequently, we conduct several consistency checks to test the sensitivity of estimation results to this aggregation of patents, all of which are robust. Counts of technology classes are widely applied to account for the breadth or scope of technologies within organizations (Katila and Ahuja, 2002). Based on the IPC classification of separate bodies of knowledge, our variable for knowledge diversity ranges from zero to a maximum of eight for consortia that cover all the different 1st level classes used in the IPC. Higher values of the variable indicate that the organizations in a consortium have knowledge from more diverse knowledge domains which can contribute to the consortium's collaborative problem-solving. We standardize the variable by rescaling it to a mean of zero and a standard deviation of one, which enables a comparison of the magnitude of effects between this and our other explanatory variables.

Collaborative experience

The second explanatory variable captures the accumulated experience of the participants in a search consortium, which we assume will facilitate coordination and communication among the partners. Repetition of search activities, even with varying partners, has been found to facilitate the development of search routines and management systems (Love et al., 2014). Accordingly, we count the number of participations in search consortia within the Sixth and Seventh Framework Programs prior to the focal search consortium as our proxy of collaborative experience. While this excludes us from observing collaborative search experience outside our dataset, it is directly applicable to reliably identifying experience with relation and relevance to the search efforts observed. Incorporating the Sixth Framework Program for the calculation of experience allows us to capture an organization's participation in Framework Programs over a long period between 2002 and 2013 as well as the most relevant and related setting. Analogous to our measure for knowledge diversity, we standardize the experience stock to enable a comparative interpretation of the measures.

Share of first-time participants

We construct a variable on first-time participants as the share of partners in a search consortium without prior experience in collaborative search in either the Sixth or Seventh Framework Program. Increasing values of the variable thus indicate an increasing share of participants with no prior experience with related search activities. Again, we standardize this measure for comparison of effect sizes in our estimation models.

Control variables

To control for factors that may influence the problem-solving potential beyond our hypothesized effects, our analysis includes variables related to the characteristics of the firm leading the search consortium, as well as the specific search strategy. First, since previous research has shown the importance of the breadth of external search strategies (Laursen and Salter, 2006), we include a variable that controls for the number of different types of partners (e.g., firms, universities, etc.) involved in each search consortium. To account for the size of the search consortium we incorporate the overall count of partners as well as the reported costs of executing the project in millions of Euros.

To control for the size and resources of the firms leading a consortium, we include a dummy variable indicating whether the firm is a small or medium sized enterprise (SME). This captures whether a firm meets the three EU criteria for the SME definition: (i) having less than 250 employees, (ii) having an annual turnover below 50 million Euros, and (iii) having a positive balance sheet of less than 43 million Euros.

Finally, we address geographical and industry differences. To account for the influence of regional differences we include dummy variables for the geographical area in which the firm leading the consortium is located (Northern, Eastern, Western, and Southern Europe, as well as non-European locations). We include industry dummies for the leading firm based on the NACE industry classification system to control for industry effects (e.g., Grimpe and Sofka, 2009). These dummies are defined in accordance with the Eurostat aggregation of sectors according to knowledge intensity, with a further aggregation made by combining high-tech and medium-high-tech manufacturing into one category, and similarly combining medium-low-tech and low-tech manufacturing.

Estimation model

To test our hypotheses we apply a fixed-effects ordinary least squares model with within-call fixed effects. This approach allows us to estimate the influence of knowledge diversity, collaborative experience and searching with inexperienced partners on the problem-solving potential of a search strategy across the 25 different calls for funding applications in our dataset. The fixed effect allows us to ensure that our analysis is conducted on firms search for solutions to the same problems (represented by the calls) on the basis of the same problem descriptions and processes. By estimating our model with call-fixed effects we avoid analyzing across problems, which would compare, e.g. the influence of knowledge diversity on

