More than a Scientific Movement: Socio-Political Influences on Green Chemistry Research in the United States and France

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Abstract

The green chemistry (GC) concept originated in the United States during the 1990s to describe an approach to chemistry that aims to lower impacts on health and the environment. Based on 70 interviews with scientists from France and the United States, I investigated green chemists' practices and motivations, and the socio-political influences on their attitudes to GC. The results show that GC has a hybrid character, bringing together scientists with different motivations (funding, career, communication, ethical, political). The boundaries of the definition of GC are constantly shifting under the influence of research funding and environmental, industrial and agricultural policies. GC reflects the perfect adaptation of a terminology to the external conditions of chemistry's socio-political contexts. While this is a strength that gives GC the potential for changing overall practices in chemistry, this might also be its major weakness as it might completely lose its original environmental relevance, depending on the evolution of external drivers.

Keywords: chemical policy, green chemistry, scientific movement

Introduction: Theoretical foundations and research questions

Green chemistry (GC) is a concept that was coined in the United States during the 1990s, in an environmental policy context that displayed priorities shifting from waste treatment downstream towards pollution prevention at source. Since then, the term green chemistry has had increasing academic success, as confirmed by the number of publications using it (Linthorst, 2010). However, the nature of this keen interest from scientists remains unclear. Few explanations have been attempted in the social sciences, among which the most coherent was published by Woodhouse & Breyman (2005), who described it as a social movement. Other research[1] has acknowledged a wide variety of meanings given to the term GC, differing in their relative scientific versus political content (Schwarzman and Wilson, 2009; Wilson and Schwarzman, 2009a, 2009b; O'Brien et al. 2009; Iles, 2011) and in the research activities and knowledge areas included (Sjöstrom, 2006; Maxim, 2011a). Accounting for this diversity, Sjöstrom (2006) proposed two models for understanding GC: a classification model of different green chemistry activities (research activities, management activities and policy activities), and a second model concerning green chemistry policy and knowledge areas (green chemistry principles, industrial biotechnology and the "green sector,'' i.e., agriculture and forestry). The debate about what exactly constitutes research in GC spans a continuum from GC as a new scientific discipline within the field of chemistry (O'Brien et al., 2009), a science (O'Brien et al., 2009), a meta-discipline covering most of chemistry and chemical engineering (Sjöstrom, 2006), or a philosophical approach that underpins chemistry (Wilson and Schwarzman, 2009b; Llored, 2012; Bensaude-Vincent, 2013), to broader approaches including chemical risk policies (Iles, 2011) and all activities aiming at greening chemistry (Sjöstrom, 2006). The term itself seems to respond to a variety of research areas and objectives, which might explain its academic success, measured by the continuously increasing number of publications using it (Linthorst, 2010; Epicoco et al., 2012). Because of this heterogeneity, and not considering it a "rival to chemistry," Roberts (2005) expressed doubts about the "scientific" nature of the movement and underlined its discursive content.

However, these previous insights on GC have lacked empirical work aimed at understanding its spread and definition for "lay" green chemists, beyond the leaders' discourses. Analyses have mixed academia and industry, and researchers' motivations for using the term remain unknown.

While GC has previously been analyzed as a social movement (Woodhouse and Breyman, 2005), and as a scientific movement (Roberts, 2005), those analyses were based on historical institutional developments around the term and the actions of the field's "champions" (for example, founders Paul Anastas and John Warner), but did not look empirically at the research community in chemistry at large. Motivated by findings about its low level of adoption in the chemical industry (Matus, 2009; Wilson and Schwarzman, 2009a; Iles, 2011), existing empirical results in the social sciences are based on (a few) interviews with GC leaders from industry and academia as well as on multi-stakeholder workshops (Matus et al., 2007; Matus et al., 2010a; Matus et al., 2012), and propose a normative approach aimed at promoting GC. This literature focuses on identifying barriers (Matus et al., 2007; Matus et al., 2012), on policy measures (Matus, 2009, 2010; Matus et al., 2010a; Matus et al., 2010b; Scruggs et al., 2014) and on marketing tools (Iles, 2008) for the adoption of GC in firms.

Some empirical research has been done in France, with a recent analysis studying the national research funding program labeled "sustainable chemistry" and concluding that such targeted funding led to multiple research projects with various shades of green on a wide range of topics (Schultz, 2017). Others have looked at "institutional entrepreneurship," i.e., stakeholder activity aimed at creating or transforming institutions, in the context of the development of bio-based chemistry and the related industry in France (Nieddu et al., 2012).

Research question

However, the question: what is truly new in GC, as compared to usual research areas and practices in chemistry? has not yet been empirically dealt with, and the existing literature simply assumes that GC is "new" and "different" from business-as-usual chemistry.

In order to understand the novelty of GC (if any), I start here from its characterization as a social movement (Woodhouse and Breyman, 2005), which I deepen significantly, while using, however, the framework built by Frickel & Gross (2005) (see the Methods section). These authors proposed a general theory of scientific / intellectual movements (SIMs) to explain the mechanisms of change in the world of knowledge and ideas. Their theory insists on the socio-political conditions for SIM emergence and institutionalization, which I document on the basis of a historical and interview-based analysis of the socio-political forces driving GC.

I thus take an approach to "novelty" that goes beyond original scientific concepts and theories alone. Describing GC as a SIM allows me to analyze its novelty both in terms of scientific, conceptual developments and of the related socio-economic and political dynamics in which science and innovation are inevitably embedded. In other words, I test the hypothesis that GC is a new form of existence of the science of chemistry in its socio-political and economic context. Analyzing novelty in GC thus comes down to focusing on both original theoretical developments and new relationships between research in chemistry and the socio-economic and political worlds.

The theoretical underpinnings of the Frickel and Gross's (2005) framework make their work particularly applicable to the green chemistry case study. First, they follow the "strong program" in the sociology of scientific knowledge, defending the idea that the truth of ideas must always be established and certified through social processes. Second, they acknowledge that scientific and intellectual fields are historically emergent phenomena, varying in time with respect to their internal social structure and academic practices. Third, they consider that SIMs are influenced by direct or indirect drivers emanating from the broader cultural and political environment. And fourth, they presuppose the measurability of phenomena associated to the emergence of SIMs. All these features of the SIM theory are extremely relevant for analysing green chemistry, for two reasons: 1) it is a scientific phenomenon having emerged as a result of socio-political forces (see the Results section), and 2) it cannot be understood - as will be shown below - without reference to the political rearrangements that it brings to the relationships inside the academic community, and between the science of chemistry and the ouside world (see the Discussion section and the definition of "political" given by Frickel and Gross, 2005: 207).

I employ empirical evidence from the scientific community in two countries – the United States and France – in order to understand how GC has changed the intellectual landscape in chemical research, and what have been the socio-political conditions of its development, including potential national specificities. I also take inspiration from the new political sociology of science (Frickel and Moore, 2005) as well as from previous work done by Woodhouse (2005), who compared GC with nanotechnology in terms of chemists' ability and responsibility in shaping their science. In particular, their analysis of the relationships between green chemistry, R&D policies and society inspired me in refining the methodological approach and in drafting the questionnaire.

