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Meeting the relational challenge of ecological engineering within ecological sciences

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ABSTRACT

Due to the current environmental problems human societies have to face and the lack of sustainability of most of their activities, the time of Ecological Engineering (EE) has surely come. To assess the development of EE within the academic world we conducted a literature survey based on an exhaustive count of all articles mentioning EE and related terms since the 1980s, and a classification of all articles published in 2008 and 2009 in the journal *Ecological Engineering*. This survey reveals that EE has quickly developed, and that the journal *Ecological Engineering* plays a preponderant role in this development. In comparison, articles mentioning the expression "ecological restoration" or "agroecology" were published in many more journals than articles referring to "ecological engineering". This analysis showed that EE is highly dominated by China and the USA, and by studies aimed at improving the chemical quality of waters (either in natural ecosystems or to treat wastewaters) and aquatic system restoration. Hence, our survey suggests that EE approaches could be widened. These results emphasize the existence of an internal relational challenge for EE, i.e. inside the academic world of ecological sciences. Scientists and engineers from all environmental and ecological sciences must be convinced to take part in the development of this discipline. We explain why meeting this challenge is required for the full development of EE and why this would also highly benefit fundamental ecology. Finally, we give some hints on how to meet this challenge. Reaching this objective should help to bridge the gap between fundamental and applied ecologies and to unify applied ecology.

1. Introduction

The time of Ecological Engineering (EE) has surely come (Mitsch and Jørgensen, 2003). Indeed, human societies have to face huge environmental challenges, e.g. coping with climate changes, feeding a still increasing human population, mitigating biodiversity and natural ecosystem losses. The only way to face these challenges is to develop more sustainable practices informed by ecological knowledge and aimed at (1) protecting and (2) restoring ecological systems, (3) modifying ecological systems to increase the quantity, quality and sustainability of the services they provide, or (4) building new ecological systems that provide services that would otherwise be provided through more conventional engineering based on non-renewable resources. This new definition of EE stresses the link between EE and ecosystem services (Costanza et al., 1997) but is in line with former definitions (Mitsch and Jørgensen, 2003; Odum and Odum, 2003). Indeed, the notion of ecosystem service is viewed as a way to acknowledge the dependence of human societies on Nature and as a tool to increase the sustainability of the relation between Nature and human societies (Millennium Ecosystem Assessment, 2005).

Many signs indicate that the idea of EE itself and the use of EE are growing and should further increase during the next decades. Indeed, environmental concerns are rising, and environmental issues and the lack of sustainability of human activities are more and more taken into account by policies and the economics world (Millennium Ecosystem Assessment, 2005). More basically, the vitality of EE groups and congresses on EE-related subjects are good signs. However, as explained by C. Jones in this issue (Jones, 2011), EE must quickly meet three main challenges – ethical, intellectual and relational – in order to expand to its fullest possible extent and become a standard tool for human societies to face their environmental and sustainability issues. Within the relational challenge (Jones, 2011), C. Jones emphasizes the importance of bringing together scientists from many fields (ecological, chemical, engineering, social and economical sciences, etc.), practitioners

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and policy makers. This is essential because otherwise EE will never find enough support from both the academic and economic worlds to reach the ambitions ecological engineers have for their field. Engineering is also, by definition, essential to EE and engineering sciences are urgently needed in EE for their capacity to (1) predict the dynamics of systems, (2) control them, (3) design robust and general solutions, and (4) design economically and socially acceptable solutions. However, we want to emphasize an internal relational challenge, inside the academic world of ecological sciences, nested within the larger one described by C. Jones: EE must first, or at least at the same time, convince as many scientists and engineers as possible from all ecological sciences of the necessity to get involved in the development of this particular field. This is highly necessary to meet the intellectual challenge outlined by C. Jones, i.e. to get scientists to quickly do the basic research necessary to design practices based on EE principles and to inform these practices with scientific ecological knowledge.

As organisers of the EECA congress ("Ecological Engineering: from concepts to applications", Paris, France, December 2009) and as scientists working in a laboratory mostly studying fundamental aspects of ecology, we feel that EE has recently gained credit in the European and French academic realms. However, this also results in some confusion. First, some scientists believe they are working in the field of EE but are probably not. Conversely, many others are doing research relevant to EE but never refer to EE. Second, taking into account the current research on EE and the currently used EE-based practices and not the general framework presented in the Odum brothers' vision (Odum and Odum, 2003), it seems to us that the realized scope of EE could be widened to encompass more types of applications and manipulations. Three questions have thus to be answered. What is the impact of EE among scientists working in ecological and environmental sciences? Could we broaden the goals of the new practices we want to develop in terms of the ecosystem services we are targeting and the situations where these practices could be applied? Could we develop EE techniques that manipulate more diverse aspects of ecological systems in terms of levels of ecological organization targeted? To answer these questions, we first achieved a systematic bibliographic survey of the literature published in the field of EE to assess more objectively the impressions we describe above. We then used the results of this survey to outline some possible solutions to increase the pace of EE development.

2. Bibliographic survey on EE

We first wanted to assess the impact of EE in the academic world and the evolution of this impact. To do so, we systematically scanned each year, from the 1970s to 2009, looking for articles dealing with EE in the ISI Web of Knowledge and the Scopus databases. To describe the temporal development of EE, we counted all articles (excluding conference proceedings) using the expression "ecological engineering" (either in the title, the abstract or the key-words) and that were published in all journals of the databases. We counted separately articles published in the journal *Ecological Engineering* that were considered automatically as dealing with EE.

To assess the general use of the expression "ecological engineering" and to compare it to the use of other expressions denoting related fields "ecotechnology" (or "ecotechnologies"), "ecosystem services" (or "ecological services"), "agroecology" and "ecological restoration" (or "restoration ecology"), we counted (in the ISI Web of Knowledge and Scopus databases, from the 1970s to 2010) all the articles (excluding conference proceedings but taking all years into account) using these expressions (either in the title, the abstract or the key-words). We then looked at the journals that published

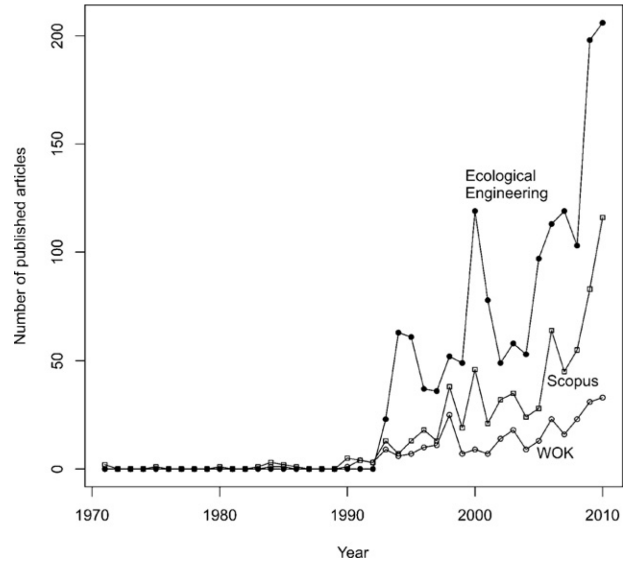

Fig. 1. Number of articles published each year in the journal *Ecological Engineering* (dots), and number of articles published in all journals (using Scopus database, open squares; using ISI Web of Knowledge, open circles, WOK) and mentioning "ecological engineering" in their title, keywords or abstract.

these articles more frequently and calculated the corresponding percentages. We included the terms "agroecology" and "ecological restoration" to assess the importance of these subfields within EE (see Section 3). We included the expression "ecosystem services" because, somehow, EE always aims at increasing the production of ecosystem services and its sustainability (see our definition above).

We then intended to describe the type and the geographic origins of studies published about EE. We thus scrutinized all the articles published in 2008 and 2009 in the journal *Ecological Engineering* (301 in total) and filled out a database with the following fields: (1) the country of the first author, (2) the broad type of EE practices aimed at by the study, (3) the type of ecosystem in which the study was achieved, (4) the ecological level of organization directly manipulated by the involved EE practices, and (5) the final goal of the manipulation (i.e. the ecological level targeted by the manipulation). For example, a study could aim at designing/assessing practices to conserve a local population of an endangered beetle species using physical soil modifications. We would put "conservation" in field (2), "physical" in field (4) and "population" in field (5).