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Table 1
Summary statistics

Variable	Mean	S.D.	Min	Max
Problem-solving potential	63.370	18.334	0	100
Number of patent classes	0	1	−1.980	1.110
Participants' total experience	0	1	−0.638	5.709
Share of first-time participants	0	1	−1.445	2.169
Number of partner types	1.893	.985	1	5
Number of participants	9.865	5.837	2	55
Project cost (million EUR)	4.099	3.089	0	23.500
SME	.546	.498	0	1
Eastern EU	.082	.275	0	1
Northern EU	.049	.217	0	1
Southern EU	.361	.481	0	1
Western EU	.482	.500	0	1
Non-European	.026	.159	0	1
Medium & high tech	.081	.273	0	1
Knowledge intense services	.725	.447	0	1
Less knowledge intense services	.038	.192	0	1
Low & medium tech	.029	.167	0	1
Other industries	.127	.333	0	1

solutions to highly complex problems to the influence of knowledge diversity on solutions to less complex problems. As such, we estimate the following equation

$$Y_{ic} = \alpha_c + \beta_1 X_{1,ic} + \beta_2 X_{2,ic} + \beta_3 X_{3,ic} + Z_{ic}{}'\beta_4 + u_{ic}$$

where α_c are the call fixed effects and u_{ic} is the error term. X_1, X_2 and X_3 represent the three independent variables *knowledge diversity*, *collaborative experience* and *share of first time participants* and Z represents our control variables. β represents the respective coefficients of the explanatory and control variables, and Y represents the dependent variable *problem-solving potential*.

Additionally, we conduct several consistency and sensitivity estimations to demonstrate the stability of our empirical findings.

Results

Descriptive findings

Table 1 shows the summary statistics of the variables in our sample. The mean problem-solving potential is 63 out of 100 with a rather low standard deviation, indicating that most submitted proposals receive a rather moderate evaluation score. We standardize the measures of knowledge diversity and experience by rescaling the means to zero and standard deviations to 1 to enable a comparative interpretation of their influence on the problem-solving potential of the search consortia. In Table 2 we provide descriptive statistics for the non-standardized versions of the explanatory variables, which show that the mean of the unstandardized knowledge diversity is 5.25, showing that the typical search strategy involves five different IPC classes. The knowledge diversity ranges from low where no IPC classes are represented in the consortia to high where eight IPC classes are represented, and the standard deviation of 2.6 shows a rather high variation of diversity within the range possible. The unstandardized means of the participants' total experience and the share of first time participants are 166.77 and 0.40 respectively. We observe consortia that consist solely of first-time participants, as well as consortia with none of these inexperienced partners. As such, the accumulated collaborative experience has a minimum value of zero, which represents consortia consisting solely of first-time participants. The maximum value of combined experience is 1659, which represents the case of a consortium where the most experienced individual organizations in our sample collaborate on a consortium.

Table 2
Summary statistics for non-standardized explanatory variables

Variable	Mean	S.D.	Min	Max
Number of patent classes (non-standardized)	5.126	2.588	0	8
Participants' total experience (non-standardized)	166.774	261.399	0	1659
Share of first-time participants (non-standardized)	0.400	0.277	0	1

Table 3
Pairwise correlations

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
(1) Problem-solving potential	1																
(2) Number of patent classes	.31	1															
(3) Participants' total experience	.24	.46	1														
(4) Share of first-time participants	.01	.38	.01	1													
(5) Number of partner types	.21	.48	.26	.48	1												
(6) Number of participants	.26	.43	.40	.23	.45	1											
(7) Project cost (million EUR)	−.01	.03	.13	−.09	.14	.35	1										
(8) SME	−.16	−.11	−.06	.02	−.01	−.09	−.12	1									
(9) Eastern EU	−.18	−.11	−.12	−.06	−.13	−.12	−.04	.10	1								
(10) Northern EU	−.07	−.01	.07	.03	.01	.04	.03	−.06	−.07	1							
(11) Southern EU	−.12	−.12	−.04	−.08	−.07	−.10	−.06	−.02	−.22	−.17	1						
(12) Western EU	.27	.18	.08	.07	.13	.15	.05	−.02	−.29	−.22	−.72	1					
(13) Non-European	−.07	−.01	−.03	.08	.01	−.02	.04	.03	−.05	−.04	−.12	−.16	1				
(14) Medium & high tech	.06	−.07	−.11	−.03	.04	−.06	.10	−.01	−.03	.03	.05	−.03	−.02	1			
(15) Knowledge intense services	−.04	.05	.06	.07	−.10	.07	−.12	.16	.05	.03	−.11	.07	−.01	−.48	1		
(16) Less knowledge intense services	−.05	−.02	−.03	−.02	.07	−.03	−.02	−.12	.02	−.01	.15	−.16	.06	−.06	−.32	1	
(17) Low & medium tech	−.03	−.06	−.08	−.04	.02	−.08	.10	−.01	−.05	−.00	.02	−.00	.02	−.05	−.28	−.03	1
(18) Other industries	.05	.03	.06	.03	.05	.00	.04	−.13	−.02	−.05	.01	.03	−.01	−.11	−.62	−.08	−.07
Mean variance inflation factor (VIF):	2.89																