A second objective of my work is to provide comparative insights, as few studies exist to help in understanding whether differences exist between countries concerning GC, and whether there is some national specificity. Matus (2009) provided a comparison between barriers to GC in the U.S., China and to some extent in India. The political background presumably influences the definition given to GC, in particular in a context of debates around policies on chemical risks (Wilson and Schwarzman, 2009a; O'Brien et al., 2009; Iles, 2011).

Methods

To respond to my research question, I build on two methodological instruments: the general theory of scientific / intellectual movements (SIM) developed by Frickel and Gross (2005), and interviews with 70 American and French researchers declaring work in GC.

Theoretical framework

The general theory of scientific / intellectual movements (SIM) developed by Frickel and Gross (2005) aimed at synthetizing work in the sociology of science, ideas and social movements, in order to explain how the world of knowledge and ideas changes. More precisely, after a definition of SIMs, and based on the assumption that they are similar to social movements, these authors sought to identify the social conditions under which SIMs "are most likely to emerge, gain adherents, win intellectual prestige, and ultimately acquire some level of institutional stability" (Frickel and Gross, 2005: 205).

SIMs are defined as "collective efforts to pursue research programs or projects for thought in the face of resistance from others in the scientific or intellectual community" (Frickel and Gross, 2005: 206). This definition is founded on several assumptions illustrated by numerous empirical cases from the natural and social sciences:

1. Having as a central goal the production and diffusion of ideas, SIMs have at their core a coherent program for scientific or intellectual change.

2. At the time of their emergence, SIMs promote intellectual practices that are contentious relative to dominant ways of approaching some problem or issue, within a given domain.
3. Because they significantly challenge past practices, SIM are inherently political, in the sense that they promote a redistribution of powers and social positions within or across intellectual fields.
4. SIMs are constituted through organized collective action, and require a certain spatial, temporal and social coordination. High-status intellectual networks are helping new ideas become influential, essentially by supporting publications, jobs for SIM participants, conference organization, grant support, and special issues of journals.
5. SIMs have a limited time span, between the announcement of a new intellectual program and either its institutionalization (subfield, discipline...) or its disappearance.
6. SIMs can vary in intellectual aim, ranging from topics previously undiscussed to new theoretical approaches to well-established terrains.

Based on these assumptions, four propositions lie at the core of the general theory proposed by Frickel and Gross (2005). These aim to provide theoretical, although pragmatic, guidance for future studies of SIMs. Each of these propositions is rooted in the sociological literature and illustrated by case studies. Given their centrality to the general theory and in order to avoid altering their meaning, I use them here in the original form proposed by their authors[2], while leaving discussion, in direct relation to the GC case study, for the next section (Results).

1. *A SIM is more likely to emerge when high-status intellectual actors harbor complaints against what they understand to be central intellectual tendencies of the day*. These actors hold higher scientific and social capital than their younger colleagues, which they can invest in a contentious intellectual / scientific proposal with less risk to their reputations.
2. *SIMs are more likely to be succesful when structural conditions provide access to key resources*. Among these resources, financial support and opportunities for publication are paramount. The intellectual opportunity structure can best be described by reference to three components: employment for SIM participants (essentially in academia), intellectual prestige (offered by the SIM to its participants), and organizational resources (university departments, and institutionalized channels of information flow such as scholarly organizations or informal personal networks).
3. *The greater a SIM's access to various micromobilization contexts, the more likely it is to be successful* (for example, conferences and symposia, research retreats, academic departments with graduate programs allowing the recruitment of students who may potentially become new members of the SIM).
4. *The success of a SIM is contingent upon the work done by movement participants to frame movement ideas in ways that resonate with the concerns of those who inhabit an intellectual field or fields*. SIM participants thus share an intellectual identity, which contributes to their motivation and gives them the feeling of belonging to a certain "type" of scientist or intellectual.

In pursuit of my research objective of highlighting the novelty brought by GC, I address each of the four propositions of Frickel & Gross (2005) in order to analyze the dynamics of GC emergence as a SIM. Depending on the proposition under analysis, my information sources are both various documents like books, articles or websites allowing historical insights into the processes of emergence and development of GC, (propositions 1 and 2), and interviews providing information that is not available in the literature (propositions 1 to 4). My respondents were 34 American and 36 French researchers declaring work in GC, interviewed between June 2013 and June 2014.

I focus exclusively on academia and leave aside developments of GC in industry, which would need specific methods and questioning (but I include interactions between researchers and industry that are relevant to my objective). My methodological choices allow an exclusively qualitative analysis, and I have no ambition for quantification at the level of the whole green chemistry community.

Interviews

Interviewees were identified using several methods:

- literature search using the keywords "GC" and Google search using "GC" plus "research", "university" and/or "United States"
- search in the projects accepted for funding by the French National Research Agency (ANR), in the program *Chemistry and Processes for Sustainable Development*
- the snowball method (asking respondents to suggest other scientists working in the field of GC).

E-mails were sent to the researchers identified, and all those who agreed to contribute were interviewed. The questionnaire (Appendix 1) was structured in terms of nine themes: 1. Definition and identification of the field of green / sustainable / ecological chemistry; 2. Driving forces and constraints for GC; 3. Research practices; 4. Partnerships and research funding; 5. Institutional role of researchers; 6. Economy of green chemistry; 7. Health and environmental issues; 8. Green chemistry and society; 9. Scenarios of green chemistry. These were drafted by the present author, based on the existing literature on GC and her own previous research in the area, in order to grasp the changes in research practices brought about by GC, if any (theme 3) and to understand the socio-economic and political determinants of research activity in GC.

My American respondents worked either in colleges / small universities (nine interviewees) or in large universities (21), most of them public. A further two worked in public structures dedicated to GC policies, one worked in a company but had a significant background in academia, and one was in retirement but had previously worked in both academia and public structures dedicated to GC policy. All but one of my French respondents worked in academia, in either public universities or public research centers. The remaining respondent worked in industry, but had rich experience in academia. All but one of my respondents had at least several years of experience after their doctorate and a large majority held positions as researchers or assistant/full professors. The remaining one was a PhD student. Many of my American respondents worked in the chemistry department of their universities and all but one of my French respondents worked in chemistry labs.

The interviews were recorded and transcribed and I carried out a thematic qualitative analysis (Silverman, 2011). The analysis followed the themes of the questionnaire, which were then related to Frickel and Gross's (2005) propositions at the stage of writing the paper.

Results

Historical analysis

Before applying the framework developed by Frickel and Gross (2005) in order to describe the conditions for emergence as a SIM, the first question to be answered was whether GC has the features required for being characterized as a SIM at all. Historical analysis allows me answer this question, and to analyze the applicability of the first two propositions of Frickel and Gross (2005). However, the literature was insufficient for discussing the third and the fourth propositions, for this reason historical analysis has been used only for the first two propositions. For the remaining third and fourth propositions, interviews allowed to me acquire the information that was not available in the literature.

Can GC be characterized as a SIM? According to Frickel and Gross (2005), SIMs are "collective efforts to pursue research programs or projects for thought in the face of resistance from others in the scientific or intellectual community."