Indeed, we acknowledge that this approach, based on a survey of articles published in the international peer-reviewed literature and on simple key-words, only gives a partial description of the development of EE. Though our survey encompasses the engineering literature published in peered-review journals, many other relevant articles are certainly published in the grey literature, often not in English. However, our survey should be pertinent especially to describe the development of EE within the academic world and to assess the importance of the internal relational challenge. Moreover, we use two databases (ISI Web of Knowledge and Scopus) to cope with possible biases and discrepancies between databases.

2.1. Temporal development of EE

Since the 1980s with some seminal papers (Odum, 1984; Ma, 1985), the field has quickly progressed. About 1500 articles have been published in *Ecological Engineering* since its creation in 1993, and about 200 articles are now published in this journal each year (Fig. 1). Moreover, about 280 articles until 2010 (now between 15

Table 1
Numbers of articles and journals using the term "ecological engineering" and four other related expressions either in their titles, abstracts or key-words. The ISI Web of Knowledge (A) and Scopus databases (B) were used to gather this information. All registered data were used. For each term, we listed the journals in which these articles were more frequently published together, with the proportion of articles they published calculated over all the journals using the term. We estimated the number of publications using the term "ecotechnol*" in order to take into account derived expressions (ecotechnology, ecotechnologies, and ecotechnological). To estimate the number of articles dealing with ecological restoration, we both counted articles using the expressions "ecological restoration" and "restoration ecology". Similarly, to count articles dealing with ecosystem services we both counted articles using the expressions "ecosystem service*" and "ecological service*".

	Ecological engineering	Ecotechnology	Ecological restoration	Agroecology	Ecosystem services
(A) ISI Web					
Total number of articles	283	96	1546	257	2665
Total number of journals	96	53	385	132	554
Journals publishing the highest proportions of the articles (>1%)	Ecol. Eng. (47.70%) Water Sci. Technol. (4.59%) Ecol. Model. (2.83%) Hydrobiologia (1.41%) Int. J. Eng. Educ. (1.41%) Ambio (1.06%) Env. Eng. Sci. (1.06%) Freshwat. Biol. (1.06%) Int. J. Sustain. Dev. World Ecol. (1.06%) J. Appl. Phyco. (1.06%) J. Environ. Sci. Health Part A (1.06%) J. Environ. Sci. China (1.06%)	Ecol. Eng. (29.17%) Water Sci. Technol. (5.21%) Hydrobiologia (4.17%) Curr. Sci. (3.13%) Int. Revue Ges. Hydrobiol. (3.13%) Acta Hydrochim. Hydrobiol. (2.08%) Chem. Biochem. Eng. Q. (2.08%) Int. Rev. Hydrobiol. (2.08%) J. Environ. Sci. Health Part A (2.08%) Limnologica (2.08%) Mater. Design (2.08%)	Restor. Ecol. (13.00%) Forest Ecol. Manage. (3.95%) J. Appl. Ecol. (3.49%) Ecol. Appl. (3.43%) Ecol. Eng. (3.30%) Environ. Manage. (3.04%) Biol. Conserv. (2.39%) Conserv. Biol. (1.49%) Biodiv. Cons. (1.42%) Appl. Veg. Sci. (1.23%) Hydrobiologia (1.23%) Landsc. Urban Plan. (1.23%) Science (1.10%) J. Forest. (1.03%)	Agric. Ecosyst. Environ. (6.61%) J. Sustain. Agric. (5.45%) Ecol. Appl. (3.11%) Agrofor. Syst. (2.33%) J. Appl. Ecol. (2.33%) Rostlinna Vyroba (2.33%) Agron. Sustain. Dev. (1.95%) Int. J. Agric. Sustain. (1.95%) Weed Res. (1.95%) Agric. Syst. (1.56%) Ann. Appl. Biol. (1.56%) Conserv. Biol. (1.56%) Interciancia (1.56%) J. Agric. Environ. Ethics (1.56%) Prof. Geograph. (1.56%) Rev. Bras. Cienc. Solo. (1.56%)	Ecol. Econ. (7.80%) Proc. Natl. Acad. Sci. USA (2.33%) Biol. Conserv. (2.06%) Conserv. Biol. (2.06%) Ecol. Appl. (1.99%) Ecol. Soc. (1.99%) Agric. Ecosyst. Environ. (1.84%) Front. Ecol. Environ. (1.80%) J. Appl. Ecol. (1.76%) Environ. Manage. (173%) Biodivers. Conserv. (1.61%) Bioscience (1.43%) Landsc. Urban Plan. (1.39%) Forest Ecol. Manage. (1.35%) Science (1.35%) Ecosystems (1.20%) J. Environ. Manage. (1.20%) Ambio (1.05%)
(B) Scopus					
Total number of articles	713	137	6900	764	3642
Total number of journals	234	86	991	310	870
Journals publishing the highest proportions of the articles (>1%)	Ecol. Eng. (24.12%) Landsc. Ecol. Eng. (19.78%) J. Environ. Sci. Health Part A (2.52%) Water Sci. Technol. (1.82%) Chinese J. Appl. Ecol. (1.82%) Ecol. Model. (1.41%) J. Environ. Sci. (1.12%)	Ecol. Eng. (21.17%) Water Sci. Technol. (5.11%) Wasser Und Boden (3.65%) Hydrobiologia (2.92%) Acta Hydrochim. Hydrobiol. (1.46%) Bioscience (1.46%) Curr. Sci. (1.46%) Ecohydrol. Hydrobiol. (1.46%) FASEB J. (1.46%) Int. Revue Hydrobiol. (1.46%) J. Environ. Sci. Health Part A (1.46%) Lakes & Reservoirs Res. Manage. (1.46%) Limnologica (1.46%) Mater. Design (1.46%)	Restor. Ecol. (13.74%) Forest Ecol. Manage. (3.16%) Ecol. Eng. (2.75%) Biol. Conserv. (2.20%) J. Appl. Ecol. (2.17%) Hydrobiologia (2.14%) Ecol. Appl. (2.07%) Ecol. Manage. Restor. (1.83%) Wetlands (1.74%) Environ. Manage. (1.65%) Chinese J. Appl. Ecol. (1.52%) Ecol. Restor. (1.29%) Cons. Biol. (1.20%) J. Arid Env. (1.09%) Biodiv. Cons. (1.04%)	Agric. Ecosyst. Environ. (6.41%) Chinese Geographic. Sci. (4.58%) Agric. Sys. (2.88%) Nut. Cycl. Agroecos. (2.62%) J. Sustain. Agric. (2.22%) Human Ecol. (1.44%) J. Appl. Ecol. (2.02%) Agrofor. Syst. (1.31%) Can. J. Soil Sci. (1.31%) Eur. J. Agro. (1.31%) Biodiv. Cons. (1.18%) Chinese J. Appl. Ecol. (1.18%) Ecol. Model. (1.18%) Eurasian Soil Sci. (1.18%) Agro. Sustain. Dev. (1.05%) Environ. Dev. Sustain. (1.05%) Soil Biol. Biochem. (1.05%)	Ecol. Econ. (5.74%) Ecol. Soc. (1.76%) Chinese J. Appl. Ecol. (1.67%) Agric. Ecosyst. Environ. (1.59%) Proc. Natl. Acad. Sci. USA (1.59%) Conserv. Biol. (1.42%) Biol. Conserv. (1.43%) J. Appl. Ecol. (1.37%) Forest Ecol. Manage. (1.35%) Ecol. Appl. (1.32%) Environ. Manage. (1.32%) Biodivers. Conserv. (1.18%) Front. Ecol. Environ. (1.10%) Chinese J. Ecol. (1.07%) Landsc. Urban Plan. (1.02%)

and 20 articles each year) are published in other journals and refer to EE, according to ISI Web of Knowledge (Fig. 1). Scopus gathers more articles referring to EI, i.e. about 690 (now between 30 and 50 each year). The difference between the two databases comes from the fact that Scopus but not ISI web of knowledge takes into account all articles published in Landscape and Ecological Engineering (starting in 2005). In the same vein, Scopus takes into account many Asian journals that are absent from ISI Web of Knowledge (see below). This represents since 1993 an annual 14% increase in the number of article published in *Ecological Engineering* and an annual 8% increase in the number of articles mentioning EE according to ISI Web of Knowledge (14% according to Scopus). This shows the key role *Ecological Engineering* has played in the development and structuring of the field. This, however, also points at the relatively slow development of EE within ecological and environmental sciences. Indeed, the number of articles published in the journal *Ecological Engineering* and the number of other articles referring to EE have increased in a parallel way. *Ecological Engineering* has always published each year, much more articles as the total number of articles referring to EE (6.2 times more according to ISI Web of Knowledge, 2.7 times more according to Scopus). It seems that EE has not fully spread out in the whole ecological literature (see also below Section 2.2 and Table 1). It is in particular strange, at least in our opinion, that journals devoted to applied ecology do not refer much to EE (e.g. *Ecological Applications* has only referred explicitly two times to EE and *Journal of Applied Ecology* once). In comparison, these journals refer more often to ecological restoration, agroecology and ecosystem services (between 30 and 50 papers published according to the journal and the term).