The majority of the firms leading a search consortium to solve environmental problems are in knowledge-intensive services. This category covers activities within transport, real estate, and sewage, as well as a range of business and service activities such as engineering and architecture. The category "other industry" includes the primary sector and utilities, both of which also have significant impacts on the environment, which explains the representation of this sector as the second largest in our sample. Approximately half of the 731 search consortia in our sample are led by SMEs, and most consortia are led by firms located in Northern and Western Europe. A majority of 59 percent of the consortia involve university participants, which would be expected given the novel research required to solve a number of the problems.

Table 3 shows the pairwise correlations. We do not detect high correlations among the explanatory variables. Moreover, we calculate the variance inflation factors for our explanatory variables to test for issues arising from multicollinearity (e.g., Belsley et al., 1980). The mean variance inflation factor for our main explanatory variables is 1.37 and 2.89 for our explanatory variables and control variables combined, which suggests that the data do not suffer from collinearity by any conventionally applied standard.

Regression results

The results of our regression models are presented in Table 4, in which we introduce our explanatory variables stepwise. Model I is the baseline model including only control variables. Model II tests our first two hypotheses. We find a positive and significant effect of the number of patent classes on the problem-solving potential. Similarly, the positive and significant effect of the participants' total experience provides evidence that the problem solving potential increases with the combined experience of the partners. Thus, Hypotheses 1 and 2 receive support. On the basis of a linear estimation model and standardized variables, we can compare effect sizes. We test whether the coefficients of our explanatory variables are equal, which would suggest that a comparative analysis of these is not possible. With a significant test score at the one percent level we can reject this and compare the effect sizes of the three variables.

While a one standard deviation increase in the number of patent classes of a search consortium raises the experts' evaluation of the problem-solving potential by 2.88, the corresponding increase in the participants' total experience results in an increase of 2.46. This provides evidence of a similarly strong influence on the problem-solving potential of a search strategy from increasing the experience and diversity of knowledge involved in the search. With the rather low standard deviation of experts' evaluation of problem solving potential, the effects of increasing knowledge breadth and experience both substantially influence the potential of search strategies for solving problems.

In model IV we introduce the share of first time participants to the model. We find that when increasing the share of first time participants by one standard deviation the experts' rating of the problem solving potential of the search strategy decreases by 3.42. This provides evidence that collaborative search suffers from the involvement of novice partners without prior collaboration experience, thereby providing support for Hypothesis 3. Finally, model V provides the full model with all explanatory variables. All estimated effects remain stable.

We do not develop hypotheses for our control variables but they show the expected signs throughout the estimation models. We find a consistently positive effect of increasing the number of partner types, as expected from extant literature (Laursen and Salter, 2006). This confirms the positive effects of involving a variety of sources in the search efforts, such as universities, customers, and others. Similarly, we see a small and significant effect of increasing the number of participants in the search effort. We interpret the negative SME effect as being due to a lack of resource availability. Larger firms have

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Table 4
Fixed-effects estimations for problem-solving potential