In light of the theoretical framework created by the GC founders and the existing STS / political sciences literature studying its emergence (Woodhouse and Breyman, 2005; Matus et al., 2007; Matus et al., 2010a; Linthorst, 2010; Iles, 2011; Matus et al., 2012), GC can be qualified as a collective movement (Frickel and Gross, 2005) within the chemistry community. Indeed, in the wake of the first EPA initiatives (see also the Discussion), the collective nature of GC has been built around multiple forms of institutionalization, and through mutual feedback from both within and outside academia. Thus, the non-profit Green Chemistry Institute was created in 1997 as a partnership between the U.S. Environmental Protection Agency (EPA), the University of North Carolina and several companies. The Presidential GC Challenge Awards were created in 1995 to honor work in this field by industry, by the academic community, or by government. The emerging field took a new institutional step in 1999, when the journal *Green Chemistry* was created in the U.K. with the support of the Royal Society of Chemistry. Its impact factor (November 2017) is 9.125, which demonstrates its success in the chemistry community (the impact factor reflects the number of citations of articles published in a journal). Since 2006, the International Union of Pure and Applied Chemistry (IUPAC) has been organizing every two years an international conference on GC.

In France, the concept of GC became entrenched later, in 2007/08, but was succesful from the very beginning due to its major driving forces, namely the ANR funding program Chemistry and Processes for Sustainable Development and the CNRS program Chemistry for Sustainable Development.

Below, I analyze the emergence of the GC SIM in terms of the four propositions of Frickel and Gross, which allows me to scrutinize the novelty brought by GC as an intellectual stance and a scientific movement, and thus to respond to my research question.

Proposition 1: *A SIM is more likely to emerge when high-status intellectual actors harbor complaints against what they understand to be central intellectual tendencies of the day.*

For the U.S., GC fits well with this proposition, as the original aim of GC was revolutionary: to change the role of the chemist in the control of chemical risks and in environmental policy more broadly. Unlike Kuhnian processes of scientific revolution (Kuhn, 1962), the roots of change were external to the scientific world and came from policy. In a context of repeated controversies concerning chemical toxicity (Mazur, 1998) and facing the failure of what were labeled as "command and control policies" and a legitimacy crisis due to inefficiency in carrying out its legal mission to control chemical risks (Brickman et al., 1985), the EPA invested energy and resources[3] in a policy philosophy that displayed a shift of priorities away from waste treatment downstream, towards pollution prevention at source using more efficient technologies (Linthorst, 2010). The first such initiatives had emerged in states affected by controversies about chemical waste, such as the Toxic Use Reduction Act (TURA) in Massachusetts in 1989. The new approach spread at the federal level with the 1990 adoption by the U.S. Congress of the Pollution Prevention Act (PPA). Later, several states introduced GC policies, such as the Michigan GC Program in 2006, the California GC Initiative in 2006-2008 (Iles, 2011), and regulations relating to chemical risk in Washington, Maine, Minnesota, Oregon, and Vermont (Duvall et al., 2016).

Given the political purposes and the enrollment program intended by its proponents, criticizing the chemistry community was not a discursive priority, although it subtly underpinned the original manifestos. The concept started to be used by chemists whose institutional positions provided ex-ante legitimacy, such as Kenneth Hancock, former director of the Chemistry Division of the U.S. National Science Foundation (NSF). Declaring that "Whether you are talking about oil spills, or landfills, or ozone holes... or any [human-made] environmental problem that has ever occurred, it comes from chemistry" (Amato, 1993: 1538), Hancock then framed these problems as opportunities for chemists: "Any solution that you will devise will come from chemistry. (Amato, 1993: 1538)"

A year later, EPA employees Paul Anastas and Carol Farris (1994) briefly mentioned the term GC in the introduction to their book, referring to "benign by design" chemistry. But the main features of the paradigm shift were already present, starting with the first chapter by Anastas, which highlighted the new role of the chemist. While synthetic chemists do not traditionally consider themselves as actors capable of influencing environmental impacts, benign by design (later called "green") chemistry placed them at the heart of pollution prevention. Hence, this would significantly alter the work of chemists, who have been concerned historically with two criteria: the functions that substances may usefully accomplish, and the cost of industrial production of said substances. In benign by design chemistry, a third criterion had to be accounted for during the molecular design phase, namely impacts on human health and the environment.

The spread of the term has been further reinforced by the success of Anastas and Warner's book (1998: 11), defining GC through 12 principles[4] with a pragmatic connotation, which have become the internationally recognized GC brand. The book insisted on the second revolutionary novelty brought by GC, its focus on the intrinsic properties of substances for control of their health and environmental impacts, instead of on risks (i.e., the relationship between exposure and intrinsic toxicity). This new approach gave scientists the power to influence pollution, while previous regulations aimed at reducing risks had placed this power solely in the hands of industry and regulators.

Thirdly, what was also new was the privileged relationship envisaged between chemistry and toxicology. With the help of toxicology, chemists could get to know the molecular characteristics responsible for the dangerous properties of substances, and thus become able to avoid these in the structures of new molecules. It thus became important to educate chemists about toxicology, a discipline previously completely absent from their curricula.

In France, in contrast to the government leadership that initiated GC in the U.S., the use of the term in was promoted through academic channels. But for this country dissatisfaction also came not from within chemical sciences, but from outside, namely from the concern of scientists for the public image of their science. In France, the "negative image of chemistry" has been an increasing concern for many years and remains an open wound for many chemists (Maxim, 2011b). If some have adopted defensive attitudes, essentially contesting the public's ability to understand their research, ANR and CNRS funding programs have been using these concerns as opportunities, in line with their American counterparts who reacted to a political framework unable to relevantly deal with chemical risks. The crisis leading to GC was not within chemistry, but outside it: while chemists have always pleaded that they work for human well-being (given the role of chemistry in agriculture, pharmacy, industry…), environmental concerns were significantly weakening this discourse about the legitimacy of chemistry as a socially relevant science.

The movement was initiated in France by well-established chemists. This also fits with the proposition of Frickel and Gross concernig SIMs. In the early 2000s, the National Institute for Agricultural Research (INRA) was the first body in France to bet on the success of GC, by investing in related research. In order to take full advantage of its specialized human resources in agricultural sciences, historically encouraged after the first oil shock of 1973-1974, INRA redefined the term GC as synonymous with bio-based chemistry. Thus, from its origins GC in France did not share the U.S. focus on reducing toxicity, but was directly linked to the country's agricultural potential and to the political context of the moment in the European Union.

The first French reference book to use GC in its title was coordinated by an INRA-based scientist (Colonna, 2005), at that time head of the department for "Characterization and elaboration of products issuing from agriculture" and currently Professor at the prestigious Collège de France. The first paragraph stated: "The choice of this book titled GC reflects the problem: what are the best uses for renewable carbon?" (Colonna, 2005: IX). The authors made no reference to the American terminology, the twelve principles, or the founding works.

In parallel, the largest fundamental research institution in the country, the CNRS, began to use the term, following the lead of chemist Isabelle Rico-Lattes. In 2006 she created the research program "Chemistry for Sustainable Development" (Chimie pour le Développement Durable, CPDD), which explicitly built on the 12 principles and had the objective of networking scientists to boost the emergence of a new research field. At the time, Isabelle Rico-Lattes was already a well-established and recognized researcher (CNRS Silver Medal in 2006, a high distinction for researchers in France, then Chevalier de la Légion d'honneur in 2008), with political responsibilities as officer on environmental health for the Ministry of Environment (2004-2006).