2.2. Global use of the expression "ecological engineering" and related terms

According to ISI Web of Knowledge, the expression "ecological engineering" has been cited 276 times in 92 journals, with a clear dominance of the journal *Ecological Engineering* (47.70% of the articles published in this journal vs. 4.59% for the second journal *Water Science and Technology,* see Table 1A). The term "ecotechnology" is less frequently used (96 articles in 53 journals) but its use presents a similar pattern. The expression "ecological restoration" has been used much more times than "ecological engineering" or "ecotechnology" (1546 articles in 385 journals). It must also be marked that the use of this expression is shared by many journals: the first journal, *Restoration Ecology*, publishes only 13% of the articles using the expression. Hence, two journals publish more than 50% of the articles using the expression "ecological engineering" while 26 journals share the publication of 50% of the articles using the expression "ecological restoration" (Table 1A). There are roughly the same numbers of articles and journals using the terms "agroecology" and "ecological engineering". However, as for "ecological restoration" there is no strong dominance of any journal (27 journals share the publication of 50% of the articles). "Ecosystem services" is extremely used (3642 articles and 870 journals). Again, there is no strong dominance of any journal using this expression. *Ecological Engineering* is not among the journals using the most the expressions "ecosystem services" and "agroecology" (Table 1A).

Scopus (Table 1B) gives the same general image as ISI Web of Knowledge (Table 1A). It confirms that Ecological Engineering plays a central role in the discipline (24.12% of articles referring to EI). The main difference with ISI web of knowledge is that only Scopus classifies all articles published in Landscape and Ecological Engineering (19.78% of articles referring to EI). Similarly, articles referring to the other terms are spread in more journals according to Scopus than according to ISI Web of Knowledge. Indeed, Scopus integrate, for example, some Chinese journals absent from ISI Web of Knowledge (Chinese Geographic Sci., Chinese J. Appl. Ecol., Chinese J. Ecol.).

Taken together, these results confirm that the field of EE and the use of the term "ecological engineering" are heavily dominated by the journal *Ecological Engineering*. However, a subfield of EE, ecological restoration, is more developed than EE itself in terms of number of articles and journals. It must also be underlined that other fields related to EE (agroecology and ecosystem services) appear as weakly linked with EE. This suggests that agroecologists do not see themselves as ecological engineers and, conversely, that ecological engineers do not always see the provision of ecosystem services and production (e.g. food) as a primary goal of EE.

2.3. Classification of articles published in the journal Ecological Engineering

Fig. 2 shows that *Ecological Engineering* publishes articles from a wide sample of countries (40 countries in 2008–2009). However, nearly half of these articles are coming from only two countries, China and the USA. Asia is well represented, since India and Taiwan have also published quite a few articles in the journal. Europe is represented by many countries (Spain, Italy, Sweden, Germany, France, UK, Portugal, etc.). However, apart from Spain, which has published about 5% of the articles in *Ecological Engineering*, each of these countries has published a very low number of articles in this journal. It is noteworthy that Africa has hardly published any studies in *Ecological Engineering* (only a few articles from Côte d'Ivoire, Cameroon and South Africa).

Fig. 3 shows at the same time that (1) studies published in *Ecological Engineering* target a wide variety of practices (Fig. 3A) and ecosystems (Fig. 3B), and that (2) the field of EE is dominated by aquatic systems such as wetlands, lakes, and rivers. In parallel, most practices studied aim at treating waters that have been used by human activities (more than 40% of articles) or at increasing *in situ* water quality of natural ecosystems (about 7% of articles), which has been primarily degraded by human activities. The restoration of lakes and rivers constitutes about 7 and 5% of the articles, respectively. It is noteworthy that, all in all, restoration ecology covers about 75% of the articles published in this journal if water treatment is considered, by extension, as a kind of restoration. Plant production constitutes 7% of articles but production is not well represented since there are nearly no articles on forestry and no articles on animal production or aquaculture (at least in 2008 and 2009). About 10% of articles deal with artificial ecosystems, which encompass mostly artificial wetlands used to treat waters but also a few studies on bioreactors.

Again, Fig. 4 shows that *Ecological Engineering* publishes a high diversity of studies but that this diversity is dominated by EE practices that manipulate physical aspects of the environment (about 40% of articles) and populations of primary producers (about 20% of articles) to improve chemical traits (more than 50% of articles) of the ecosystems (see Fig. 5 for the description of the associations between what is manipulated and the goal of manipulations). As already mentioned, this particular pool of studies corresponds to all EE practices manipulating physical aspects of aquatic systems or manipulating a population of plants or algae to increase the capacity of these systems to treat waters, or improve *in situ* the chemical quality of river and lake waters. In these latter cases, manipulations of plant populations fall into the broad category of phytoremediation but are not systematically classified as such in the articles. Finally, some studies target several ecological compartments and wider scales. They are coined as targeting "ecosystem" (about 8% of articles), "human community" (about 2%) or "landscape" (about 1%, see Fig. 4B).

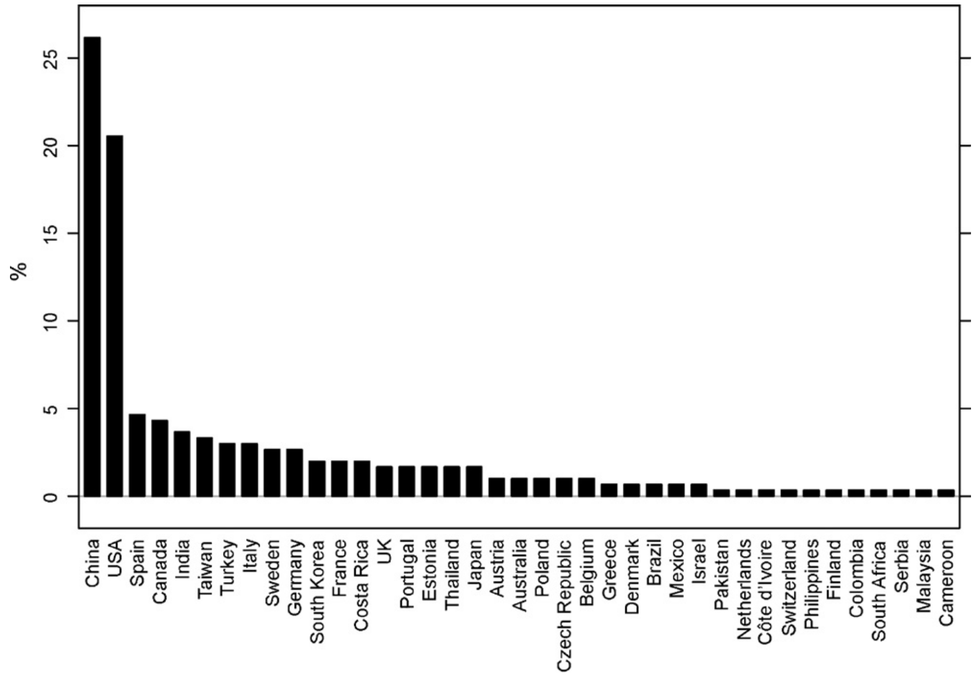

Fig. 2. Distribution of articles published in the journal *Ecological Engineering* in 2008 and 2009 according to the country of their first author.

