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From unseen to seen in post-mining polluted territories: (in)visibilisation processes at work in soil contamination management

Tessa Bonincontro [1,2]✉, Juliette Cerceau[2], Florian Tena-Chollet[1] & Sylvia Becerra[3]

In line with EU recommendations, the potential 'mining revival' in France focuses on (re) opening mines. In this context, political discussions on post-mining areas have increased, driven by past mismanagements. Scientists are key in these regions, studying contamination, advising policy, and seeking solutions. Based on a case study of phytoremediation research in Saint-Laurent-Le Minier, we explore how lay and expert knowledge intersect. By examining what is hidden and by whom, we unveil research practices and stakeholder dynamics, sparking reflection on the research process while promoting a reflexive approach for researchers. We show research and its application spotlight specific topics (such as soil contamination), select, and make visible certain lay knowledge and local stakeholders and visibilises certain technological choices.

[1] Laboratory for the Science of Risks (LSR), IMT Mines Ales, Ales, France. [2] HSM, Univ Montpellier, IMT Mines Ales, IRD, CNRS, 6 avenue Clavières, 30100 Alès, France. [3] Laboratoire Géosciences Environnement Toulouse (GET), Observatoire Midi Pyrénées, Université de Toulouse, CNRS, IRD, 14 avenue E. Belin, 31400 Toulouse, France. ✉email: tessa.bonincontro@gmail.com

Introduction

In alignment with the recommendations of the European Union, the prospect of a 'mining revival' in metropolitan France is centred on the potential opening or reopening of mines. The ecological transition and desire for national energy independence serve to legitimise these political orientations. As a result, this potential mining revival triggers a (incomplete) renewed politicisation of the underground (Arnauld de Sartre and Chailleux, 2021). It brings to the forefront the economic, environmental, sanitary, and social challenges associated with (post-) mining issues, prompting a new examination of the historical problems, in particular instances of mismanagement (Balan, 2021). This is especially true for former metallic mines, which pose a significant risk of polymetallic contamination, particularly in the Mediterranean context (Doumas et al. 2018).

The Cévennes region in southern France has a rich mining history, dating back to the Gallo-Roman era (Domergue et al. 2006), with polymetallic mining activities spanning various periods. Coal mining emerged as a significant economic sector in more recent times. However, by the late 20th century, these mines gradually closed due to competition from foreign sources, leading to enduring local consequences. These include economic and social crises (Gaillard, 1977), health and environmental impacts, and geotechnical instability. Soil pollution, stemming from the region's mining legacy, remains a prominent issue, both visible and invisible. As Zanetti (2018) reminds us, because of its invisible, silent and buried nature, soil pollution is often ignored and forgotten. It is therefore difficult to turn into a public problem unless it is made visible by economic, land or health issues.

Among the post-mining territories in the Cevennes, Saint Laurent-Le Minier (Fig. 1) is home to one of the world's largest lead-zinc deposits, with traces of mining activity dating back to Gallo-Roman times (Maton, Laperche, and Negrel, 2010). During the most recent period, two mining sites were in operation: Les Avinières (1873–1911) and Les Malines (1885–1934 and 1940–1991). The sites were managed by a succession of operating companies, ultimately by Metaleurop (now Recyclex) from 1940 to 1991. At Les Avinières, 40,000 tonnes of lead zinc were extracted between 1873 and 1911, and a total of 800,000 tonnes of lead zinc and 225 tonnes of silver at Les Malines between 1885 and 1991 (Maton et al. 2010). The first alert concerning soil pollution came in 2003 after a local resident, hoping to set up a campsite, carried out soil analyses. Concerns were raised about the neighbouring hamlet of La Papeterie, due to its proximity to the Avinières mine dump, the settling ponds, and the former activity of the ore processing units which left heavily contaminated soil. Lead concentrations at Les Avinières can reach 30 g per kg of soil, which is 600 times higher than at a 'normal' site (ADEME, n.d).

In 2006, excavation work and the addition of healthy soil at La Papeterie were financed by the former mine operator (Lemaire-Crespy 2013). However, the persistence of high levels of lead in the population led the French government to carry out further investigations from 2011 onwards and to propose a management strategy that was made public in 2014. In 2016, ADEME (the French Agency for Ecological Transition) was officially tasked with rehabilitating the site (ADEME n.d). This included securing the Avinières waste rock dump, restoring the pond and repairing the hamlet's road networks.

Phytoremediation is frequently chosen to tackle contamination issues as it offers an in situ alternative to the removal or deep burial of waste. This solution has two main applications: phytostabilisation (chosen in Saint-Laurent-Le Minier) and phytoextraction. Phytostabilisation consists of using plants to limit erosion and dispersion of pollutants. Phytoextraction refers to the extraction of pollutant particles from the soil by using hyperaccumulating plants and recycling them as eco-catalysts (Grison et al. 2015). Both are associated with the idea of plants as a 'remedy' for pollution issues. The technical choice for phytoremediation has implications for the territory, potentially influencing emotions (*e.g.* decreasing anxiety), behaviours (collaborating, promoting, hiding, challenging the solutions proposed), and ultimately impacting the implementation of pollution-tackling solutions. According to Zanetti (2018), technical-scientific management of polluted soils is part of the physical concealment of the pollution, making it invisible and forgotten in the environmental and social arenas.

While there is current advocacy for mining renewal, acknowledging its necessity in the face of challenges posed by

Fig. 1 Localisation of Saint-Laurent-Le Minier and its former mining sites. The background map comes from géoportail.