With CNRS including a significant number of researchers on ecology (whereas toxicology was essentially based in other research institutes), the CPDD programme promoted interdisciplinary collaboration between chemistry and ecology (Maxim, 2011a; Rico-Lattes and Maxim, 2014). The network included about 900 researchers in different universities and research institutions in France, and four working groups on: renewable resources; new synthesis pathways including biotechnologies; improving synthesis processes, and assessing/reducing the impact of chemistry on the environment. Thus, they enlarged the semantic boundaries of the term GC beyond the only "renewable carbon" definition in 2005.

Also in parallel, a new regulatory framework was developing in Europe. The White Paper on a new chemicals strategy for the European Union (2001) contained the main elements of a regulation to be known as REACH (Registration, Evaluation, and Authorization of CHemicals), covering all chemicals produced or imported in volumes larger than 1 t/year, as well as replacing over 40 existing directives and regulations. Guided by the precautionary principle, REACH was adopted in 2006 and aimed at improving knowledge of the properties and uses of individual chemical substances, all by encouraging the substitution of the most dangerous chemicals on the market. In France, a working group including ANR and some research institutions issued a report on the relationships between REACH and research in chemistry (De Guillebon et al., 2009). This work contributed to the inclusion of REACH in ANR calls for projects in sustainable chemistry.

Proposition 2: *SIMs are more likely to be successful when structural conditions provide access to key resources.*

In the U.S., following Kenneth Hancock's commitment in 1992, the NSF funded a call for research projects on Environmentally Benign Chemical Synthesis and Processing ($ 950,000), and then a partnership between the NSF and the EPA, which led to a common call for such projects in 1993. The NSF further promoted GC in the early 1990s through its Industry / University Cooperative Research Centers Program (Anastas and Farris, 1994). Also, the Department of Energy reserved a part of its Environmentally Conscious Manufacturing Program for environmentally friendly chemistry.

Later, a proposal for a specific funding mechanism, the GC Research and Development Act, was proposed to and rejected by the U.S. Congress three times. Finally, an amendment was introduced to the America Competes Reauthorization Act (signed into law by President Obama in January 2011) to fund GC projects through the NSF.

The spread of the term GC in France was top-down, driven by research funding policy that explicitly linked chemistry and sustainable development. In the CPDD programme, funding was relatively modest and dedicated to networking through seminars, conferences, and interdisciplinary PhDs. From 2007 to 2013, the ANR programs labeled "Chemistry and Processes for Sustainable Development" (2007-2010) then "Sustainable Chemistry – Innovation – Industry" (2011-2013) represented the main national funding source for French chemists and reached about 9 million euros / year (Schultz, 2017).

Funding sources in France are more numerous than in the U.S. At a national level, the main funders of GC research are the ANR and the Environment and Energy Management Agency (ADEME). The Government also funds applied research through the Unique Interministerial Fund (FUI) mechanism. Specific national or regional funding mechanisms have been created in France, such as the Institutes of Excellence for Decarbonated Energy (IEED), the Institute for Plant Chemistry, Picardy, Innovation in Plant, Education, Research and Technology (PIVERT) and the French Institute for Agro-based Materials (IFMAS). Some regions, such as Poitou-Charentes, have also had their own research funding programs. Additionally, funding from the European Commission can be important.

Among the structures encouraging collaboration between public research and industry, competitiveness clusters bring together companies, research laboratories and training institutions, by geographical area and specific topic.

Another effective mechanism in France is the CIFRE PhD program, which funds doctoral students who must undertake part of their activities in a public research laboratory and another part in a company.

In the following, the results of interviews are again organized by proposition from Frickel and Gross's (2005) theoretical framework. Whereas historical analysis was relevant to discussing the first two propositions but insufficient to address the third and the fourth, interviews provided me with the additional information needed to complete that discussion and to analyse the last two propositions.

Results from interviews

Proposition 1: *A SIM is more likely to emerge when high-status intellectual actors harbor complaints against what they understand to be central intellectual tendencies of the day.*

According to Frickel and Gross (2005), a SIM most often stems from dissatisfaction with dominant intellectual practices in a field. The major trigger for scientific movements is doubt, which can be occasioned by multiple factors: anomalous research findings questioning the generally agreed "truth" of the discipline, but also changes in the structure of research personnel inducing changes in the values embedded in research, theoretical developments in other scientific domains or unexpected discoveries. The success of a SIM will be conditional upon its promotion by high-status intellectual actors who occupy prestigious positions and for whom professional risk is lower if they diverge from mainstream research pathways. Usually these actors are older individuals and their younger protégés.

In the historical analysis-based discussion of Proposition 1, I have looked at the role of GC founders (high-status intellectuals) in promoting criticism of the "central tendencies of the day" in conventional chemistry. Here, I further address the positions of "regular" chemists towards the business-as-usual paradigms of their discipline regarding health and environmental concerns. For a SIM to emerge, it needs collective work, and to be spread over a part of the scientific community. In order to understand those who make up this collective unit forming a SIM, and their distinctive features as compared to their colleagues, I asked my respondents whether GC opened new avenues of research and what novelties this term had brought to their work.

In the U.S., my respondents worked in areas some of which already existed before the term GC spread through the chemistry community: catalysis and biocatalysis, alternative solvents (ionic liquids, supercritical fluids, water), the chemistry of biofuels, or bio-based chemistry. For many, the term GC shed new light on work that was already being done, albeit with more attention now being paid to environmental issues: "But, in my view, the twelve principles are more like a cover for what, in the 1990s, were existing things." While the term was not yet in use, specialists in catalysis had already been pursuing GC "unknowingly." For a scientist engaged in research on supercritical fluids, "We were taking advantage of the environmental benefits of supercritical fluids before anybody had coined the term GC."

For those who say that GC has changed the way they work, the main change concerns the choice of research topics, for example, deciding to engage in polymer chemistry for the first time, or undertaking a new project on energy storage.

Yet the concept of GC has not created a new field of research and green chemists come from very different thematic areas in chemistry. The only new field of research mentioned was targeted molecular design for creating "benign by design" substances, brought up in the 1990s in the founding literature. But, despite its originality, my respondents mentioned this subject only rarely.

Like their American colleagues, French respondents reported a wide range of research topics. They all had a long history in chemistry that preceded the term GC in areas such as: catalysis and electrochemistry in soft chemistry conditions, chemical catalysis (homogeneous, heterogeneous, asymmetric, organometallic), biocatalysis, bio-based chemistry, supercritical fluids, synthesis of organic polymers including bio-based, with particular applications in the field of energy.

As in the U.S., GC was not a new field of research in France, except for developing less toxic solvents to meet REACH requirements and new algorithms to better implement the environmental factor (E-factor).

As for the definition of GC, American chemists routinely referred to the 12 principles, a cohesive element in an otherwise heterogenous community. The definitions of GC are diverse. For example, a substance might be termed "sustainable" because it could be extracted from nature (for example, ethyl lactate derived from corn). The sustainable character was even more important when the raw resource was usually treated as waste (for example, orange peel or rice husks). Ionic liquids and supercritical fluids were "green" because they can replace toxic organic solvents. In the case of bio-based materials, biodegradation in certain conditions was an interesting property that made chemistry "greener." Some nanoparticles were "green" because they reduced the amount of biocides released into nature during the treatment of trees.