Variable	Model I	Model II	Model III	Model IV
Number of patent classes		2.88***		3.03***
		(0.85)		(0.84)
Participants' total experience		2.46***		1.99***
		(0.74)		(0.74)
Share of first-time participants			−3.42***	−2.93***
			(0.87)	(0.87)
Number of partner types	3.25***	2.23***	4.70***	3.45***
	(0.79)	(0.81)	(0.86)	(0.88)
Number of participants	0.65***	0.42***	0.60***	0.40***
	(0.13)	(0.14)	(0.13)	(0.14)
Project cost (million EUR)	−0.85***	−0.88***	−0.89***	−0.91***
	(0.23)	(0.23)	(0.23)	(0.23)
SME	−6.05***	−5.53***	−5.86***	−5.35***
	(1.31)	(1.29)	(1.30)	(1.28)
Eastern EU	−3.03	−3.02	−3.37	−3.40
	(4.41)	(4.32)	(4.37)	(4.29)
Northern EU	−2.01	−2.65	−2.19	−2.69
	(4.77)	(4.66)	(4.72)	(4.63)
Southern EU	3.35	2.68	2.74	2.17
	(3.98)	(3.89)	(3.95)	(3.87)
Western EU	10.36***	9.26**	9.73**	8.72**
	(3.96)	(3.88)	(3.92)	(3.85)
Medium & high tech	3.84	5.10*	3.87	4.99*
	(2.85)	(2.80)	(2.82)	(2.78)
Knowledge-intense services	−0.93	−0.44	−1.15	−0.66
	(1.98)	(1.93)	(1.96)	(1.92)
Less knowledge-intense services	−5.49	−4.50	−5.65	−4.72
	(3.71)	(3.63)	(3.67)	(3.60)
Low & medium tech	−3.42	−1.90	−3.42	−2.01
	(4.14)	(4.05)	(4.10)	(4.02)
Constant	52.41***	56.72***	50.94***	55.29***
	(4.52)	(4.48)	(4.49)	(4.47)
Observations	731	731	731	731
R-squared	0.20	0.24	0.22	0.25
Number of calls	25	25	25	25

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.
Reference categories: Non-European location; Other industry.

been found to invest more in the training of their employees, which has previously been found to positively influence absorptive capacity (Ketata et al., 2015). We also observe a small negative effect of increasing project costs. This could indicate that the experts are attentive to inflated project costs. In terms of industry effects, we find a significant positive effect from the medium-high and high tech sector dummy, which is to be expected given the technological focus of the industry. Finally, a positive and significant effect is found for firms located in Western Europe. This is likely caused by the nature of firms located in this geographical area and the tradition of focusing on environmental technologies and innovation in such countries.

Consistency and sensitivity estimations

We conduct several additional estimations to test the stability of our findings and rule out alternative explanations. In Appendix 2 we provide tests for potential bias from university participation and the consistency of our results to alternative specifications of the knowledge diversity measure. In model V we estimate the main model with the inclusion of a dummy variable indicating the participation of a university, as scientific knowledge is potentially particularly valuable in innovation efforts. Fifty-nine percent of the consortia involve a university participant, and while this has the significant and positive effect that would be expected, the effects of our explanatory variables remain consistent. As a result we conclude that our main results are not biased by the participation of universities in certain consortia.

Furthermore, Appendix 2 introduces a number of consistency checks to ensure the validity of our knowledge diversity measure and the validity of our findings regarding its importance to problem-solving. Our measure is based on patent information at the level of the organizations, which entails an assumption of access to knowledge across organizational units. This assumption could be particularly strong in the case of universities, which are often in possession of highly diverse knowledge in departments with different scientific foci. As our measure of knowledge diversity could potentially be inflated by this characteristic of university knowledge model VI provides a consistency check with a knowledge diversity measure, which excludes university patents. Similarly, model VII provides a consistency check using a knowledge diversity measure that is exclusively based on firm-held patents since non-firm organizations' motivations for and use of patenting is likely to vary from that of commercial firms.

These alternative specifications of knowledge diversity produce consistent results to those in our main model, which shows that our hypothesized relations are not sensitive to alternative definitions.

In Appendix 3 we conduct four additional consistency checks to ensure that our results are not the result of misspecifications. First, we estimate our model using robust standard errors to account for potential outliers and heteroskedasticity in our data. Model VIII presents the results, which are consistent with those of our main estimation model. Second, since we construct our measure for knowledge diversity from patent statistics we would like to rule out that the effect is merely driven by the number of patents. We calculate patent stocks for each partner in a search consortium using a constant annual depreciation rate of 15 percent, as is standard in the literature (e.g., Hall et al., 2005), covering the period up to the year of the formation of the search consortium. These stocks are summed up for each consortium and included in model IX. All hypothesized effects remain stable. Third, larger firms may have more resources available to manage and coordinate their consortia. To test whether this factor influences the estimation results we restrict the model to search consortia led by SMEs. Model X in the Appendix shows the results of the SME sample, which are fully aligned with our main results.