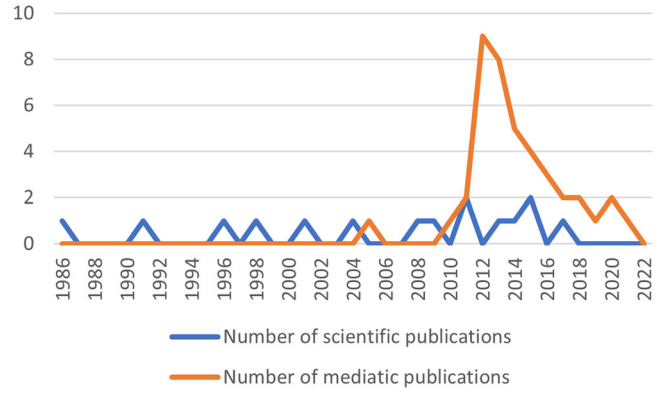

Fig. 2 Kinetics of scientific and media publications on Saint-Laurent-Le Minier post-mining issues from 1986 to 2022. Scientific publications are represented in blue and media publications in red.

digital and energy transitions (Commission et al. 2020; European Commission. Directorate General for Internal Market, Industry, Entrepreneurship and SMEs. 2020), it is crucial to recognise that tensions stemming from historical mismanagement continue to impact the present. Progress in post-mining research is therefore becoming increasingly vital at both political and social levels. This is necessary to support the advocacy for mining renewal at the national level as well as the territorial development of contaminated areas at the local level. As a result, scientists occupy a pre-eminent position in post-mining areas, whether their research aims to characterise contamination, inform public policy or study potential remediation solutions. As Gaille (2016) emphasises, in a context where the development of science and the formation of a socio-technical, political and economic space are intertwined processes, the question of the researcher's social and political responsibility becomes essential.

Through an in-depth study of research into phytoremediation in Saint-Laurent-Le Minier, this article illustrates the dynamics of visibilisation and invisibilisation at work in the interweaving of scientific and lay knowledge, lay knowledge being here defined as held by non-scientists. Using the lens of specific remediation projects, it explores research practices, problem framing and inclusion/exclusion of people and questions. The first part of this article outlines the methodology and the underlying theoretical background. Subsequently, the results are presented and discussed in five sections: we start by providing an overview of invisibilisation processes at play in both media and scientific arenas; then, we demonstrate how research focused on soil contamination led to an institutionalised solution: phytostabilisation ; we analyse unconscious and strategic invisibilisation processes happening during the research; and finally, we discuss the impacts of research on phytoremediation in Saint-Laurent-Le Minier in terms of empowerment, the dialectics of dispossession and landscapes.

Materials and methods

This work is based on an extensive data collection and analysis carried out from January 2022 to June 2023.

Scientific and media-related literature analysis. The first stage of the data collection was based on a background study through the review of scientific literature and the media between the closure of the last mines and May 2022. 17 scientific papers were identified in this period *via* the *Web of Science*. In addition, 52 media articles were identified via the database *Europresse* (see additional data). It should be noted that on the database we used, very few articles prior 2010 were mentioned as the main local newspaper wasn't listed yet. These literature reviews allowed us to characterise the dynamics of visibilisation and invisibilisation at work in scientific and media literature since the closure of mining activity.

Semi-directive interviews and discourse analysis. The second stage of the data collection consisted of semi-structured interviews that took place between 2022 and 2023. Following Paille and Mucchieli (2021), our sampling strategy consisted of targeting people familiar with this post-mining territory and relevant to our research question (Table 1). We interviewed researchers specialised in microbiology and environmental chemistry directly involved in phytoremediation research in Saint-Laurent-Le Minier. Our questions covered their scientific content, future developments, stakeholder interactions, scientific stance, and impact perceptions. Subsequently, we interviewed local inhabitants, some affected by post-mining situations, to gather their perceptions of the research projects, impacts, expectations of researchers, and efforts in addressing post-mining challenges. They also shared insights on potential interactions with researchers and fellow inhabitants and their perspectives on the research efforts.

The researchers and local stakeholders interviewed referred to research projects associated with both phytoextraction and phytoremediation. Table 2 summarises the research projects carried out by the interviewed researchers. However, our analysis also considers additional research projects, particularly some related to phytoextraction. Data for these were collected mainly from researchers who were not directly involved, as well as from the literature and from local stakeholders.

Visibility and invisibility: existing literature and scientific stance. This part reviews the literature on visibility and invisibility issues applied to research work, a mining territories and in our specific case study. The last part will focus on our own scientific stance regarding visibilisation and invisibilisation aspects.

About visibility and invisibility in research and post-mining territories. As Fontaine (2016) highlights, considering (post-)mining territories means dealing with visibility and invisibility. During the mining period, underground mining operations are hidden while the visible mining waste is brought to the surface. Once the mines are closed, two opposite dynamics coexist: removing as many remnants if mining history as possible versus valuing the latter by establishing it as part of our heritage. Other authors also focused on post-mining risks, in particular contamination, arguing that 'stakeholders could take more seriously visible risks' (Becerra et al. 2016b) or questioning the means of communicating about them (Doumas et al. 2018). These processes of invisibilisation are found throughout the mineral resource value chain, from extraction to consumption. Hidden behind equipment and uses, metals are invisible. But, more fundamentally, these metals are '*dis-origined*' (McKay, 2021) i.e. 'unconnected to their place of origin' (p.2). This is part of the invisibility of the extraction process itself.

We propose to address the notion of visibility and its opposite, invisibility of post-mining issues, at two levels. First, on a very tangible level, it challenges human sight; environmental contaminations are indeed characterised either by high visibility (spectacular colours of acidic mine drainage for instance) or heightened invisibility (microscopic pollutant particles). By using measuring instruments able to quantify for example a concentration of contaminants in the water, soil or body, scientists try to make visible an invisible pollution, from a human perspective.

Table 1 Panel of interviewed stakeholders in Saint-Laurent-Le Minier.