Thus, "green" was not a characteristic that defined a field of research (for example, catalysis) or a particular research topic — it was always contextual. The very use of the term GC seemed to be specific to each chemist and to the corresponding context: "It depends on the audience." For another chemist, the "green" was virtually impossible to verify, because the environmental impact criteria for a substance or a process could be diverse, numerous and sometimes contradictory; a process might be considered "green" by some chemists and "not green" by others. Further, for some, chemistry was green not only if environment and health impacts were less, but also if it lowered costs: "My definition of green chemistry is something that has superior performance, has superior cost benefits and, all by the way, has an environmental benefit."

It was the toxicity issue that seemed the most difficult to integrate. The interviewees gave several examples of work described as GC that they recognized, however, as double-edged regarding toxicity concerns. For example, ionic liquids could replace toxic organic solvents, but some of these were also toxic. Nanoparticles fitted within the field of GC for some respondents (for example, because they were used as catalysts to produce bio-fuels), but others raised the question of their potential toxicity. While GC was born of the idea that all chemists should be trained in toxicology, most respondents said that they ignored it, were not trained in this discipline, and some considered it a separate scientific field beyond the realm of chemists.

Like their American colleagues, French chemists defined "green" in a manner that was context specific: "Finally, no theme will be purely green. The boundaries are quite fluctuating." "We must also accept that we can move GC forward a little bit in lots of directions, and it will not always be 100% green (...) but everything that improves things — replacing a solvent, doing something less toxic, using less natural resources — in the end is always a win."

As for American researchers, the meanings of the term were varied. For a researcher "working on catalysis, one immediately respects one of the twelve principles of GC." But, arguing that GC was not only about that single principle, this researcher highlighted other elements: the use of agricultural resources, the use of aqueous solvents, work on making conditions of pressure and temperature as low as possible. For another, GC could be just "a simpler chemistry," i.e., one that avoided additional molecules as far as possible. Chemistry was green if it was bio-based: "Rule number 7 should be, I do not remember the exact formula, but it was about using biological carbon, so renewable carbon." "Fischer Tropsch is going to be considered as a green chemistry in the sense that if we start from the biomass which is a renewable source which is decarbonated, we can consider that it is rather a green Fischer Tropsch." But, again, the respondents insisted on respecting more than one of the 12 principles.

But, as in the U.S., GC was often losing here a key element of its original definition, namely the idea of limiting substances' intrinsic toxicity and using predictive toxicology to obtain benign by design substances. Some viewed this as an impossible goal because the impacts of chemicals were considered to be not only a function of their intrinsic properties, but "also the dose, the quantity, the time... so it's extremely complicated." Chemists thought, overwhelmingly, that toxicity issues were not part of their job: "There are people specialized in it, who will watch this stuff." For these French chemists, toxicity needed to be studied only after the development of a substance or method, by toxicologists, and usually in a regulatory context. For this reason, the study of toxicity would be an additional constraint, often expensive and irrelevant to research.

As with American green chemists, the treatment of toxicity was the weakest point in French GC, although chemists stated a priori that this was an important aspect: “We are also working on nano catalysts, nanoparticles etc. and we must admit that, for the moment, we do not ask ourselves much about the toxicity of these compounds.”

As for teaching, one toxicology course in a Master’s program was mentioned. When lessons on environmental and health impacts of chemicals were included (three cases), such topics as life cycle analysis and the regulation of chemical risks were addressed.

Proposition 2: *SIMs are more likely to be successful when structural conditions provide access to key resources (employment for SIM participants, intellectual prestige, organizational resources)***.**
According to Frickel & Gross (2005), opportunities for gaining access to resources are vital to SIM emergence, as much at individual, local level (university, laboratory) as at a wider, collective level (funding programs, opportunities for publication, employment for SIM participants, intellectual prestige, organizational resources such as university departments or institutionalized channels of information flow).

Research funding

For the American interviewees, funding played a critical role in the direction they took in their work. Funding, often public, facilitated entering the field of GC. The main source of U.S. funding is the NSF, but some respondents thought that this institution lacked clear criteria for what was “green,” which remained at the reviewers’s discretion. For this reason “It hadn’t really shifted the money…” Funding from the EPA had favored GC since the late 1990s, yet its financial resources had since been reduced significantly. Also, the U.S. government Departments of Energy, Agriculture and Defense were considered useful sources. Finally, respondents mentioned the ACS “round tables” mechanism supporting topics related to the specific needs of companies and providing scholarships for students, or the Petroleum Research Fund. However, few projects could be financed, and with relatively low amounts. Other sources cited as marginal supporters of the field included the Toxics Use Reduction Institute (TURI) at the University of Massachusetts Lowell, the Dreyfus Foundation, some states including Michigan, the United Soybean Board’s fund, the student competition of the EPA titled People, Prosperity and Planet, and private donors.

Regarding industry funding for academic research, the essential criterion for collaborations remained the desired functionality; “greening” tended to be a side effect of initiatives by academic researchers, instead of at the explicit request of a manufacturer. Generally, the American respondents reported little or no industry funding for GC; the average ratio of private to public funding for research varied from 0 to 30% of total funding per researcher from private industry and foundations, versus 70 to 100% public funding. In two cases, the ratio was 50:50, but those funds were not targeted solely at research in GC, but rather to all the activities of my respondents.

As in the U.S., in France, overall, “it helps a lot to find funding”. Unlike their American colleagues, almost all of the researchers surveyed had industrial GC collaborations, with the ANR strongly encouraging industrial partnerships, and specific financial incentives giving tax benefits to firms investing in R&D.

Of the total budget of my French respondents’ teams working in GC, direct industrial funding on contract covered 5 to 50% (mean 28%). This was their operating budget, which excluded permanent salaries (publicly funded in France) but included salaries of temporary staff such as trainees, PhD students and postdocs.

Local organizational resources

American respondents said they were integrating GC into larger classes (for example, organic chemistry), although actual changes made to the courses taught remained unclear.

The term GC seems to have gained a legitimate place in academic language, so that the hierarchical status of the research taking this approach was usually favorable or neutral, with wide range of positions represented:

1. The hierarchy of universities, including chemistry departments, had seized a funding opportunity to make space for teaching and research in GC. In one case, institutional investment in GC could not have existed without support from the Dean of the Chemistry Faculty. In other cases, GC was a strategic investment area like any other, but was subject to explicit support: "The hierarchy of the university is concerned with economic development, and green is a product of that."
2. The hierarchy itself provided opportunities for GC, creating specific courses labeled as such. This reaction was partly a move in the competition with other universities and aimed at attracting students, whose favorable attitude to GC seemed clear. GC was included in the university's brand image, which was a useful strategy for small private universities. By contrast, in some already well known and competitive universities, "we have not tried to do that (GC) here, in part because we have a sufficient number of students (...) I like to say that we already did a good job for them, and we have other more urgent problems."
3. GC was part of a communication strategy around the greening of the university campus, coinciding with a range of environmental criteria such as energy saving and responsible waste management. Hierarchies were not providing additional institutional support by, for example, creating positions or adapting curricula.
4. The hierarchy was indifferent to GC, an attitude that seemed to be predominant in the universities of my interviewees. When professors proposed to "green" their chemistry classes, they were able to do this, but without obtaining specific financial or institutional resources. GC was in some cases a question of reducing students' exposure and costs related to equipment, reagents or waste treatment from chemistry laboratories dedicated to practical work. This cost-benefit thinking often happened in particular circumstances, for example during the renovation of laboratory buildings. Costs were reduced by modifying the experiments proposed, which could then be characterized as greening.