Fourth, approximately 12% of our sample consists of consortia in which none of the participants hold patents. As a result our main model contains observations that are registered with zero in the knowledge diversity measure. Arguably this speaks to the limitations of patents as a proxy for knowledge as described above. Strictly speaking our measure thus ascribes no knowledge diversity to these consortia, which is likely to be an oversimplification. We provide an additional consistency check in model XI by excluding all consortia that have no participants with patents. Restricting our sample in this way ensures that our results are not driven by the zeroes assigned to consortia without any patents among the partners. The results of our consistency check on this restricted sample are aligned with those found in our full sample.

Discussion

We conduct this study to answer the question of how firms develop promising strategies to solve environmental problems, which typically requires knowledge from multiple firms or organizations. Search strategies for addressing environmental problems are therefore particularly likely to be collaborative in nature, i.e., requiring the collaborative effort of diverse sets of partners. To answer our question we draw on collaborative and problemistic search theory. We predict that under conditions of collaborative search for solutions to complex problems, such as environmental ones, the diversity of prior knowledge of the partners in a search consortium can only partly explain the ability to jointly develop a search strategy with a high problem-solving potential.

We develop theoretical arguments for why it matters how well the partners have learned to collaborate, i.e., their collaborative experience, and why there is a price to pay for including first-time partners. We find that collaborative experience is equally important as the diversity of the existing knowledge of the partners for the problem-solving potential of collaborative search. Moreover, we find that first-time participants in a search consortium reduce its problem-solving potential significantly.

For academic research we provide new insights in two research streams. For research in sustainable innovation we provide a more detailed understanding of how firms can form promising search strategies that go beyond breadth and depth measures of knowledge sources (e.g., Ketata et al., 2015). We find that sustainable innovation requires not only collaborative efforts that span existing fields of expertise, but also partners who can communicate and coordinate effectively. What is more, we find that involving a novice partner is costly. These findings provide important new variables for theorizing on how the search for solutions to important societal challenges can best be addressed.

Our findings are not limited to sustainable innovation and have significant implications for the broader research streams on knowledge search and open innovation. First, we conceptualize a firm's search strategy as a multilateral process in which partners interact and need to be coordinated. Second, we show that the problem-solving potential of a search strategy is not strictly determined by the screening capacities (Laursen and Salter, 2006) or search routines (Love et al., 2014) of the searching firm. Rather, collaborative experience of the partners has an important impact on the ability to collaboratively develop solutions. This is supported by the finding that engaging with inexperienced collaborators can have significant negative effects for the problem-solving potential because first-time participants need to develop routines and collaborative capabilities. Hence, we provide a way for future research to conceptualize the search for external knowledge as a more interactive process than the simplistic collection and combination of external knowledge by a searching firm. Finally, we show that firms are heterogeneous in the problem-solving potential of the search strategies that they devise and that focusing exclusively on successful search strategies that led to "finding" may severely underestimate the diversity and complexity of a firm's search.

Our results also have immediate relevance for management practice and policy making. We develop a profile of search consortia that are likely to provide promising solutions to environmental challenges and result in sustainable innovations. Firms should strive to collaborate with partners with diverse knowledge and collaborative experience, while novice partners should be avoided. Especially the latter finding may be challenging for policy makers. On the one hand, many organizations should be encouraged to participate in the search for sustainable innovation, including start-ups with little if any collaborative experience. On the other hand, search consortia including first-time participants develop search strategies with less potential. Our results suggest that for generating search strategies for sustainable innovation, policy support is best directed at strengthening the collaborative experience of existing search consortia and their partners. This can, for example, be achieved by organizing networking events for experienced partners. Inexperienced organizations interested in joining search consortia need opportunities to develop collaboration capabilities prior to collaborations taking place. Such efforts are likely to benefit both collaborators and society through search strategies with higher problem-solving potential.