	Researchers	Inhabitants	Institutional stakeholders
Number of interviewees	5	10	6
Details	Microbiologists, environmental chemists	Former mayor, inhabitants, former miners, members of mining heritage associations	ARS (Regional Health Agency), DREAL (Regional Directorate for Environment, Development and Housing), Géodéris (public interest group on post-mining expert studies), Ademe (the French Agency for Ecological Transition)

Table 2 Table summarising the phytoremediation projects referred to by the people interviewed.

Name of the research project	Dates	Objectives	Potential application
PhD	Late 90 s	Explore processes of phytoextraction of metals from metalliferous soils and their applications	Phytoextraction
EMETER	2005–2008	Preliminary study : - Inventory of plants and bacteria species adapted to local constraints (metallic soil pollution) - Characterisation of contaminated soils - Basis for phytoremediation in Les Avinières	Phytostabilisation
APTITUDE	2009–2012	- Fundamental research goals on soil microorganisms with fieldwork and Saint-Laurent-Le Minier and New Caledonia	Phytostabilisation
SyMetal	2010–2014	- More applied: 'proof of concept' A pilot project to demonstrate the feasibility of phytoremediation In Les Avinières	Phytostabilisation

A wealth of STS literature showed the limits of entrusting scientists alone with studying facts and eventually finding solutions. The use of procedures and experimental tools by a small group necessarily results in a partial understanding of the phenomenon studied (Latour and Woolgar, 1986; Frickel and Vincent, 2007). Likewise, this small but dominant group of stakeholders defines how research topics are framed (Harding, 2015). Thus, the materiality of toxic particles is not self-evident and needs to be revealed by special means, which is considered being the role of scientists.

The second level is immaterial and challenges human discourses upon post-mining issues. Studying visibility and invisibility in the context of mining environmental contaminations on the immaterial level reveals that the pollution emitted is a crucial intangible dimension forged by narratives. In particular, Beck (1992) explains:

> "[Toxins and pollutants] generally remain invisible, are based on causal interpretations, and thus initially only exist in terms of the (scientific or anti-scientific) knowledge about them. They can thus be changed, magnified, dramatized or minimised within knowledge, and to that extent, they are particularly open to social definition and construction" (p.23)

In other words, scientific 'facts' about contamination are subjected to different patterns of narratives, necessarily visibilising some aspects and invisibilising others. Likewise, Schneider et al. (2016) identified five rhetorical strategies used by the US coal industry to protect its interests in the context of increasing environmental regulations and changing the marks of energy. For example, one of these strategies is the technological shell rhetoric, based on strategic ambiguity: the industry publicly promotes 'green coal' but uses various definitions of the concept, concealing *de facto* its precise meaning. The consequences are double: bringing together several audiences and masking the coal industry's reluctance to comply with environmental regulations while appearing proactive (Schneider et al. 2016). With a similar approach, Paliewicz (2024) investigates narratives and rhetoric created by the mining company Rio Tinto aiming at influencing interpretations and perspectives regarding the environment. The author demonstrates the company generates 'flexible corporate identities'. In addition, the author shows that the opposite side, the activists, adopt a similar strategy.

Highlighting the invisibilisation of pollution in Saint-Laurent-Le Minier: building on an existing study. In a book chapter, Lemaire-Crespy (2013) highlights the dynamics of visibilisation/invisibilisation surrounding the pollution in Saint-Laurent-Le Minier, which differ according to the type of local stakeholders: long-standing residents tend to make pollution invisible, in an ordinary, pragmatic approach with the aim of 'living with'; new residents, fuelled by the media, tend to make soil pollution issues more visible in their discourse; institutional stakeholders (local authorities, associations), via 'sustainable development' projects in polluted areas, demonstrate a desire to distance themselves from the mining legacy and change their image by greening the area's identity. While the author documented the gradual invisibilisation of post-mining pollution in public discourse, researchers were not included in her fieldwork, likely because research projects were still in their early stages at the time. This paper seeks to build on Lemaire-Crespy's work by extending the study period to 2023 and focusing on research in Saint-Laurent-Le Minier to explore the invisibilisation of pollution in greater depth.

As proposed by Lemaire-Crespy (2013), we will use the word 'invisibilisation' rather than 'invisibility' to emphasise the deliberate act of making something invisible. In the case of pollution, invisibilisation can be seen as a means for the local population to take ownership of it, as the author explains.

Building on this literature, we will try to push further the analysis of visibility/invisibility processes in the emergence of narratives and the construction of identities regarding the post-mining territories with a focus on researchers. Our focus will be

on the entire research process, from fieldwork to its reception and appropriation by local people.

Our scientific stance: the invisibilisation processes at play in our methodology. We are aware that our research is itself a part of this local post-mining context, where the development of science and the formation of a socio-technical, political and economic space determining the development trajectory of the region have been and are still being interwoven. It is interesting to look at the dynamics of invisibilisation at work in our own research, through the methodological choices we made concerning the people we interviewed, the questions we chose to address or ignore, etc. For instance, our data collection and analysis have been driven by the narratives built locally concerning the story of scientific and local collaboration and by the ecosystem of stakeholders crystallised around these narratives. Consequently, a prominent place was given to the most visible research projects, because both the researchers and the inhabitants involved were prone to accept interviews. Likewise, our study is mostly based on data about inhabitants who were the most involved in the research, and therefore visible in the research arena. As a consequence, data saturation was rapidly reached, due simply to the fact that the number of people able to talk about, and who were concerned about soil pollution was limited. Moreover, we were confronted with invisibilisation dynamics concerning the information shared during the interviews, in particular the hesitance of some stakeholders to discuss certain topics on the record, due to past tensions. As a result, informal interactions played a crucial role in our data collection process. Four field trips with scientists, inhabitants and students provided relevant observations enabling the collection of more situated data about the research projects that did not emerge during interviews. Some of the stakeholders were more willing to talk about interpersonal tensions off the record and observing them interacting with each other also revealed the types of relationships they share. These observations proved to be important to properly understand invisibilisation dynamics in research projects.