Among the 132 possible combinations between the ecological level of organization manipulated and the level of organization targeted by the manipulation, 41 combinations are represented by at least one article (Fig. 5). It must be marked that no study appears in this figure as targeting a "human community" because studies targeting the sustainability of human communities, e.g. villages, do not really implement manipulation at the relevant scale. Most of the time, they develop tools to compare the functioning and the sustainability of these communities. Such studies, however, give information on the economical, social, and technical levers that could increase the sustainability of human communities.

3. EE as an integrative discipline

3.1. Unifying applied ecology

Of course, the use of a term is not enough to define a scientific field or to describe its development. It is very likely that many studies are relevant to EE but have not been published in the journal *Ecological Engineering* and do not mention explicitly the term. In fact, many traditional practices such as agriculture, forestry or aquaculture can be turned into EE, at least as soon as they seek sustainability and use knowledge on underlying ecological processes. The growing acknowledgement of the poor sustainability of these activities (see for example Vitousek et al., 1997; Tilman et al., 2002) has triggered the development of new research programs aiming at developing more sustainable practices, i.e. at developing EE practices. This has triggered the development of a new field, agroecology (Altieri, 1989; Gliessman, 2006). This discipline has been defined, for agriculture, in a very similar way as EE: "agroecology should delineate the ecological principles necessary to develop sustainable production systems" (Altieri, 1989). All this suggests that a wealth of studies has EE-relevant goals and means, but does not refer at all to EE. Such studies are either published in traditional journals of agronomy, forestry and aquaculture (etc.) or in more recent and specialized journals such as *Journal of Sustainable Agriculture*.

Similarly, many articles deal with ecological restoration and do not mention the expression "ecological engineering". These articles participate to the development of EE. In fact, the development of ecological restoration is closely linked to the development of EE, as suggested by the fact that *Ecological Engineering* publishes a high proportion of articles about this thematic (Fig. 3 and Table 1). This also suggests that scientists working in this field recognized themselves as ecosystem engineers, while it is probably less the case for agroecologists, agronomists or foresters.

On the one hand, our bibliographic assessment suggests that EE has experienced an important scientific development (Fig. 1) but that this development is primarily documented in the journal *Ecological Engineering* (Table 1 and Fig. 1). On the other hand, many studies relevant to EE are published in other journals without mentioning EE. This supports the existence of the internal relational challenge, i.e. within the academic word, we pointed out in the introduction. Our primary goal should be to help developing more sustainable practices whatever the name given to these practices and whatever the name of the corresponding scientific field. However, terms are important to structure the way we think, to determine the distribution of knowledge among journals, and to help us advertising our findings for other scientists and the society (Powell et al., 2007). This suggests that giving the same name, i.e. EE, to all research and practices seeking to take into account ecological processes to provide ecosystem services in a more sustainable way would probably increase the development and the societal impact of these practices. Most important, this would also help to meet the intellectual challenge described by Jones (2011).

First, people developing research on the various types of practices relevant to EE (conservation, restoration, agriculture, livestock farming, forestry and aquaculture), probably face some common theoretical and practical problems. (1) They have to design robust and efficient practices using an incomplete ecological knowledge, which rarely leads to precise predictions and general laws (Lawton, 1999). (2) The types of ecological processes involved in these apparently extremely different practices might be quite similar. For example, conservation, restoration and agriculture might all

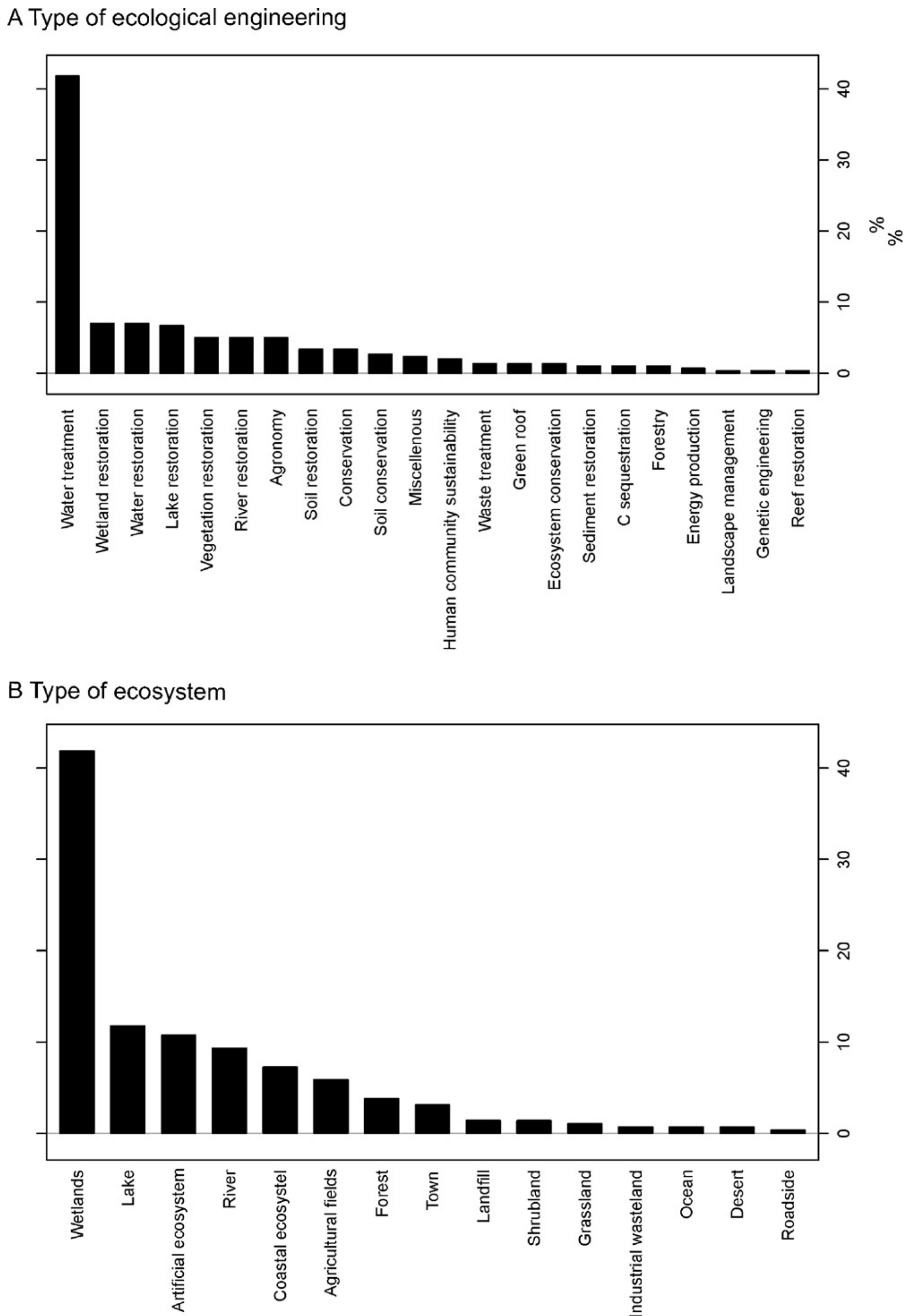

Fig. 3. Distribution of the articles published in the journal *Ecological Engineering* in 2008 and 2009 according to (A) the broad type of EE practice they are related to, (B) the type of ecosystem this practice is targeting. "Water treatment" corresponds to the treatment of waste water, while "water restoration" corresponds to the *in situ* restoration of chemical water quality in natural ecosystems. The terms "lake restoration" or "river restoration" were kept for the general restoration of these ecosystems, which covers more than the restoration of water chemical quality.

depend on our capacity to introduce or reintroduce species and allow their self-maintaining in a more or less artificial ecosystem. (3) At some point, all EE practices come down to a problem of system dynamics or system control, where we want to guide ecological systems from one point to another (and generally to maintain it there) at the lesser energetic, economical and ecological cost.

Second, though many practitioners and scientists working in traditional fields such as agriculture, forestry or aquaculture are genuinely concerned by sustainability issues, they often have difficulties integrating scientific ecological knowledge (and obviously ecologists have difficulties integrating the knowledge of these fields) and turning towards drastically new practices. Taken together, this rationale shows that EE should seek the unification of all branches of applied ecology as already suggested (see for example Gosselin, 2008). In a somehow similar way, medicine unifies all the applications of biology to human health.

