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Review

Exploring Citizen Science over Time: Sensing, Technology and the Law

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Abstract: People over the course of history have survived by developing their ability to 'sense' their environment as an embryonic form of citizen science. With the emergence of modern states, governments have assumed responsibility for monitoring the quality of the environment, and progressively the practice and role of citizen science has changed. This review explores the different manifestations of citizen science over time, with a focus on its law and governance dimensions, reading this evolution as a critical analysis of the current discourses around citizen science. The evolution of citizen science throughout history and its transformation shows certain patterns that are highlighted in this article as 'constant' features, whereas other features are instead interrupted and reversed, and new ones emerge. We thus examined citizen science over time by asking what is really new about this phenomenon, focusing on constants—permanent features—and turning points—changes in direction. We argue that these dynamics are central to understanding the promises and perils of the practice, to fully grasping the forms of uninvited, reactive environmental citizen science and to scoping foreseeable future scenarios.

Keywords: citizen science; sensing; history; environmental law; environmental rights; (dis)trust

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1. Introduction

Citizen science, meaning the active engagement of lay people in scientific research [1,2], is on the rise. Responding to proliferating environmental problems and enabled by technological developments (more recently enhanced by artificial intelligence—AI) [3], ordinary people are increasingly taking an active role in the monitoring of their surroundings. In the literature, citizen science has been approached through multifaceted definitions. We endorse its definition as 'a research method, aiming for scientific output, [. . .] as public engagement, aiming to establish legitimacy for science and science policy in society, and, as civic mobilization, aiming for legal or political influence in relation to specific issues' [4]. In particular this latter dimension has undergone a distinctive evolution throughout history, from an understanding of citizen science as 'subordinate' to officially appointed (scientific) institutions to an uninvited form of *reaction* to institutional science. Here, it is worth stressing that by 'citizens', we refer to ordinary people, to differentiate them from professional scientists, institutions and private companies. We do not imply any notion of citizenship (i.e., the belonging to a certain nation state), as citizen science practices can be performed by everyone, regardless their citizenship. Several scholars have further provided a contextualization of citizen science not only in space, but also *over time* [5–11]. In the words of Crain and others, citizen science can be understood as a 'time-honoured, evolving practice' [12]. Vasiliades et al., for example, offer a systematic review of the literature on empirical studies, addressing citizens' participation in environmental and nature-based citizen science initiatives over the last two decades, paying particular attention to the 'citizen' component of the practice [13]. Adamou et al. enrich this knowledge base with

a systematic review on how citizens' participation in environmental citizen science over the last twenty years has contributed to Education for Environmental Citizenship (EEC), understood as the behaviour of ordinary people that participate in society as agents of change for the benefit of the environment [14].

In this review article, we build on this scholarship to explore the different manifestations of citizen science from a historical perspective, contextualizing this evolution into a critical analysis of recurring discourses around citizen science. The evolution of citizen science throughout history and its transformation shows certain patterns that we could consider 'constant', whereas other features are instead interrupted and reversed, and new ones emerge. We thus examined citizen science over time through a thematic review and juxtaposition of the existing literature on this and adjacent topics. The criteria that guided the selection of our sources were the thematic relevance for our research question (i.e., constants and turning points in citizen science evolution throughout history) and the engagement of the literature with forms of more 'domesticated' citizen science or, conversely, with more 'reactive' forms of citizen science. We decided to select our literature mostly within the arena of environmental citizen science, as we posited that forms of civic monitoring around environmental matters could offer an interesting study case for how the practice has evolved over time (as 'sensing' the environment is at the root of our humanity) and which social and political dynamics this evolution implies. Guiding our review is ultimately the question on what is *really* new about this practice. In light of this question, we read the literature through a lens based on constants—permanent features—and turning points—changes in direction. We believe that these dynamics are central to understanding the promises and perils of the practice and foreseeable future scenarios.

2. Citizen Science as an Ancient Practice

In the Anthropocene ('human epoch'), humans have become the main determinants of their living environments [15,16], with an influence on the planet that is 'unmistakable and undeniable' [17]. It is increasingly apparent how the effects of our impact on our living environment, including global heating, weather extremes and desertification, pose detrimental risks to our life on this planet [18–20].