Kinetics of scientific and media publications: from invisibility of soil contamination to hypervisibility of phytoremediation methods

From the work carried out by Gaille (2016), we report here knowledge-sharing processes at work throughout research projects in Saint-Laurent-Le Minier. We highlight what is made visible, what is hidden and how it contributes to delimiting the field of knowledge production.

The kinetics of scientific and media publications on Saint-Laurent-Le Minier post-mining issues are presented in Fig. 2. As described in detail by these authors (2023), the acceleration in the publication rate of scientific articles since 2010 is linked to the specialisation of scientific research in post-mining topics. One topic is particularly detailed: soil pollution, in the footsteps of the exploratory study of Robinson et al. (1998). The research resulted in the suggestion of actual remediation methods (Escarré et al. 2011; Grison et al. 2015), which we will consider in the next section.

A close look at the 50 relevant media articles published was interesting. It is noteworthy that major events such as the ADEME taking charge of part of the site do not correspond to a peak in media coverage. Likewise, very few articles mention pollution issues. When they do, euphemisms are used most of the time, which reflects the invisibilisation of pollution in the media. Finally, media attention to research work is selective. Phytoextraction is in the spotlight, whereas phytostabilisation is ignored, even though the latter topic constitutes the dominant body of research. Paradoxically at first sight, the focus on phytoextraction tends to hide the problems linked with pollution: this phytoremediation method is seen as a technical miracle based on nature that turns a problem (the pollution) into an opportunity (recovering metals from the soil).

Shedding light on soil contamination: from research on plants resistant to post-mining contaminations to an institutionalised solution

What do researchers make visible in their scientific papers and the media? In Saint-Laurent-Le Minier, Les Avinières has aroused the interest of several research teams. According to the local narrative, relayed by an inhabitant during an interview, a local researcher in hydrogeology worked on water-contaminated issues in the Vis Valley. The quality of the water was not very worrying[1] for him, but he noticed no vegetation was growing in some parts. This moment marks what Bessy and Chateauraynaud (2014) called the 'emergence of doubt[2]' (Lemieux, 1995). The researcher was concerned by the presence of a farmer living on and cultivating a plot that seemed contaminated. He contacted him to share his suspicions and suggested that he reaches out to a New Zealand specialist in contaminated soils to get more information. This specialist showed great interest in the area and advised a PhD student to go there.

Most of the research articles then focused on the understanding of the symbiotic association between Thlaspi (*Noccaea caerulescens*), (Robinson et al. 1998), or *Anthyllis Vulneraria* and a bacteria, *Rhizobium metallidurans*. The Avinières are intensely contaminated having among the highest zinc level in Europe in some specific places (Escarré et al. 2011). These research focused in particular on the resistance of these plants to polluted land for phytostabilisation applications (Escarré et al. 2011; Mahieu et al. 2013). A local stakeholder also explained that many researchers from all over Europe came to Saint-Laurent-Le Minier to gather soil samples and perform their experiments in their laboratory, reflecting the attractiveness of the area.

This research dynamic focalising on one topic echoes a 'demonstrative capitalisation' conceptualised by Rosental (2009). The first article written on the topic (Robinson et al. 1998) followed the visit of the New Zealand researcher and was the first of many. Thanks to word-of-mouth and/or mediatisation, each project opened new perspectives for the following.

It resulted in a local specialisation of the research performed, as the site became more and more well-known in scientific networks. The interest in phytoremediation increased, and the site was described as being in a situation where researchers 'were fighting for areas to do their experiments, areas to plant because there are many (researchers) who have planted experiments there' (local inhabitant).

This focus of the research on soil bioaccumulation of pollutants and phytoremediation implies that other topics were neglected in the academic arena, such as the impacts of pollution on human health. Thus, visibilisation of bioaccumulation delimits the field of knowledge production (Gaille, 2016). However, it is noteworthy that sanitary consequences of contaminations have been studied by state agencies (*e.g.* for lead-poisoning detection in children, see Gard et Cellule interrégionale d'épidémiologie, 2006).

When a local farmer influences what is made visible in the research. At the time of the research, the farmer still owned the contaminated land of Les Avinières which was of such interest to the researchers. He agreed to host field experiments as he could not use his land for agricultural purposes. Direct interactions between the researchers and the farmer have been initiated through logistical aspects such as gate openings and help to

transport equipment on the tiny bridge leading to the property. A friendly relationship progressively arose as the researchers relied on the farmer's aid. As time went by, the farmer became intimately linked to the research *via* a mutual exchange of knowledge.

Before the start of the research projects, the farmer had grown vegetables on his land, and in doing so, had acquired a rich knowledge of where plants grow, where they do not, which compost may help, and how to plant. This knowledge was then used for the experimental plantations and the researchers became more rapidly operational, especially during the 1990s, as online resources were less prevalent than today:

> "[The farmer] would tell me where the plants would grow when they would flower, all this type of information, which wasn't available at that stage." (researcher)

The farmer then seems to have had a direct impact on the research process, contributing to the visibilisation of certain phenomena interesting for the researchers. According to the researchers interviewed, the farmer became a source of ideas, offering a fresh and rooted perspective that is 'interesting to translate into research questions. Bleicher (2016) explains how phytoremediation is linked to 'nonknowledge' (i.e. knowledge of the unknown in Gross' terms (Gross, 2007) and thus benefits from the integration of other types of knowledge, here understood as interdisciplinary but always in the field of science. However, our example shows researchers are conscious of the limits of their knowledge and welcome the farmer's input because his deep-rooted knowledge is essential to applying phytoremediation to this specific local context. The farmer helped to enrich research work and make it more relevant to pollution issues.