Concluding remarks

We have discovered several unresolved research opportunities while conducting this study. First, we cannot observe the detailed interactions between partners in a search consortium prior to their search strategy. We suspect that the quality and quantity of personal interactions as well as the use of digital tools may influence the development of a search strategy. Studying these intra-consortium interactions would require a dedicated research design that goes beyond our current setting. Relatedly, observing interactions in a more detailed fashion would also allow constructing a measure for particularly deep search effort with certain partners (Laursen and Salter, 2006). Second, collaboration experience can originate from a variety of sources and manifest itself in multiple ways, e.g., employee mobility between organizations. While our study focuses on a particular source of collaboration experience, dedicated studies may collect primary data on broader sets of collaboration experience and how they influence search strategies. This would also allow disentangling the two mechanisms we have outlined through which experience benefits the problem-solving potential, which is currently a limitation to our study. Similarly, diversity of knowledge can also be captured in various ways. We rely on patent statistics since they provide us with countable representations based on a shared standard. It could be very interesting to see how our measures correlate with alternative operationalizations, e.g. based on scientific publications. Third, future studies may want to analyze the content of the search strategy documents themselves. Such analyses could reveal information at the level of the grant proposal, e.g. how search strategies are structured or integrated. Given the advances of automated content analysis tools, this could be a fruitful path for a dedicated project. Finally, we focus on collaborative search strategies, which are likely to be among the most important and longest running ones of participating firms because of the large budgets and intensive collaboration. It is not obvious that our theoretical logic would be equally applicable in settings where firms can more easily dissolve search partnerships or switch partners in more routine search efforts. In a similar vein, it would be interesting to study the differences that emerge when problems to be solved only lead to incremental innovations and not radical ones. In this sense, the current study opens up many new pathways for studying the interaction between firms and their external knowledge sources, particularly in the early stages of formulating strategies to solve problems.

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Appendixes

Appendix 1Examples of calls

Call number: ENV.2013.6.3-1

Title: Turning waste into a resource through innovative technologies, processes and services

Description: The overall objective of this topic is to reduce environmental impacts through innovative, breakthrough solutions that lead to a reduced demand for raw materials and contribute to more efficient use of materials generally, thus supporting important EU policy commitments reflected in the Roadmap to a Resource-Efficient Europe and helping to create a bridge with future Horizon 2020 activities on 'Climate action, resource efficiency and raw materials'. Proposals must focus on solid waste management (including existing industrial and urban waste dumps) and address one of the following two sub-topics:

a) Valorization of urban solid waste. Research should focus on the development of innovative solutions which aim for a radical change in the way of collecting, handling, separating, processing, upcycling or transforming urban solid wastes and/or the development of new added-value products and services with good market potential based on recycled urban waste. This activity should contribute to more efficient and cost-effective urban mining and to a more circular economy.
b) Recovery of valuable raw materials from industrial waste. Research should address new, radical, different and sustainable solutions for the collection, recovery and preparation for reuse of raw materials (like e.g. critical metals and minerals as defined in the context of the Raw Materials initiative40) from waste from key industrial sectors such as construction, chemicals, aerospace, machinery and equipment, automotive or ICT. New business models and reuse-oriented services to enable an efficient management of raw materials should be also considered. This topic complements related activities to be supported under Theme 4 Nanosciences, Nanotechnologies, Materials and New Production Technologies. In both cases, proposals should demonstrate how the research foreseen will contribute to improving the environment, including how it will promote the development of new economic opportunities, improve resource efficiency and boost competitiveness. Proposals should also demonstrate that the proposed solutions have the potential

to be substantially more sustainable, from a life cycle perspective, than current practice, should consider both direct and indirect, both positive and adverse impacts and, where appropriate, contribute to the standardization process. Pilot trials at an appropriate scale should be envisaged to facilitate future market uptake.

Expected impact: Breakthrough innovation in novel technologies, products or services with high potential to achieve a more green economy. More sustainable consumption and production patterns. Improved resource efficiency and reduced environmental impacts. Reduced waste production and pressure on raw materials. New business models, industrial symbiosis, and cradle-to-cradle approaches. Substantial contribution towards the sustainable supply of raw materials of economic importance in Europe. Improved communication and transfer of knowledge to policy making, business and to the general public.