At the same time, it is important to recognize that, 'environment-wise', the Earth has never been a 'risk-free' place to live. A need to monitor the environment can therefore be regarded as an inherent part of human life [21]. Abe [5] quotes Schudson's conceptualization of 'the monitorial citizen', capturing this idea of an intrinsic drive of the human being toward environmental surveillance [21]. Water—on which our very existence crucially depends—is a prime example here. It is estimated that, approximately 50.000 years ago, humans had started populating most parts of the world [22]. As Juuti and others argue, people will naturally have come across waters contaminated with various pathogens, and therefore had to develop an environmental sense for odious looking, smelly or foul-tasting water, which let them know when to avoid such water and move on to a different site [22]. This development of our senses to detect environmental risks could already be considered an embryonic form of citizen science, since environmental information was collected for making assumptions on what was safe, although at the time there were not defined roles such as scientists and lay citizens, or governors, for that matter [22].

As people started to settle down some 10,000 years ago, developing agricultural settlements, the problem of contaminated water became much more prevalent. Generally, settlements would be centred around drinking water sites and often steadily grew into villages and towns filled with humans and livestock. This growth also increased the amount of sewage that made its way into catchments, thus contaminating the drinking water. Having settled, however, it was no longer a matter of simply moving camp; instead, a solution to the problem of dealing with waste and sustaining safe drinking water had to be developed [23].

At this point, sensing alone was not enough to ensure that the water consumed would be safe. Humans at a very early age started developing technologies for securing the contin-

ued safety of their drinking water resources. Illustrative here are the water supply networks found in ancient civilizations such as Egypt and the Sumerians of Mesopotamia, but also the Roman system of aqueducts, pipes and sewers [23]. From the industrial revolution of the 18th century onwards, not only did the human populations grow exponentially but so did the environmental pressures on *inter alia* drinking water resources due to increased industrialization. As Gleick concludes, an unprecedented construction of engineering projects designed to protect clean water supplies and improve sewer systems helped to sustain a steady supply of safe drinking water in many industrialized countries where previously rampant water-related diseases such as cholera and typhoid have now largely been eradicated [24]. Yet, as the author estimated, around half of the world's population 'still suffers with water services inferior to those available to the ancient Greeks and Romans'. As the United Nations concluded in its latest report on clean water and sanitation, however, the health of tens of millions of people is still at risk from polluted surface waters [24], which shows the fact that human sensing of water quality is by no means obsolete.

However, in present times, the 'original' solution to ensure that the water humans consume is safe—namely our sensing capacity to detect foul water—can no longer match the increasingly industrialized, populous and complex world we live in [25]. As will be discussed further, both technology and law can effectively be seen as factors that have increasingly 'replaced' ancient citizen science as focal points for securing human survival. Nevertheless, citizen science has remained an important activity throughout human history, as we illustrate below.

3. The Emergence of Citizen Science as Participatory Data Collection

Aside from this example of sensing the quality of drinking water, a human devotion to 'check' with their own eyes appears primordial and can be considered a constant in the history of citizen science. One can think of the curiosity that led humans to refine their sensory skills in order to be able to touch, see, smell and hear better. As warned already in the 1970s by the ecologist Robert Pyle, however, the urbanization of society and the growing time spent indoors has incrementally led to a reduction in opportunities for people to interact with their environment [25]. To conceptualize this process of alienation from nature, Pyle coined the term 'extinction of experience', which in our terminology could be framed as a progressive loss of the ability to sense the connection with the surrounding environment and its changes [26]. Increasingly, citizen science in the environmental domain is seen as a way 'to reconnect people to nature', by stimulating desires for nature preservation and 'emotional connections to and empathy for nature' [27]. Conceivably, reconnecting with nature may also trigger a *need* for sensing with the aim of protecting oneself from the pollution of one's living environment, recalling the ancient meaning of citizen science. This tendency suggests however a rather individual-based and unstructured form of sensing.

Conversely, a more structured understanding of the practice can be found in the longstanding tradition of involving citizens in scientific environmental data gathering. In particular, citizen science as participatory data collection that involves scientists and laypersons collaborating to gather scientific data has existed for decades, even without being characterized by a specific terminology [28,29]. Silvertown, for instance, underlines how civic actors have often been involved in collecting nature observations in a number of disciplines, such as archaeology, astronomy and natural history [29]. Vetter adds that, already in the 19th century, the gathering of meteorological information in the United States relied on a wide network of volunteer observers committed to regularly sending their observational data to the government [6]. These volunteers were both recruited and engaged to support appointed institutions in obtaining more fine-grained information on specific matters with a limited budget. In addition, the citizens could gain knowledge and pursue their curiosity, as they were mostly amateurs in the fields of engagement. Such involvement of citizens in the development of scientific data was eventually even acknowledged through the codification of a 'right to science', protected as a fundamental

human right by the Universal Declaration of Human Rights and by the International Covenant on Economic, Social and Cultural Rights [30].