   For universities where research played an important role, the conventional metrics of research were priorities for the hierarchy and above any other considerations: "Publish and get funded, that's the pressure, whatever the field." When the hierarchy of universities, and in particular chemistry departments, were opposed to GC, it was because they associated it with a critical attitude to industry practices or because of ideological disagreement.

In France, while they were not enthusiastic to the point of investing significant resources, hierarchies were often not opposed to GC either: "For the lab, what matters is metrics, metrics... good publications and a maximum of contracts." But such criteria also motivated some researchers: "What is important is the impact factor, and quoting indices, so we are lucky that GC is at this moment on a roll, so GC articles are well cited."

When hierarchies were favorable to GC, this was due to its research, funding and partnerships potential: "It was well received. (…) It was called GC, but behind this we put the science that goes with it… then we can label it GC, or sustainable chemistry, in order to get funded. But behind this we must put scientific principles…. and when the science was there, it has always turned out well."

The teaching of GC has targeted essentially Master's and PhD students and only in rare cases the lower level. While some courses or Master's programs were specifically labeled with the term GC, the associated concepts were usually included in more general courses.

There has been no tendency to undertake green practical work in France, and U.S. initiatives on the topic are unknown. Moreover, toxicology, and environmental science more generally, are almost absent from teaching provided to chemists.

Contextual organisational opportunities and resources for GC

In the U.S., the direct effect of chemical risk policies on chemists' work in GC is insignificant. Environmental regulations are usually not a parameter of chemists' thinking when choosing topics or working methods. However, high-media-profile controversies have impacted chemists (plastic bags, brominated flame retardants, endocrine disruptors...), giving them hints about the nature of the problems to solve.

One could assume that regulation would be a pressure on manufacturers, who would then be encouraged to innovate and to fund public research on GC. However, this was not the case in my sample, as researchers were not receiving demands from industry explicitely driven by greening or regulatory objectives.

Unlike American chemists, French chemists knew of the existence of REACH and talked spontaneously about it. Yet this was a very superficial knowledge. The respondents understood that substances had to pass the regulatory filter, but did not know what this filter was, and what properties substances should or should not have. As a consequence, the respondents did not consider REACH as a reality they should be integrating into their research: "We do not feel really concerned, because REACH affects rather the commercial level and people selling products, while we… we are doing research, we are far upstream of REACH in fact."

Proposition 3: *The greater a SIM's access to various micromobilization contexts, the more likely it is to be successful***.**

According to Frickel & Gross (2005), academic departments play the prime role in the emergence of a SIM, in particular through the access they provide to students and to the recruitment of new young members, and through their capacity to deliver degrees.

The role of university departments as micromobilization contexts

My results indicate that in the U.S. university departments were usually not places of micromobilization. Many of my respondents were a minority or even isolated, rather atypical individuals in their universities: "I try to bring GC into the department, but it is difficult to sell."

Some universities nevertheless had a tradition of promoting GC and made institutional investments: the University of California at Berkeley, the University of Oregon, to some degree Yale University, and the University of Massachusetts. But globally, it was rare for chemists displaying their work in GC to be part of chemistry departments where a majority of their colleagues showed the same orientation.

The presence of GC in my respondents' universities was often associated with the existence of a department or program in environmental science. While in some cases the green chemists had a dual attachment to the two departments, in other cases collaborative research or teaching took place between the two disciplines, or courses in GC were provided to students pursuing a degree in environmental science. Yet collaboration was not systematic.

Unlike by American respondents, in France GC is viewed as a trend that all chemists should adopt, more or less: "Everyone wants to do so because they have an awareness or because it helps sell their work… there is a bit of both, I think." "Yes, I do not know if this is opportunism, but many people hastened to go down this route. But it was very, very much welcomed by the community." The concept has further spread through the creation, in several laboratories, of teams with common GC objectives and research strategies. An important difference from the U.S. was that respondents in France were part of whole teams working on GC, the smallest being of between three and ten people with permanent and non-permanent positions, and the largest bringing together dozens of people.

I was not able to observe a systematic correlation between the presence of chemical laboratories that display research in GC and laboratories in environmental science that are geographically close or present in the same research institution or university. Geographical or institutional proximity does not particularly favor such collaboration.

Other micromobilization contexts

In the U.S., conferences played an essential role in GC socialization. One respondent, for example, met Paul Anastas and John Warner at a conference: "I was immediately converted. I understood what it was and, all of a sudden, I realized that ... wow! It was exactly what I wanted to do! That day, my career swung." Also, Anastas and Warner's (1998) book was cited routinely as a gateway to the world of GC, as an obvious "must" and sometimes as a revelation, a discovery.

The role of organized networks was important in spreading the concept. On issues related to teaching GC, for example, the University of Oregon organized training programs each year for teachers in chemistry from other American universities. To encourage networking, a map provided the names and details of various professionals who asked to register (available at: http://greenchem.uoregon.edu/).

Concerning the spread from the U.S. to France, for one of my respondents, who was among the first to use the term in the latter country, the trigger for adopting the concept was meeting Paul Anastas at a conference. Another heard the term at a conference in the 2000s. Publications were an important source of terminology transfer, but also contacts with the industry and the national ANR funding program.

Proposition 4: *The success of a SIM is contingent upon the work done by movement participants to frame the movement in a way that resonates with the concerns of those who inhabit an intellectual field or fields.*
Frickel & Gross (2005) consider social values and broader world views as lively roots for SIM, which are "ultimately sustained by ideas." SIM participants frame their movement through books, articles, grant applications, conference proposals, which all form their "intellectual identity." Unlike the first three propositions, this one reveals the specificity of GC, because, as a general pattern, I could not identify particular motivations which would render it different from any other research topic or thematic area. Besides their common use of the term, most green chemists do not seem to share a common intellectual identity that would differentiate them from the rest of the chemistry world. Some exceptions remain, of individuals being strongly motivated by environmental commitments.

What motivates chemists to use the term GC?

The major motivation for using or not using the term, for both U.S. and French researchers, is the strategic management of their teaching and research topics, of funding and of their image and credibility as researchers. Funding is a very significant, but not the only, reason why U.S. respondents chose the field. GC sets challenging new questions and opens up new research paths, and therefore represents an intellectual motivation and presages career opportunities: "A lot of the older, complex problems... there are too many people in the field, and it is hard to break into, this is an opportunity… you could start at the ground level and… it's kind of the beauty of new ideas coming out, and people trying to wrestle with those."

The ability to attract good students to internships and doctoral studies is an important motivation for university professors involved in postgraduate programs. Greening may allow universities to reduce operating costs by reducing expenses for waste treatment and for facilities like fume hoods, while limiting students' exposure to toxic substances.