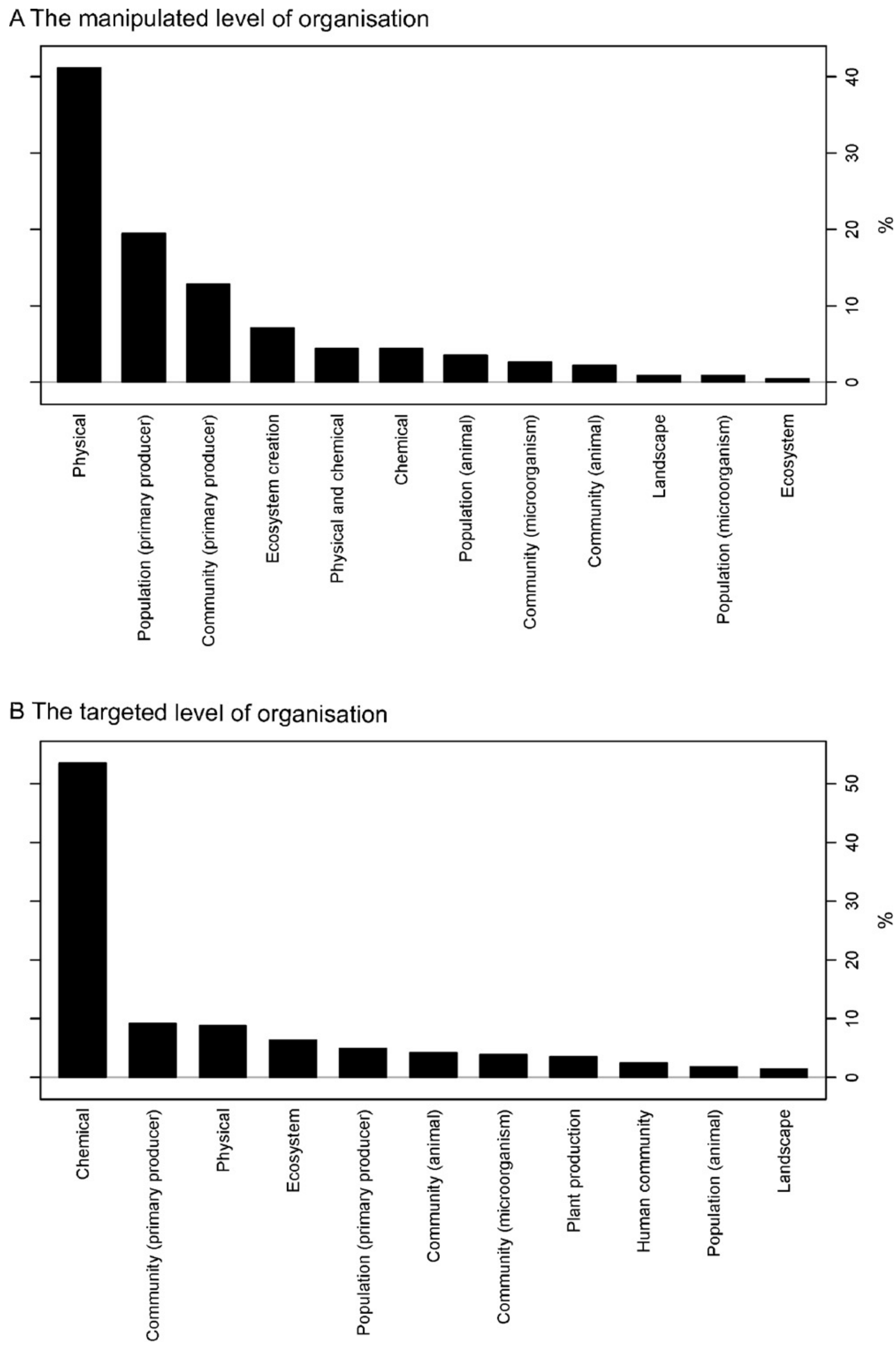

Fig. 4. Distribution of the articles published in the journal *Ecological Engineering* in 2008 and 2009 according to (A) the level of ecological organization manipulated, or the type of lever used by the EE practice; (B) the level of ecological organization that is targeted by this manipulation. When a biotic compartment is involved (population or community), the type of organism is indicated (animal, primary producer, microorganism). When the abiotic environment is involved, it is indicated whether chemical, physical or both aspects of this environment are involved. It is considered that the ecological level of organization manipulated or targeted by EE, is the ecosystem in the case of more integrated studies where different compartments of the ecosystem are manipulated, or the consequences of manipulations on different aspects of the ecosystem are considered.

Besides, beyond the diversity of EE practices and sustainability issues, problems of communication between scientists, stakeholders, citizens and policy makers are quite similar (see for example Castillo, 2000; Janse, 2007) in all fields of applied ecology. Thus, the unification of applied ecology would probably also help meeting the general relational challenge of EE through the design of general methodologies to improve the communication between scientists and users/developers of the applications of ecological knowledge.

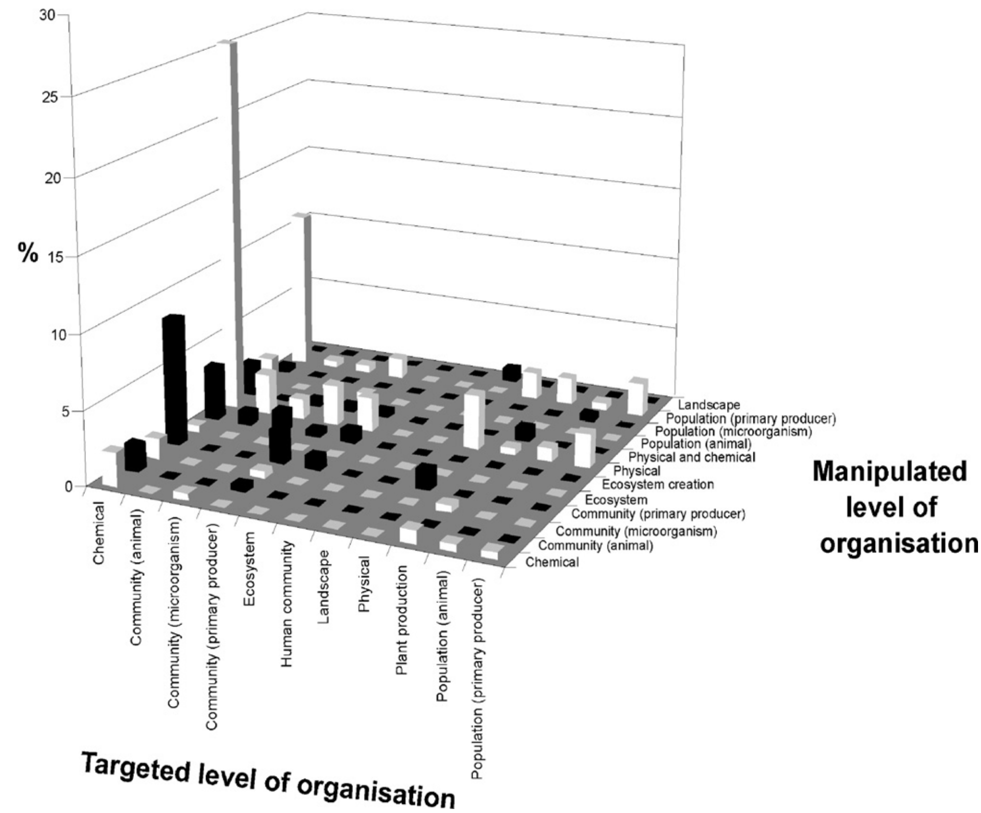

Fig. 5. Distribution of the articles published in the journal *Ecological Engineering* in 2008 and 2009 according to the two criteria used in Fig. 4A and B: (A) the level of ecological organization manipulated, or the type of lever used by the EE practice; (B) the level of ecological organization that is targeted by this manipulation. For a better readability, white and black rows of 3D bars are alternating.