Towards phytoremediation: visibilising phenomena relevant to remediation work. There was a direct transfer of knowledge between researchers studying phytostabilisation and the Ademe (in charge of the rehabilitation of orphaned post-mining sites). The Ademe expressed early interest in applying aspects of the research, deeming it relevant for phytoremediation. Approximately a decade after the initial collaborations between the farmer and researchers, another research team began a collaborative project which was financed by the Ademe (Grant Emeter), with the explicit goal of being operationally straightforward.

Among other relevant results for the Ademe, the researchers found they could differentiate and thus visualise dust from the mining dump and basins. They were then able to source the dust coming to La Papeterie from the mining dump, contradicting a study by the INERIS (French National Institute for Industrial Environment and Risks). They shared their findings with the Ademe, which initiated closer collaborations. When questioned about the factors favouring links with the agency, a researcher involved in the collaboration mentioned his constant effort to communicate relevant knowledge to the Ademe. This strengthened the relationship to the point that a start-up founded by one of the scientists involved in the research projects ended up being in charge of the site remediation.

Therefore, the chosen phytoremediation method in Les Avinières is directly rooted in research. The research projects revealed, among other findings, the significance of selecting plants/rhizobium associations most suited to local environmental conditions (Soussou, 2013). In practical terms, this is implemented through specific features of the project utilising local biodiversity. Seeds of local plants on the site were harvested, cultivated in a plant nursery, and then transplanted on the site. This innovative methodology was described by the former researcher and president of the startup as 'a first in France' and 'a very promising approach' (ADEME n.d:7).

In a common conception of research, although quite challenged in recent years, academics perform research and then, in a disconnected manner, the results may be used at some point by citizens and governments. This is the 'supply side model of science' (Oreskes, 2022). In this view, theoretical knowledge produced by researchers may be at some point translated into technical solutions by state agencies or others, if they are interested, but this is not systematic. Most of the time, this translation only happens if the knowledge produced by researchers is usable.

As Dilling and Lemos (2011) remind us, the usability of science should not be taken for granted. This is explained by the fact that '(…) different stakeholders perceive the usefulness of scientific information differently. Scientists, for example, when choosing the focus of their research, may make an assumption of what they think decision-makers need and hope their work will meet that need' (Dilling and Lemos, 2011 in Lemos and Rood, 2010:673). As described earlier, the close but informal relationship between researchers and employees of the Ademe during the first stage of the research was helpful to realise that they could be mutually beneficial and had common interests. The second stage of the research, more applied and funded by the Ademe, is paradigmatic of an institutional arrangement that favours 'usable' science. The iterations this contract implied impulsed the formalisation of the expectations and needs of each stakeholder which was certainly decisive in achieving site management. This seems to describe the 'push-pull' model in which 'usability is a function of both how science is produced (the push side) and how it is needed (the pull side) in different decision contexts' (Dilling and Lemos, 2011:681). This 'science pull' and 'demand push' results in a co-production model which 'better fits users' needs than that produced by more traditional models" (p. 682).

Towards the implementation of phytostabilisation: visibilisation and invisibilisation at play to weight in the decision-making mechanism. Scientific controversies and different stakeholders may shape the choice of a technical solution and how it will be received by the public. In Saint-Laurent-Le Minier, the research on phytoremediation was polarised by two research teams, one working on phytostabilisation[3] and the other one on phytoextraction[4]. The two projects were rivals, leading to a controversy when the Ademe assumed responsibility for the remediation and determined which method was most suitable. Inhabitants were also involved at this stage, many of them strongly favouring phytoextraction. For instance, the then mayor campaigned in favour of the implementation of phytoextraction rather than phytostabilisation. This preference was further emphasised by media coverage, which featured an abundance of articles about phytoextraction, while phytostabilisation had no dedicated articles (Bonincontro et al. 2023).

A researcher explained during an interview that the preferred solution 'depends on the people they (the inhabitants and the mayor) meet, where they form certain opinions and favour certain actions or not.' In this case, the mayor and several inhabitants were seduced by the idea phytoextraction could be economically beneficial[5] and 'decontaminate' the polluted soils, as extensively suggested in the media. This also illustrates the importance of serendipity in sciences (Catellin and Loty, 2013) and its influence on the framing of research questions and solutions. We could use the expression 'imprint effect' (Brun et al. 2007) applied to the choice of phytostabilisation as a solution. The author defines this effect as 'the result of a process of impregnation which takes place in space and time, and which

makes a 'trace' (p.179) on a scientific stance. This could also describe accurately the process of choosing a technical solution, here phytostabilisation: only visibilised data leave a trace.

According to a researcher, this controversy 'dragged things out', as there were a few unsuccessful attempts to combine both methods. However, the final choice seems to have been heavily influenced by relationships between stakeholders (here the researchers about phytostabilisation and the Ademe). The Ademe argued scientific evidence was proving that phytostabilisation was a more robust solution, ultimately chosing this method considered as already having a track record. The tensions were such that the agency carefully justified this choice on a leaflet for the general public, arguing that phytoextraction would require regular harvests and treatment, its effectiveness was still to assess and if it were effective, it would probably take hundreds of years to actually decontaminate the soil (ADEME n.d).