Call number: ENV.2013.6.2-1

Title: Water resources management under complex, multi-stressor conditions

Description: The challenge is to underpin decision making, risk assessment and management of water systems under complex multiple stress conditions (combination of organic and in organic pollution, flow and morphology alteration, surface and groundwater abstraction, land use change, climate variability and change, invasive species, pathogens, etc.). Research should have a clear user perspective and aim to enhance our understanding of stressors interactions, species interactions, species–stressor-relationships and impacts on the ecological functioning, stability and resilience of the aquatic ecosystems. Based on innovative methodologies, research should develop holistic approaches and tools to diagnose changes in the ecological, quantitative and chemical status of water bodies, as defined in the Water Framework directive (WFD)16, and in water availability, in relation to multiple stress conditions, identify the relevant stressors which are responsible for their deterioration, and forecast and predict the ecosystem responses and ecological recovery as a consequence of alternative management measures on different spatial scales.

It should also aim at the development of integrated impact assessment tools, coupling biophysical with socio-economic assessment of impacts (provision of ecosystem services) to improve water resource protection and management, including water related extreme event prevention and management, at EU and river basin levels.

Expected impact: Improved water status and availability of clean water, better implementation of water policy and optimal decision making in water resources management under complex multiple stress conditions, with the aim of achieving sustainable resource use and flood risk reduction. Development of more cost-effective Programmes of Measures (POMs) to improve the ecological status of surface water bodies from the local to the river basin scale and improve the groundwater body status — also in the context of ecosystem goods and services — in line with the EU Water Framework Directive.

Appendix 2Consistency checks

Variable	Model V	Model VI	Model VII
Number of patent classes	2.57***		
	(0.86)		
Participants' total experience	1.48*	1.46*	2.01***
	(0.77)	(0.77)	(0.74)
Share of first-time participants	−3.05***	−3.10***	−3.19***
	(0.87)	(0.87)	(0.87)
University participant	4.60**		
	(1.83)		
Number of patent classes (excl. university patents)		2.19***	
		(0.79)	
Number of patent classes (firm patents only)			1.75**
			(0.72)
Number of partner types	3.08***	3.06***	3.21***
	(0.89)	(0.89)	(0.89)
Number of participants	0.37***	0.37***	0.36***
	(0.14)	(0.14)	(0.14)
Project cost (million EUR)	−0.88***	−0.88***	−0.89***
	(0.22)	(0.23)	(0.23)
SME	−5.55***	−5.64***	−5.57***
	(1.28)	(1.28)	(1.28)
Constant	53.45***	52.88***	52.61***
	(4.51)	(4.49)	(4.49)
Location dummies	Y	Y	Y
Industry dummies	Y	Y	Y
Observations	731	731	731
R-squared	0.26	0.26	0.26
Number of calls	25	25	25

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Reference categories: Non-European location; Other industry.

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Appendix 3Consistency checks

Variable	Model VIII	Model IX	Model X	Model XI
Number of patent classes	3.03***	2.89***	2.85**	3.08***
	(0.70)	(0.86)	(1.12)	(1.14)
Participants' total experience	1.99*	1.81**	2.88***	1.92**
	(1.04)	(0.77)	(1.09)	(0.75)
Share of first-time participants	–2.93***	–2.94***	–3.30***	–2.56***
	(0.96)	(0.87)	(1.20)	(0.91)
Participants' total patent stock		0.70		
		(0.76)		
Number of partner types	3.45***	3.39***	3.92***	3.23***
	(1.01)	(0.88)	(1.21)	(0.89)
Number of participants	0.40***	0.40***	0.33*	0.45***
	(0.14)	(0.14)	(0.17)	(0.14)
Project cost (million EUR)	–0.91***	–0.91***	–1.23***	–1.00***
	(0.20)	(0.23)	(0.32)	(0.25)
SME	–5.35***	–5.35***		–5.16***
	(1.37)	(1.28)		(1.36)
Constant	55.29***	55.53***	61.24***	54.35***
	(3.50)	(4.47)	(6.09)	(4.62)
Location dummies	Y	Y	Y	Y
Industry dummies	Y	Y	Y	Y
Observations	731	731	399	641
R-squared	0.25	0.25	0.25	0.24
Number of calls	25	25	22	25

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.
Reference categories: Non-European location; Other industry.

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