3.2. Bridging the gap between applied and fundamental ecologies

Our bibliographic survey shows that generalist journals specialized in applied ecology (*Ecological Applications* and *Journal of Applied Ecology*) as well as journals specialized in traditional disciplines such as agronomy, forestry or aquaculture do not refer often to EE. This might be a problem for the development of EE (see above) but this might also be, as explained below, the mark of a more profound problem: research in fundamental and applied ecologies are not associated as intimately as they should be.

A first argument for this hypothesis (a lack of integration of fundamental and applied ecologies) is that fundamental aspects of scientific ecology are put forward by the publication system and citations: the generalist ecology journals (e.g. *Ecology*, *Journal of Animal Ecology*, *Ecology Letters*, and *Trends in Ecology and Evolution*), which have the highest impact factors, mostly publish fundamental studies. Meanwhile, more applied journals (e.g. *Agronomy Journal, Forest Ecology and Management*, and *Aquaculture*) tend to have lower impact factors. *Ecological Applications* and *Journal of Applied Ecology*, which have higher impact factors, publish studies that point to "possible" applications. However, they are often only presenting some new knowledge that, as a perspective, could be used to diagnostic environmental problems or guide actions and policies (see for example Barot et al., 2004; Bobbink et al., 2010). These actions or possible new practices are not always tested in these journals. This also explains why these two journals do not often refer to EE.

A second argument is the existence *per se* of journals specialized in applied ecology or EE, which physically separates theory- and application-oriented ecological knowledge. Of course, all articles can be easily found in the same bibliographic databases but due to overwhelming wealth of journals and published articles, this might deter scientists to read articles from both types of journals.

A third argument is the partial disconnection between fundamental and applied ecology-oriented founds and proposals. A fourth argument is that individual scientists and institutions are often specialized either in fundamental or applied ecology. Of course, in some areas of ecology, fundamental knowledge and theory are more strongly linked to applications. This might be the case with conservation ecology that highly benefits from up-to-date results on population dynamics and genetics (see for example Ferrière et al., 1996; Armstrong and Seddon, 2008). This might also be the case for the biomanipulations of lakes and rivers that are proposed as possible methods to reduce the negative effects of eutrophication and improve water quality (Shapiro and Wright, 1984). Indeed, these techniques have always been closely linked to the development of the trophic cascade theory (Carpenter and Kitchell, 1993; Lacroix et al., 1996). This theory and biomanipulations have led to a more synthetic and integrated view on the coupling between food-web structure and ecosystem functioning, and to experimental tests of this theory at the scale of whole ecosystem (Jeppesen, 2011). Of course, our vision of a gap existing between fundamental and applied ecologies might be biased by the fact that these aspects are strongly separated in the French academic system. However, the arguments above and the relatively slow development of EE inside the standard ecological literature do support the idea that efforts have still to be made to bridge the gap between fundamental and applied ecologies.

Developing applied ecology and bridging the gap between applied ecology and fundamental ecologies would have many benefits for both fields. They are obviously complementary and should work synergistically. Indeed, EE (or applied ecology) needs the empirical results and the theories developed by fundamental ecology. Conversely, fundamental ecology needs applied ecology as a source of problems, opportunities and challenges. In fact, such a strong interaction between applied and fundamental aspects of sciences is developed in many fields, i.e. biology, physics, and mathematics. This is probably also crucial to ensure the visibility of these fields and their legitimacy in front of the society. Tightening the links between applied and fundamental ecologies could be particularly profitable because ecological theories and empirical results are probably underused by EE and because, conversely, fundamental ecology might not always produce the type of results and theories required for the development of EE.

The relatively low development of applied ecology could be attributed to: (1) the youth of ecology as a science (Mayr, 1996); (2) the fact that some traditional fields (e.g. agronomy, forestry) aiming concretely at developing practices, have evolved for a longer time than ecology, and partially independently from ecology (Jackson and Piper, 1989); (3) the fact that applied ecology aims at manipulating extremely complex systems. Indeed, ecological systems host a huge variety of molecules, species and genotypes within species that are themselves linked by a wealth of biotic, abiotic and biotic–abiotic interactions. Moreover, these organisms are the result of a long history of Darwinian evolution and are still evolving at a speed that has often been underestimated (Thompson, 1998). Besides Darwinian evolution, ecological dynamics cause all ecological systems to have a history that leads to long term and complex dynamics: e.g. successions (Odum, 1969), long term impact of human activities (Dupouey et al., 2002), bistability (Mumby et al., 2007). These elements contribute to the previously highlighted difficulty (Lawton, 1999) for ecology to make robust and precise predictions or to derive general laws.

Nevertheless, applied ecology or EE are surely the acid test of ecology (Bradshaw, 1987; Mitsch and Jørgensen, 2003) and overcoming these difficulties is necessary to further develop EE and to improve and secure the position of ecology as a science. As relevant as this idea might sound it seems to us that it has never been fully exploited. For example, we have seldom read any EE article concluding that its results disproved a well-known ecological theory. Conversely, it seems that there is so far no general methodology to convert the results and theories of fundamental ecology into robust EE practices. Some efforts should probably be made in that direction.

In the same vein, experimental, practical and financial constraints often oblige to implement micro- or mesocosm experiences. While these approaches are necessary they are also often criticized because experimental treatments might not have the same effects when applied at larger temporal and spatial scales (Carpenter, 1996; Schindler, 1998; Kampichler et al., 2001). Since EE can often be applied in more realistic conditions and at wider scales than traditional experiments, EE could thus provide scientists with the occasion to test their hypotheses at larger scales, in more realistic and representative conditions.

Another incentive for fundamental ecologists to go towards applications would be that their development really requires interdisciplinary approaches. Indeed, scientific ecology is already very diverse regarding its approaches, scales and objects of study. This even sometimes put ecology at a risk of balkanisation (Barot et al., 2007; Menge et al., 2009). In fundamental ecology a scientist can well confine himself within the framework or paradigm of his disciplinary sub-field. This will not impede him to publish in good journals and to be quoted. This is even sometimes favoured by the publication system, institutions and the necessity for ecologists to master an ever widening ecological knowledge, and more and more sophisticated technical tools. On the contrary, if we are to tackle practical issues and develop successfully robust applications, we have to find the suitable concepts and knowledge wherever they are, and cannot limit ourselves to a given sub-field. As developed below, EE is bound to manipulate many aspects of ecological systems using levers at potentially all possible levels of ecological organization. Indeed, it is not possible to determine *a priori* the best lever and the corresponding level of organization to solve a given problem, i.e. to push an ecological system towards a desired state.

3.3. Widening the approaches in ecological engineering

In our bibliographic survey we have classified studies published in the journal *Ecological Engineering* according to broad types of EE and, in a bivariate way, according to the ecological levels of organization directly manipulated and ultimately targeted by the manipulation: the manipulations of a component of an ecological system at a given level of organization should cascade to the component that we initially wanted to change (at the same level of organization or not). Of course, this classification is necessarily simplistic because scientific studies could be described along many discrete and continuous variables, and because studies have often several goals at the same time. However, the general trends we have emphasized are probably meaningful trends that have not emerged by chance. Apart from the fact that *Ecological Engineering* is particularly linked, probably for historical reasons, to the fields of water treatment, water restoration, wetland creation and restoration, it is noteworthy that many potentially possible combinations of manipulated and targeted levels of ecological organization are not represented. Some of the potential combinations might not be relevant or feasible, however, we advocate for more diverse approaches.

Indeed, as suggested by Gosselin (2008), EE can operate at any level of organization: molecules, genes, individuals, populations, communities, ecosystems, landscapes, and the earth. Moreover, ecological functioning is by definition based on many different kinds of interaction that link all system components. Consequently, any modification of a component of an ecological system – change in a chemical or physical property, addition or elimination of a species – can influence any other component of the system such as other chemical or physical properties, or another species. The difficulty is thus to find the appropriate lever to reach any given goal knowing that its action will not be necessarily direct. For example, we could modify a chemical characteristic of the environment to favour a particular type of organism, an ecosystem engineer, which is in turn expected to modify some physical characteristic of the ecosystem in a suitable way. This is typical of the agricultural Zaï system where the local enrichment in organic matter favours the activity of termites. This in turn improves soil structure and increases the penetration of rainwater and the growth of crops (Sawadogo et al., 2008).