An analysis of the science in the making through unconscious and strategic invisibilisation processes

Explicit and implicit in the way collaboration works. This example illustrates the co-construction of science and society at work in the field of phytoremediation in Saint-Laurent-Le Minier. It shows the close connections between researchers and a local inhabitant. This questions the validity of 'Mode 1 of knowledge production' (Gibbons et al. 1994), a way of performing research only driven by scientific logic and the paradigm of the autonomy of the research, illustrated by the image of the 'ivory tower' (Scholz and Steiner, 2015; in Rigolot, 2020). In contrast, this case study is in line with the literature showing that science and society always co-construct each other (Pestre, 1997; Jasanoff, 2004; Ingold, 2021). The collaboration being spontaneous (Gaille, 2016), it is based on a tacit agreement between the researcher and this local stakeholder, driven by personal goals from both sides. We can assume at this stage that the farmer was interested in this collaboration to learn about the toxicity of his land and adapt his lifestyle accordingly. The researchers were eager to continue the collaboration to get more reliable and rooted data. As long as the collaboration was fruitful and in line with each party's expectations, both were happy to keep the collaboration going, but they would certainly have felt free to stop the collaboration if they felt like it. To a certain extent, the initial research goals may be renegotiated as described in Callon (1986). This represents a tacit agreement in informal collaborations. Tactics from both parties to convince the other party may be adopted:

> "But that sometimes happens with the job of researcher, you have to move forward with the person in front of you, who has their own convictions, and see where you can make a difference. That's why you need the field and the discussion to show that and then to actually show in the field: "Yes, it works", "no, it doesn't", "maybe it worked this time, but not this time". (…) there isn't one truth that is… That just comes out like that, that is always true." (researcher)

This researcher employed the field and the experiments as mediators to present arguments understandable to the other person. This quote also highlights the comprehensive stance adopted, acknowledging the existence of multiple truths and 'other interests' (i.e. other topics that people would like to make visible) which is essential for fostering a fruitful relationship.

Hence, this example of a relationship between scientific and lay knowledge is based upon a reciprocal exchange of knowledge which occurs spontaneously, without being defined upstream at the research proposal stage. It relies on a dialectic between visibilisation and invisibilisation in discreet and confidential arenas, based on a tacit agreement and moral contract between researchers and local stakeholders. It revolves here around one specific topic (resistance mechanisms of plants to contaminated soils), one specific cause (its applications on the farmer's land) and one specific territory (Les Avinières).

Visibilisation of some local stakeholders in the research and feeling of invisibilisation of other stakeholders. In the research on phytostabilisation in Saint-Laurent-Le Minier, the main participant was the farmer. His participation seems to have been thorough, as the research questions became co-constructed to address the needs of the farmer, although they aligned with the general need for contaminated territories. During the fundamental research phase, the farmer seemed to belong to the category of people involved 'who are passionate about knowledge or who invest in subjects that are close to their hearts' (Pestre, 2011). The co-construction of the research questions at this stage was more aimed at addressing the farmer's curiosity than concrete issues on his land. The research included his lay knowledge: he was the one who knew where the polluted areas were, who offered his view on the experiments, based on his empirical or experiential knowledge (Akrich, Barthe (2010)), i.e. what he witnessed by being on the field daily and his knowledge of plants in general.

The relationship appears to be quite horizontal: the researcher acknowledged his input and seemed to encourage him to take part. The farmer was quite comfortable and conscious of his contribution to the research. The field trip for agronomy engineering students organised annually by the researchers illustrates the balance of the relationship. The place given to the farmer by the researcher is prominent: he is the first to speak about the context and the research and feels comfortable enough to spontaneously add scientific details to what the researchers explain. An anecdote speaks for itself in terms of the visibility of the farmer in the research: a new bacteria species was named after him.

In this example, researchers had the final word and were the most visible: they focused mainly on the scientific results and, eventually, their applications when the research took a more applied orientation. They also signed the published papers. One could argue that in this context, the farmer is considered an informant more than an equal (Lake and Wendland, 2018), although he did not seem to have demands. All in all, his visibility is somewhat restricted.

If every stakeholder of this research project seemed happy with the process and its results, it was not the case for all research projects in Saint-Laurent-Le Minier. Some stakeholders felt invisibilised at some point in other research processes, even though they felt they had an important role:

> "Initially, they [researchers] are interested because they know they can't be everywhere. And that the local farmer is often in possession of information whose importance he doesn't appreciate. And it can be capital. And once they've appropriated this thing, we (the local people) become a nuisance."

This stakeholder, who took part in research projects not related to phytostabilisation, analysed the opportunistic approach of some researchers: he explained the dispossession of lay knowledge at play and its instrumentalisation, in line with the literature (on extractive epistemology of indigenous knowledge, see for instance Agrawal, 2002). The strong terms used echo the frustration he felt, as he explained later during the interview: he was eager to take part in research work, provided he felt respected by the researchers. The same feelings were shared by local stakeholders

regarding some phytoremediation projects in Saint-Laurent-Le Minier as they explained us during informal interactions.

Which knowledge is shared in practice? Voluntary and involuntary withholding of information. Not disclosing all knowledge is a strategy implemented both by scientists and local stakeholders. As a response to extractive methodologies, some local stakeholders decided not to share their knowledge or at least not all their knowledge with researchers, depending on the alignment of their objectives and the level of mutual trust. An inhabitant involved in phytoremediation research explained during an interview:

'I was already aware of quite a few things that were working, but I didn't tell them everything either (laughs).

- Why? Why didn't you tell them everything?

- Because I didn't want there to be an agromine[6].'

The slight laugh suggested the awkwardness felt by the respondent but also the pride of inversing the traditional roles. Since a collaboration is above all a question of personal affinity between people, research work in which the relationships are non-existent or unbalanced may have rather negative outcomes, such as the absence of knowledge circulation and a general distrust towards scientists.

On the researcher's side, if no example of active dissimulation of knowledge was mentioned, some local stakeholders explained that once the fieldwork was over, some researchers stopped communicating. It is not the case for all researchers though: the farmer still has visits from some of the scientists he interacted with. Finally, the setup of fieldwork also has impacts on the awareness of inhabitants of the existence of research projects. For instance, working on the soil of the settling basin that has high walls tends to visually hide researchers.