Finally, for a small minority in my sample[5,] GC was above all about strong personal beliefs and ethical engagement, and these researchers have, if this was needed, pushed the limits of the academic system.

Similarly, some of the French respondents were aware of the term GC early on, in the mid-1990s, but did not adopt it immediately: "At the beginning I did not want to use the term GC. I was considering that it had an ideological connotation, and I think this complicated things, it did not help."

Chemists adopted GC "without knowing", so using the term was merely a strategic positioning issue, "at the whim of tenders" or of the requirements of international publications. But GC was equally a scientific challenge: "There is so much to discover in there... (...) This is a fantastic new exploration field." For those who refused to label their work as GC, the term had a negative connotation because it was "overused": "people put everything and anything inside it."

Is GC involving a change in the views of chemists about their own responsibility as regards the potential health and environmental impacts of their work?[6]

The great philosophical change promoted by GC — in the conception of its founders — concerned the role of chemists in the chain of responsibility linking laboratory, industry, users and policy-makers. Unlike other techno-sciences, the founders of GC claimed for their science a new social awareness: as chemists invent substances and processes in their laboratories that will eventually impact health and the environment, they also have the power to mitigate pollution. But, besides the field's "champions", do "regular" chemists agree with this new social role of their research?

For U.S. respondents there was no simple answer to this question, because the definition of green was blurry, given the complexity of potential health and environmental impacts of chemicals and the impossibility of measuring these absolutely. Furthermore, chemists' cannot control the uses of the knowledge they produce:

> if I'm making a chemical, and I publish and then I'm reponsible for, you know, to bring it to lab… But then, the issue is if I do publish it because, whatever it's a non-interesting reason, and someone finds a different negative use for it, and we find out later that, you know, there is a mistake (…) how guilty I am? Of bringing this to the world, that is a question that I don't have a good answer for.

The principle of lowering the intrinsic toxicity of substances was questioned, based on the idea that exposure was the primary cause of risk, and the chemist had no control over the use of substances. Faced with the question of moral responsibility, chemists often returned to a more traditional philosophy of techno-science and the criterion of use outweighed the reference to intrinsic properties specific to GC:

> I think it's stretching it too far, because the similar thing would be someone doing, nuclear physics should think about the bomb possibilities every time they think, which is too far. I mean you know, that's part of your consideration but it can't be the dominant one.

Those in my sample who promoted the "benign by design" proposals of the field's founders were also professionally close to them.

Like their American counterparts, French respondents essentially thought they had limited power to influence the potential health and environmental impacts of their work. Little control was associated with their work, which was only a part of the final product or process. The responsibility for these impacts thus lay mainly with industry employees who made production decisions. The toxicity of substances was viewed as a function of exposure, making the user mainly responsible for the impacts:

> Now, the (problem of) endocrine disruptors, it stems from excessive consumption ... just take the case of Doliprane (n.a.: paracetamol), for example, I think there are problems of rejection of Doliprane in wastewater, because it has more and more people who consume this drug. Is this the fault of the pharmaceutical industry? Is it the fault of the chemist who developed this product or is it the fault of consumers who use the drug in an extremely unthinking way?

Pursuing an objective of minimizing the possible impacts was also dependent on each specific research situation. A good idea that leads to solving a theoretical problem could be based on "brown" chemistry, which could later be improved: "If it is to understand a mechanism, if it is to understand an interaction or things like that, one should not start by saying that there is a trick, it's dangerous, there will be waste."

Discussion and conclusions

Based on historical analysis and a sample of 70 interviews with green chemists in France and the U.S., my objective was to understand what is new in GC as compared with conventional chemistry, investigating the characterization of GC as a SIM (Frickel and Gross, 2005). The analysis of the emergence of and present developments in GC showed that three of Frickel and Gross's propositions fit well, while the fourth proposition underlines the specificity of GC as compared with other SIMs. Regarding its theoretical content, the novelty of GC lies essentially in a different mobilisation of existing research having an environmental potential (biobased chemistry, catalysis) but is not as radical as intended in its original, critical formulations (green molecular design).

In particular, my results show that GC has a hybrid character, bringing together scientists with different, sometimes nested, motivations (funding, career and publication opportunities, communicational, ethical and political motivations). Most of these motivations could characterize more generally any academic activity, independently of greening objectives. My respondents used different definitions of the term and adapted its use to the specific context and public. This is not necessarily in contradiction with other SIMs, as Frickel and Gross (2005, 206) noted: "This is not to say that all participants in a SIM will agree as to the meaning of its ideational or knowledge core." Nevertheless, for GC, the diversity of meanings is particularly high. The definition of GC is proteiform, multiple and changing. The term has been continuously redefined by chemists; it took on additional meanings as more researchers working on new subjects came to consider their work as part of this field. It was built, and is still being rebuilt, by permanently passing from one space of legitimacy to another (research proposals for funding, journals and conferences, policy-makers, non-specialist public). Its boundaries are constantly shifting and its meanings differ not only from one person to another, but also from one context to another, and from one audience to another, including for the same chemist. The 12 principles play a symbolic role of unique historic reference, but, with their ultimate flexibility, they adapt to every field of chemistry. Therefore, some do not adopt the term because they perceive it as disadvantageous to their image. In short, the term plays a strategic role, which does not exclude ethical underpinnings, but whose main function is political and interactional. It allows a restructuring of the research community in chemistry, reorganizing the balance of powers on certain topics, reinventing some of its rules, and expressing its position relative to the outer world - especially that part of the outside world that challenges its legitimacy due to controversies over risks, jeopardizing the community's social position and respectability.

In short, GC is essentially defined in response to external influences from research funding and from the framing of environmental, industrial or agricultural policies. The comparison between the U.S. and France is illustrative of this influence of policy. In the U.S., the meaning was influenced from the beginning by the context of the PPA, with central emphasis on toxic waste management. In France, the term was shaped by chemists' perception of the negative public image of their science, and by policies that governed agriculture, research funding, and industrial practices.

These initial political drivers make of GC an original case of a research community fully created by external forces originating in the non-scientific arena. Paul Anastas himself is a particular case, by comparison with other SIM founders, since his age and academic status at the first moments of GC were not his major assets. His resources were political legitimacy (EPA), his charisma, his discursive and working capacity. On the other hand, the role of well-established scientists in a SIM is confirmed for France.

Roberts (2005) also proposed an analysis using Frickel and Gross's (2005) general theory, as I did, but expressed doubts about the characterization of GC as a scientific movement, among other factors because he did not consider it a rival to chemistry. However, my large empirical basis, which was not available to Roberts, and my comparison between two historical national pathways of GC, allowed me to produce a more nuanced analysis of the "dissatisfaction" driving the movement, and of the role of academic leaders (important in France, as compared with the U.S.). Furthermore, I argued that GC had truly proposed a revolution in chemical thinking (the Results section). However, more than ten years later, I arrived at similar conclusions about the heterogenous and partly discursive nature of GC.

The comparison between the two countries is rich in insights. First, about the relative roles of government in the emergence of a SIM: whereas in the two countries the movement began as a top-down impulse, in the U.S. the push came originally from the EPA, whereas in France the major role was played by the national funding agency, as well as by the top-level hierarchies of the two largest research centers in the country, CNRS and INRA.