In our opinion, there is also a deficit of studies targeting integrated changes at the whole ecosystem scale (about 8% of articles). Indeed, many studies test treatments that modify an ecosystem property at a large scale (e.g. water chemical quality). There are fewer studies targeting modifications of many compartments of an ecosystem (chemical, physical and several types of organisms) or testing for the modification of the whole ecosystem functioning. However, several arguments demonstrate the importance of such studies: (1) some aspects of ecological functioning might work in a synergetic way (e.g. improving water quality of a lake is likely to favour more diverse communities of phytoplankton, zooplankton and fish and vice versa); (2) some other aspects might not react to EE; (3) some other aspects are even likely to work in an antagonistic way, which could lead to trade-offs between the provided ecosystem services (Chisholm, 2010; Harrison et al., 2010); (4) some aspects may not react at the same time scale. Distinguishing these different cases is useful either to improve EE practices or to determine precisely their pros and cons. Of course, we understand that all the processes potentially impacted by an EE project cannot be monitored in all studies; however, such studies targeting many aspects of ecological functioning and monitoring many ecosystem services would be useful to improve EE practices and increase their success in terms of provision of ecosystem services.

EE can also potentially be based on any kind of tool, even high-tech techniques. For example, genetically modified organisms or biotechnological breeding methods are not necessarily prohibited in an EE context (Lammerts van Bueren et al., 2010). However, the consecutive risks and benefits have to be carefully assessed. This requires replacing these technologies in a systemic and ecological framework. For example, when plant cultivars resistant to a pathogen are to be developed, the evolution capacity of the pathogen has to be taken into account (Burdon and Thrall, 2008). Basically, when a new organism, either imported or created through breeding, is introduced its influence on the whole web of ecological interactions should be assessed both at the ecological and evolutionary time scales.

In this context, an important challenge for EE is probably to design proper methods to select mixtures of species or genotypes. It is more and more recognized that agriculture should increase the genetic and specific diversities of plants grown together in the same field (e.g. Zhu et al., 2000). However, it is probably still not clear how to optimize the mixtures of organisms choosing them from a pool of available species/genotypes. It could even be possible to design methods to "breed the mixtures" themselves through "practical group selection" (Denison et al., 2003). Such approaches could help foster artificially the kind of synergetic mechanisms that probably evolves in natural ecosystems through coevolution and species sorting, and that are probably often disrupted in anthropized systems. This could also be applied to multispecies livestock systems, or to the selection of crops together with species supporting them (symbiotically or not) (e.g. Sawers et al., 2008). More generally, evolutionary thinking could probably be employed fruitfully in EE (Denison et al., 2003; Thrall et al., 2010).

At a larger scale, human societies have engineered the whole biosphere in a way that is often not sustainable (Vitousek et al., 1997): they have deeply modified the use of continental surfaces, global fluxes of nutrients and carbon, etc. This leads to huge changes in biodiversity and to the current climate change that are generally considered to have negative impacts on the services provided by ecological systems and on human societies (Millennium Ecosystem Assessment, 2005). This means that we somehow have to reverse the current trend: we have to apply EE to the whole biosphere in order to return to more sustainability. This involves local actions that are judged to be necessarily positive but also a capacity of global prediction and planning. This will help predicting the large scale consequences of these actions and check that they are efficient and do not lead to new risks. Some engineering techniques are already proposed to mitigate global warming (e.g. Gussow et al., 2010) and have an important impact in the media. This raises many heavy ethical and intellectual problems but ecological engineers have to tackle this kind of issue because, otherwise, people who are less prone to ecological and system thinking will "do the job", for better or for worse. In the same vein, terraforming is typical of science fiction (Robinson, 1993) but researches are already made in this direction (Graham, 2004). Again, ecological knowledge and the capacity to engineer ecological systems in a sustainable way are required to develop this field.

4. Geographic development of EE

Our bibliographic survey reveals that scientists of many countries do work in the field of EE. However, it is strongly dominated by the USA and China. This is probably due to historical factors: EE initially sprouted in the USA with the Odum brothers (Mitsch, 2003), and many EE-relevant practices – such as integrated farming systems or sustainable aquaculture – have been developed in China for centuries (Chan, 1993). Moreover, China also faces huge environmental problems due to fast industrial development (Liu and Diamond, 2005), which in turn calls for the development of restoration methods and more sustainable practices. Besides, it is noteworthy that apart from Spain, Europe and particularly France are not well represented in the journal *Ecological Engineering*. The causes of this pattern are not fully clear to us. The low implication of France in the field of EE could, however, be linked to an overall low integration of research and education systems that target fundamental (developed in universities) and applied aspects of environmental sciences (developed in engineering schools). This suggests in any event that the EECA congress was very timely and that further initiatives to develop EE in Europe are highly needed.

Similarly, African and South and Central American (apart from Costa Rica) countries are poorly represented in the journal, probably due to the their overall scarce scientific production, which reflects their low level of development. Moreover, newly industrialized countries (NICs) such as South Africa or Brazil do not publish much in the field of EE whereas they are among the world fastest growing economies. Least developed countries would benefit in two ways from EE (Wang et al., 1998): (1) all countries need more sustainable practices; (2) in many cases these countries do not benefit from the technical developments that lead to productive (and often unsustainable) systems in developed countries (e.g. agriculture and fertilizers). Therefore, EE practices could be used to increase productivity without having to turn to techniques, energy sources, chemicals that the least developed countries cannot afford anyway. This suggests that special actions and programs should be implemented for a quicker development of EE in Africa and South America. These actions should also foster fundamental knowledge on tropical ecological systems.

5. Steps forward

The future of EE is wide open but, as suggested by our bibliographic survey, a lot of work is still to be made to allow EE reaching all its objectives. As outlined above, this should involve a better integration of fundamental and applied ecologies. However, what can we do concretely on a daily basis? We probably have to foster interactions between fundamental and applied ecologies on all the fronts of scientific life: developing institutions (teams, laboratories, institutes, and universities) that mix together people from both applied and fundamental environmental fields, fostering evaluation practices (for institutions and scientists) that take into account both academics and non-academic outputs, organizing conferences that connect people form applied and more fundamental ecological fields, editing journals where both applied and fundamental results are published, launching calls for proposals that explicitly target EE and the continuum between applications and theories. Besides, publishing studies relevant to EE in *Ecological Engineering* is logical, but the development of EE also requires publishing some of these studies in other journals of applied ecology, more generalist ecology journals and journals specialized in traditional fields such as agronomy, forestry or aquaculture. Education is also fundamental, and the full development of EE probably requires settling specific lectures, training, and diploma. This would be the only way to take into account all specificities of EE and help linking ecological and engineering sciences. Of course, all these types of initiatives already exist. We just have to go on developing them.

Finally, as any scientific paradigm, EE must avoid two main traps: trivialization and sectarianism. Trivialization would lead to the use of the term EE as a gimmick and EE would subsequently lose its useful content and its real capacity to increase the sustainability of the relation between human societies and the biosphere. Sectarianism would on the contrary impede the field of EE to develop and to build the necessary contacts with all the required academic fields and the relevant parts of the society. Our discussion gives some hints in order to meet the relational challenge we have emphasized within the academic world and more specifically within ecological sciences. This should avoid the danger of sectarianism among ecologists but, as explained by C. Jones (2011), EE has also to meet a more general relational challenge and to make connection with economists, sociologists, engineers, practitioners, policy makers. . .. Huge efforts are thus needed. Building these connections and avoiding at the same time the risk of trivialization will require even more efforts and skills. This probably requires, among other things, consolidating the theoretical bases of EE and widening EE approaches.