Embeddedness of expert and lay knowledge: empowerment and dispossession dialectics linked to the visibilisation of phytoremediation

Empowerment and lay knowledge acquisition. The attention paid by researchers to results dissemination *via* direct interactions and the media enhanced the knowledge of local inhabitants interested in questions related to post-mining impacts. This happened on a global level (understanding of post-mining processes, dangers, and challenges at play on the territory) but also at the level of private property. In a difficult economic context, having researchers quantify soil contamination for research purposes may be an opportunity for the inhabitants to understand the contamination of their land for free.

Close direct interactions with researchers awaken new expertise of local inhabitants about the post-mining contaminations. They became capable of diagnosing the territory to some extent without the help of experts and of building their own knowledge about their territory. A local inhabitant who engaged frequently with researchers explains she learnt to recognise an indicator plant for polluted soils (*Noccaea caerulescens*, previously called *Thlaspi caerulescens*):

> "It [La Papeterie hamlet, heavily polluted] was supposedly already depolluted. It was already finished. Except for the roads. The roads and the pavements, you could see the little plants I was studying there. They were still growing there, all along. So, you could see it was still bad soil."

This quote suggests the knowledge acquired becomes a great counter-expertise, in line with the literature (see Mélard and Gramaglia, 2022), enabling the inhabitants to identify shortcomings of rehabilitation actions.

Repurposing initiatives: when visibilising a problem enables to take advantage of soil contamination. Researchers' knowledge and their dissemination may be used by local stakeholders to transform the situation and leverage soil contamination. In Saint-Laurent-Le Minier, researchers catalyse such a reappropriation and instrumentalization of knowledge by the farmer:

> "When he saw this hyperaccumulator plant, plus many other metal-resistant plants he said to me, "Oh, that one, I've never seen as much concentration except from in China, for example, for a plant" and all that. And he was the one who told me, "Collect some seeds, he said, from that one, that one, that one, and I'll sell you some". But that was it. Because I couldn't farm any more. I was on the verge of a breakdown when a prefectural decree forbade me to grow vegetables in Saint-Laurent-Le Minier, especially to sell them. So to be able to get into the pollution control business… (…) And he sent me customers. (…) And I received letters by word of mouth from the Professor, who was also working on phytoremediation or phytoextraction, from all over the world. (…) But it was for their faculty, for their lab. They wanted this species, *Noccaea caerulescens*, which was hyperaccumulative. And I collected seeds and sent them to them. (…) So I asked the professor how much I should sell it for. He told me "At the price of gold". I was selling it for the price of gold (laughs). But one gram contains 1000 seeds. And often, one gram was enough for them to do their studies. So I didn't get rich on that."

This long quote is interesting in several ways. First, it shows the researcher mentioned helds a prominent place in the project. He came up with how to use soil unfit for agriculture and also created the network and the business plan. Second, it highlights the global scale of the enterprise which is somewhat rewarding for the farmer: from an unproductive soil, he manages to sell seeds to the entire world. Third, the psychological dimension of the interactions is apparent. The farmer explained his psychological condition due to his situation, but although he did not finish his sentence, his silence suggests that getting involved in the remediation process helped him. It kept him occupied and he felt he was contributing to something bigger: research into phytoremediation. It also reveals how with this project he transitioned from victim to beneficiary in the post-mining situation, which is a way of regaining the territory, even though he specified that he had no hope for his own land. This example perfectly illustrates the idea of 'vulnerability as an agent of resilience' (Becerra, 2019).

Moreover, the academic knowledge (co)produced by inhabitants and researchers visibilises sometimes unexpected aspects and were used in other forms of expertise and purposes:

> "There was a girl (…) who had done a thesis on remediation. She explained that she used to go to certain places to collect thlaspi carulescens. (…) And there was a map with the points where she had collected these plants. And these points were the old mine."

This person, interested in the rich mining history of the region, uses the scientific knowledge for other purposes than remediation: it is a way of spotting the location of mining remains when they do not necessarily appear in available documents and eventually exploring them when accessible.

From what is described above, research work seems to have had a positive impact on the individuals questioned: the knowledge acquired gave them the possibility of reclaiming their territory. Another important impact, linked to the previous one, is the improved psychological state of the inhabitants who interacted with the researchers. The unfinished sentence of the farmer when he talks about his depression in the previous quote

suggests the collaboration with researchers helped him on a psychological level: it was a way for him to remain busy, find answers to his questions concerning pollution, and have the feeling of contributing to a greater cause. It is an example of 'toxic sublime' (Peeples, 2011), as the unveiling of pollution by scientists pushes the farmer to consider himself as part of the contaminated environment and to act.

Becerra et al. (2016) termed this phenomenon a 'culture of emergency'[7]. Drawing from fieldwork in Amazon oil regions, the authors defined this 'culture of emergency' as 'a set of practices, ways of being and thinking in which antagonistic positions coexist due to the social and economic emergency of the inhabitants of the oil region, leading them to adapt, transforming risks into opportunities to improve their lives.'[8] (p.222). It is based on narratives and rhetoric which tends to invisibilise the contaminations by visibilising its utility (to gain some money from an unusable land or to explore the local mining history). If for some people this rhetoric is destined to improve the region's image (for example by presenting it as an innovative region in the field of phytostabilisation or a place steeped in history), it is also a means of appeasing the inhabitant's psychological distress.

Repurposing 'utilises elements of the existing mining infrastructure (i.e. roads, mine housing, operational buildings) and/or the reconfigured aspects of the landscape (*i.e.* mine voids and mine features) for a different activity post-closure' (Keenan and Holcombe, 2021:3). While Keenan and Holcombe focus on the repurposing of infrastructural mining features, we suggest considering polluted land is highly relevant to the analysis of repurposing in line with the literature (Becerra et al. 2015).