Secondly, the American interviewees referred to greening practical work for students in chemistry and to including toxicology in their curricula, yet these ideas had no resonance in France. French respondents mentioned no American source other than "the 12 principles," so I infer that the original sources of GC were not much read in

France, and that the concept was rebuilt and propagated through French channels, taking on a national connotation.

The two countries show the same striking difficulty in integrating concerns for toxicology into the teaching of chemistry, research practices and the mentality of chemists. While this was the original impulse of GC, the SIM developed and grew without it, losing its main original feature on the way. This difference persists, with recent literature in the U.S. acknowledging the "chemistry – toxicology gap" and encouraging green chemists to move towards green molecular design (Zimmerman et al., 2014; Anastas and Zimmerman, 2016), while this is absent in France.

In conclusion, GC is an example of perfect adaptation of a terminology to the external conditions and socio-political contexts of chemistry. While this is a strength that gives GC an important potential for changing overall practices in chemistry in the direction of better inclusion of health and environmental concerns, this might also be its major weakness as it might die or completely lose its original environmental relevance, depending on the evolution of external drivers.

1. In line with the methodological approach taken in this paper, this overview of the literature focuses on the social sciences and excludes the numerous definitional papers published by chemists, who are themselves the subject of study.
2. I restrict myself here to a minimalistic presentation of the four propositions, which are extensively discussed and demonstrated in the original article, in order to allow enough space for communicating results directly related to the GC case study. Furthermore, I come back to the particularities of each of these propositions during their exemplification on the GC case study.
3. The Office of Pollution Prevention and Toxics (OPPT) was created in 1988.
4. A good source for the 12 principles is the website of the American Chemical Society : https://www.acs.org/content/acs/en/greenchemistry/what-is-green-chemistry/principles/12-principles-of-green-chemistry.html
5. This might not be the case in the whole GC community, as my sample is not statistically representative. Feedback from the respondents does confirm my findings, showing that strong environmental commitment characterizes a minority of green chemists, but a statistical confirmation of this finding should involve quantitative research insuring the representativeness of researchers declaring work in GC.
6. The question of chemists' moral responsability in relation with green chemistry has been extensively addressed in Maxim (2017).

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Appendix 1

RESEARCH

Definition and identification of the field of green / sustainable / ecological chemistry

1. Personal presentation:
   - Current position
   - Past positions
   - Training
   - Past and current research topics

2. How did you start working on green chemistry?

3. As regards the relationship between chemistry and sustainable development (including health, environment, social and economic issues, etc.), do you prefer talking about:
   - sustainable chemistry
   - green chemistry
   - chemistry for sustainable development
   - ecological chemistry
   - any of these terms ; a proposal ?

4. How do you define ***"green" (or other term)*** chemistry? Could you please provide key words defining:
   - your work in ***green*** chemistry
   - ***green*** chemistry in general

5. Which are, in your opinion, the priority research domains in ***green*** chemistry?

6. How do you measure the "green" character of your activities? Do you use a specific metrics?

7. When did you heard for the first time the term green chemistry? Do you remember in which context?

8. Is green chemistry:
   - innovation for substitution (replacing existing substances by other substances having a lower risk)
   - breakthrough innovation (changing not only substances but also uses, industrial practices, economic model, etc.) ; e.g., nanotechnologies, GMOs, synthetic biology, etc.

Driving forces and constraints

9. In your opinion, which are the driving forces for green chemistry? (e.g., policies, internal dynamics of research in chemistry, funding, industrial demand, etc.)

10. Which are the barriers for the emergence of green chemistry? (e.g., funding, forming new researchers, regulation, markets…)

11. Is green chemistry currently (enough) taught in universities? (if no) Why?

12. Are toxicology / environmental sciences taught in classes for chemists today? (If NO) Why?

13. Which are the jobs chosen by your students after they finish their education?

14. Is the hierarchy of your lab encouraging research in green chemistry?

Research practices

15. In your research practices, work on green chemistry has changed significantly your working practices? Or these changes are in line with your previous work?

16. In your team, working on green chemistry involves collaborations with other disciplines, with which you were not used to work before?

17. Do you work with toxicologists? With ecotoxicologists? With ecologists? With agronomists? With researchers in social sciences?

18. How do you know if the substances you use are toxic or not? Do you use specific databases, your own knowledge, or other sources?

19. Are there many of your team / lab colleagues working in green chemistry?

20. Is there an Environment department or an Agriculture department in your university / research center? Is it big? Do you work with?

21. In your opinion, which is the attitude of most chemists in your country as regards green chemistry ?
    - very favorable, green chemistry is a major challenge for chemists
    - favorable, but one cannot be sure yet that green chemistry has a future
    - Green chemistry is a transient fashion
    - Green chemistry is a continuation of currently existing practices (chemists have always tried to reduce the impact of their activity on health and the environment)
    - Others

    Do you consider yourself as being part of a minority?

Partnerships and research funding

22. Green chemistry has allowed you and your team to obtain new research funding? Funding that you wouldn't have had without this green approach?

23. Have you already developed partnerships with the industry on green chemistry? If yes, which kind? (e.g., common laboratory, contract, project). How do you perceive these collaborations?

24. Which are the other sources of research funding for your activity on green chemistry?

25. Which is the proportion between funding by industry and other sources, on green chemistry?

26. You and your team are members of particular research and innovation clusters or organizations related to green chemistry? Which is their role on the direction taken by your work?

27. Did you benefit of help from public structures aiming at facilitating the transfer of research in the industry?

Institutional role of researchers

28. Do you have responsibilities in research management or at the interface between research and policy or private arena? For example in Scientific Boards, policy, expert or other advisory activities, in research funding organisms, in reviewing research projects, in companies…?

29. Are you editor of a journal?

Economy of green chemistry

30. Which are the perspectives for applying in practice your research in green chemistry?

31. Do you protect your research with patents? If yes, how many did you develop on green chemistry subjects?

32. Have you already been concerned by a commercially successful application of your research by the industry? (if yes) what do you think about this experience?

33. Have you already been involved, with or without industry partner, in a start-up or similar structures?

Health and environmental issues

34. In your opinion, concern for risks can be included in the design of chemicals since the very beginning step of synthesis (benign by design) ? If yes how? (feasibility). Do you think chemists should act on intrinsic properties (hazards).

35. In your opinion, researchers in chemistry have a responsibility as regards the risks of the substances they develop?

Green chemistry and society

36. What do you think about criticism from civil society (NGOs) on chemical risks?

37. Do you think that NGOs and the public should, and can, get involved in orientations given to research and innovation in chemistry?

38. (if yes) at which level?

39. Research funding agencies

40. Directly at the level of research projects or laboratories, even common research with researchers?

41. At the level of research applications, via public consultations and NGO involvement in the work of safety agencies?

42. Which are the opportunities for publicizing the green character of your activities? (patents labeled "green chemistry", publication in specialized journals, communications for the general public, interactions with journalists, books, etc.)

Scenarios of green chemistry

43. How do you imagine green chemistry in 2030, as scientific discipline, and as technique present in society and economy? For example, evolution of: research? relations between research and industry? the industry? consumers? Policies?

Could you please communicate me other names of researchers working in green chemistry?