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References

Altieri, M.A., 1989. Agroecology—a new research and development paradigm for world agriculture. Agric. Ecosyst. Environ. 27, 37–46.
Armstrong, D.P., Seddon, P.J., 2008. Directions in reintroduction biology. Trends Ecol. Evol. 23, 20–25.
Barot, S., Blouin, M., Fontaine, S., Jouquet, P., Lata, J.-C., Mathieu, J., 2007. A tale of four stories: soil ecology, theory, evolution and the publication system. PLoS ONE 2, 1–8.
Barot, S., Heino, M., O'Brien, L., Dieckmann, U., 2004. Reaction norms for age and size at maturation: study of the long term trend (1970–1998) for Georges Bank and Gulf of Maine cod stocks. Ecol. Appl. 14, 1257–1271.
Bobbink, R., Hicks, K., Galloway, J., Spranger, T., Alkemade, R., Ashmore, M., Bustamante, M., Cinderby, S., Davidson, E., Dentener, F., Emmett, B., Erisman, J.W., Fenn, M., Gilliam, F., Nordin, A., Pardo, L., De Vries, W., 2010. Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis. Ecol. Appl. 20, 30–59.
Bradshaw, A.D., 1987. Restoration: the acid test for ecology. In: Jordan III, W.R., Gilpin, M.E., Aber, J.D. (Eds.), Restoration Ecology: A Synthetic Approach to Ecological Research. Cambridge University Press, Cambridge, pp. 23–29.
Burdon, J.J., Thrall, P.H., 2008. Pathogen evolution across the agro-ecological interface: implications for disease management. Evol. Appl. 1, 57–65.
Carpenter, S.R., 1996. Microcosm experiments have limited relevance for community and ecosystem ecology. Ecology 77, 677–680.
Carpenter, S.R., Kitchell, J.F., 1993. The Trophic Cascade in Lakes. Cambridge University Press, Cambridge, UK.
Castillo, A., 2000. Communication and utilization of science in developing countries—The case of Mexican ecology. Sci. Commun. 22, 46–72.
Chan, G.L., 1993. Aquaculture, ecological engineering—lessons from China. Ambio 22, 491–494.
Chisholm, R.A., 2010. Trade-offs between ecosystem services: water and carbon in a biodiversity hotspot. Ecol. Econ. 69, 1973–1987.
Costanza, R., dArge, R., deGroot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., Oneill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., vandenBelt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.
Denison, R.F., Kiers, E.T., West, S.A., 2003. Darwinian agriculture: when can humans find solution beyond the research of natural selection? Q. Rev. Biol. 78, 145–168.
Dupouey, J.L., Dambrine, E., Lafitte, J.D., Moares, C., 2002. Irreversible impact of past land use on forest soils and biodiversity. Ecology 83, 2978–2984.
Ferrière, R., Sarrazin, F., Legendre, S., Baron, J.-P., 1996. Matrix population models applied to viability analysis and conservation: theory and practice using ULM software. Acta Oecologica 17, 629–656.
Gliessman, S.R., 2006. Agroecology: the ecology of sustainable food systems. CRC Press, Boca Raton, FL.
Gosselin, F., 2008. Redefining ecological engineering to promote its integration with sustainable development and tighten its links with the whole of ecology. Ecol. Eng. 32, 199–205.
Graham, J.M., 2004. The biological terraforming of Mars: planetary ecosynthesis as ecological succession on a global scale. Astrobiology 4, 168–195.
Gussow, K., Proelss, A., Oschlies, A., Rehdanz, K., Rickels, W., 2010. Ocean iron fertilization: why further research is needed. Marine Policy 34, 911–918.
Harrison, P.A., Vandewalle, M., Sykes, M.T., Berry, P.M., Bugter, R., de Bello, F., Feld, C.K., Grandin, U., Harrington, R., Haslett, J.R., Jongman, R.H.G., Luck, G.W., da Silva, P.M., Moora, M., Settele, J., Sousa, J.P., Zobel, M., 2010. Identifying and prioritising services in European terrestrial and freshwater ecosystems. Biodivers. Conserv. 19, 2791–2821.
Jackson, W., Piper, J., 1989. The necessary marriage between ecology and agriculture. Ecology 70, 1591–1593.
Janse, G., 2007. Communication between forest scientists and forest policy-makers in Europe—+A survey on both sides of the science/policy interface. Forest Pol. Econ. 10, 183–194.
Jeppesen, E., 2011. Restoration of lakes in different climate zones: from theory to practice. Ecol. Eng..
Jones, C., 2011. Grand challenges for the future of ecological engineering. Ecol. Eng..
Kampichler, C., Bruckner, A., Kandeler, E., 2001. Use of enclosed model ecosystems in soil ecology: a bias towards laboratory research. Soil Biol. Biochem. 33, 269–275.
Lacroix, G., Lescher-Moutoué, F., Pourriot, R., 1996. Trophic interactions, nutrient supply, and structure of freshwater pelagic food webs. In: Hochberg, M., Clobert, J., Barbault, R. (Eds.), Aspects in the Genesis and Maintenance of Biological Diversity. Oxford University Press, pp. 162–179.
Lammerts van Bueren, E.T., Backes, G., de Vriend, H., Østergård, H., 2010. The role of molecular markers and marker assisted selection in breeding for organic agriculture. Euphytica 175, 51–64.
Lawton, J.H., 1999. Are there general laws in ecology? Oikos 84, 177–192.
Liu, J.G., Diamond, J., 2005. China's environment in a globalizing world. Nature 435, 1179–1186.
Ma, S.J., 1985. Ecological engineering—application of ecosystem principles. Environ. Conserv. 12, 331–335.
Mayr, E., 1996. The autonomy of biology: the position of biology among sciences. Q. Rev. Biol. 71, 97–106.
Menge, B.A., Chan, F., Dudas, S., Eerkes-Medrano, D., Grorud-Colvert, K., Heiman, K., Hessing-Lewis, M., Iles, A., Milston-Clements, R., Noble, M., Page-Albins, K., Richmond, E., Rilov, G., Rose, J., Tyburczy, J., Vinueza, L., Zarnetske, P., 2009. Terrestrial ecologists ignore aquatic literature: asymmetry in citation breadth in ecological publications and implications for generality and progress in ecology. J. Exp. Marine Biol. Ecol. 377, 93–100.
Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.
Mitsch, W.J., 2003. Ecology, ecological engineering, and the Odum brothers. Ecol. Eng. 20, 331–338.
Mitsch, W.J., Jørgensen, S.E., 2003. Ecological engineering: a field whose time has come. Ecol. Eng. 20, 363–377.
Mumby, P.J., Hastings, A., Edwards, H.J., 2007. Thresholds and the resilience of Caribbean coral reefs. Nature 450, 98–101.
Odum, E.P., 1969. The strategy of ecosystem development. Science 164, 262–270.
Odum, H.T., 1984. Ecological engineering of coastal management—opening address of symposium. Water Sci. Technol. 16, R15–R20.
Odum, H.T., Odum, B., 2003. Concepts and methods of ecological engineering. Ecol. Eng. 20, 339–361.
Powell, A., O'Malley, M.A., Muller-Wille, S., Calvert, J., Dupré, J., 2007. Disciplinary baptisms: a comparison of the naming stories of genetics, molecular biology, genomics, and systems biology. Hist. Philos. Life Sci. 29, 5–32.
Robinson, K.S., 1993. Red Mars. Bentam Spectra Book, New York.
Sawadogo, H., Bock, L., Lacroix, D., Zombre, N.P., 2008. Restoring soil potentialities using zai and compost in Yatenga (Burkina Faso). Biotech. Agronom. Soc. Environ. 12, 279–290.
Sawers, R.J.H., Gutjahr, C., Paszkowski, U., 2008. Cereal mycorrhiza: an ancient symbiosis in modern agriculture. Trends Plant Sci. 13, 93–97.
Schindler, D.W., 1998. Replication versus realism: the need for ecosystem-scale experiments. Ecosystems 1, 323–334.
Shapiro, J., Wright, D.I., 1984. Lake restoration by biomanipulation. Round Lake, Minnesota—the first 2 years. Freshwater Biol. 14, 371–383.
Thompson, J.N., 1998. Rapid evolution as an ecological process. Trends Ecol. Evol. 13, 329–332.
Thrall, P.H., Bever, J.D., Burdon, J.J., 2010. Evolutionary change in agriculture: the past, present and future. Evol. Appl. 3, 405–408.
Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677.
Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human domination of earth's ecosystems. Science 277, 494–499.
Wang, R., Yan, J., Mitsch, W.J., 1998. Ecological engineering: a promising approach towards sustainable development in developing countries. Ecol. Eng. 11, 1–15.
Zhu, Y., Chen, H., Fan, J., Wang, Y., Li, Y., Chen, J., Fan, J., Yang, S., Hu, L., Leung, H., Mew, T.W., Teng, P.S., Wang, Z., Mundt, C.C., 2000. Genetic diversity and disease control in rice. Nature 406, 718–722.