Consequences of phytostabilisation: invisibilisation of pollution through revegetation. Phytostabilisation as a solution to contain polluted soils tends to invisiblise their toxicity. The greening of mining waste gives a natural and pleasant appearance to what was before considered unnatural and unaesthetic. Management measures can furthermore encourage denial (Zanetti, 2018). Although the revegetation process is ongoing in Saint-Laurent-Le Minier, this invisibilisation is already happening. Nonetheless, different perceptions towards this remediation emerged. When questioned about their perception of the remediation work, some inhabitants were quite positive, assessing '[the remediation company] are doing a great job on the heap, it's well grassed and re-vegetated'. As Ferrieux and Noan (2018) explain, because of containment actions, toxicity stops being considered a problem. The remediation might seem all the more natural in Les Avinières as indigenous species were used. Others, on the other hand, had a more cautious opinion, stating that these actions were important 'to prevent dust from flying away and so on' but regretting 'we'll see less of the village's [mining] history'. This reveals an awareness of the invisibilisation of the post-mining situation brought about by remediation work. At the other end of the spectrum, several people underlined their embarrassment at the situation:

> "You can have blinders on. It's easy, we hid [the pollution *via* revegetation] very well. Hidden… When I say hidden, it's because I'm really worried about it. I say to myself [the problem] is not solved".

This quote shows the emotions (uncertainty, anxiety) triggered by pollution. They were related to prior experiential knowledge, as this person's family was affected by mining-related diseases. Consequently, there is a sense of distrust towards remediation actions. Some inhabitants go even further, attributing a perceived hastiness to the local and national government. Recent literature on nuclear waste disposal is in line with the inhabitants' intuitions. Kinsella (2020) highlights not only the material but also the symbolic value of waste disposal projects in the case of the Yucca Mountain repository project. The author explains that such a project aims not only at containing pollution but also at 'purifying the atomic enterprise' (p. 526) thereby creating a new narrative. In our case study, the 'purifying' seems to be two-fold: first, on a very local scale and in the short term it appeases tensions related to contamination in the population and eventually on a national and longer-term level it legitimises the mining renewal policy.

Finally, the repurposing described above somehow invisibilises the pollution. If by selling seeds of pollution-resistant plants, the farmer gives a glimpse of pollution in the international research arena, he also accepts it and normalises it in his daily life. Likewise, the person interested in the mining history does not focus on the pollution but only uses it as an indicator of former mines. As Zanetti (2018) explains, inhabitants don't aspire to eliminate pollution, but to 'live with it'.

Conclusion

In this study of phytoremediation research in Saint-Laurent-Le Minier, we explored the interplay between lay and expert knowledge, focusing on processes of visibility and invisibility. The visibility of certain aspects is shaped by tacit agreements among stakeholders with shared interests, subject to constant renegotiation. By examining what is made invisible, by whom, and for whom, we revealed the influence of invisibilisation processes on research practices, problem framing, and stakeholder inclusion/exclusion.

This paper advocates for researchers to adopt a reflexive stance, emphasising their influence on what is (in)visible. Their work impacts the solutions implemented and may contribute to the memory of the history of the place, and therefore its contamination. We showed that mindful decision-making in research processes and stakeholder interactions can enhance knowledge transfer, empower inhabitants, and increase social impact.

We raise several issues from this case study that could be useful to bear in mind for contaminated soil management. Any research and its application bring to the fore one specific topic (soil contamination here) for a limited period; selects and makes visible certain lay knowledge and local stakeholders; visibilise certain technological choices.

This microsociological study could be expanded to other post-mining territories for greater generality. We could also consider the impact of global contexts, such as national and European policies and legislative aspects, for a more insightful understanding of invisibilization processes.

On the 18th of April 2024, the French Council of State (supreme administrative jurisdiction) allocated waste management in Saint-Félix-de-Pallières, a post-mining territory near Saint-Laurent-Le Minier, to the former mining operator (decision n°474208). This case could set a precedent, but also raises questions among local stakeholders: Which technical choices will be made? Will the measures only invisibilise the pollution because it is in the mining company's best interest?

Data availability

The data supporting the conclusions (interviews) of this study is not readily available due to privacy concerns (Application of the General Data Protection Regulation) and language constraints (French).

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Notes

1 'it (Saint-Laurent-Le Minier) is a chalky soil, so it has an alkaline pH, precipitation, which means that the water isn't contaminated' (researcher working in Saint-Laurent-Le Minier)
2 'Surgissement du doute' in the text
3 the use of plants to limit erosion and dispersion of pollutants
4 extracting the zinc from the soil by using hyperaccumulating plants and recycling it as an eco-catalyst (Grison et al. 2015)
5 By extracting metals and using them as eco-catalysts (Grison et al. 2015)
6 "Agromining is the recovery of valuable heavy metals from soils with high metal concentrations, using hyperaccumulator plants, to produce value added products." (Rodrigues et al. 2016)
7 « Culture d'urgence » in the original text
8 « un ensemble de pratiques, façons d'être et modes de penser où cohabitent des positions antagonistes en raison de la situation d'urgence sociale et économique des habitants de la région pétrolière, les conduisant à s'adapter, transformant les risques en opportunités d'améliorer leur vie » in the original text

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Author contributions

TB: literature review, data collection, analysis, and results interpretation as well as manuscript preparation. JC: manuscript preparation, proofreading FTC: proofreading SB: literature review, proofreading

Competing interests

The authors declare no competing interests.

Ethical approval

IMT Mines Alès does not have an ethical committee for research in human and social sciences. However, this study being partly based on interviews the question of the anonymisation of the data was crucial. The authors, backed by IMT Mines Ales data protection officer, ensured this research was conducted in line with the General Data Protection Regulation (GDPR) in accordance with Regulation 2016/679 of the European Parliament.

Informed consent

All respondents gave their free and informed consent before the study. Every participant's personal information has been anonymized.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1057/s41599-024-03290-0.

Correspondence and requests for materials should be addressed to Tessa Bonincontro.