As Eitzel and others emphasize, however, lay citizens were 'valued only for their observations rather than their ability to elucidate meaning from observations' [22]. Eitzel offers the example of the famous Cornell Lab of Ornithology, established at Cornell University in 1915, where lay citizens were engaged in supporting appointed scientists in biodiversity research. Conceivably, such amateurs also shared with scientists the meanings they derived from their observations, but the relevance of their perspectives on the issues studied was generally not recognized as valuable [7]. This was mostly because at the time the authority of appointed scientists was undisputed. As scholars commonly agree, throughout the 19th and early 20th centuries the role of volunteers was to 'assist, rather than to challenge or critique, the scientific establishment [as] they were supposed to work together in a kind of division of labor' [13]. Nonetheless, even more recent studies that reviewed citizen science over time point to the 'lack of recognition' of volunteers' contribution as a barrier to engagement in citizen science, signalling that the issue of truly valuing citizens' input is still present today [31]. Over time, a 'professionalization' of science—with widespread use of jargon and specialized procedures—made it so that citizens increasingly faced hurdles when trying to participate in scientific enterprises [32], whilst at the same time increasing the gap between science and ordinary people and fuelling people's scepticism towards science. In turn, technological developments, as we further discuss below, have both *enabled* and *urged* citizens to increasingly turn to citizen science again. This time, however, citizen science is less of a 'functional' support to established environmental science, but more a reactive enterprise fuelled by a distrust in official environmental monitoring (what we will frame as 'reactive, uninvited citizen science').

Interestingly, the trend of citizen science becoming less 'functional' to 'official' science, and at times even developing in contrast with it, signals a progressive erosion of civic trust in science more generally. The sense of uncertainty that has characterized the last decades and especially years has increasingly triggered movements that contest science, defending the legitimacy of 'alternative' perspectives on given matters. This can be said to be the case, for example, for 'anti-vaccination' movements [8]. Mahr and Dickel offer a critical perspective on how a claim to 'autonomous' citizen science (which resembles our notion of 'reactive' citizen science mentioned above) emerged in the wake of the current societal backlash dominating western societies' discourses on scientific matters [8]. Such discourses, according to the authors, are increasingly characterized by distrust in mainstream expertise, while also mentioning the case of the anti-vaccination movements, in addition to flat earth theories and climate change denialism. The authors also discuss other forms of contesting official science, for example through 'autonomous' forms of citizen science that reclaim the ownership of women and transgender people's bodies and the inclusion of minorities in evidence-making. All these practices have in common the fact that they challenge who claims to possess epistemic authority on a given scientific matter [8]. Mahr and Dickel's study shows that a historical link can be found for today's struggles of autonomous citizen science. The authors envisage a scenario where uninvited citizen science will develop in a 'niche', researching neglected knowledge matters [33], while official science will keep engaging citizen scientists but more as 'crowd-workers' [34] (especially in scientific fields that need large amounts of data) rather than as holders of different and at times contrasting values and knowledge systems.

Faced with uncertainty, science seems to have become more contested in recent times and more distant from general society overall. The knowledge that has emerged, and still emerges, in recent history outside established paths with a clear reactive and political connotation has been differently framed, negotiated and resisted by the scientific and political institutions faced with it. At times, it is embraced as a legitimate voicing of alternative imaginaries and viewpoints, and in other cases it is discarded and contested as 'misinformation' and 'science populism' [35]. Specifically in the field of reactive environmental citizen science, the existing literature has investigated how citizens use data as a rhetorical

resource for contesting official interventions and advancing justice claims. In doing so, people have to 'justify' their role and do so through a variety of arguments. A study that reviewed a series of citizen science cases that enacted such strategies summarize them as follows: the argument that listening to civic data is a governmental obligation and that of the ultimate benefit of such data for informing environmental decisions [35]. In negotiating these claims, people use discourses that include showing the scientific strength and contributory potential of civic data, whereas environmental rights and democracy-based discourses were found to be rare [35]. In addition, these arguments could be seen as recurring or varying over time, disappearing or newly manifesting, and are important to understand the evolution of citizen science.

4. Technology as an Enabler and a Driver for Citizen Science

Sensing has inevitably been shaped and amplified through the support of technologies and by the transformative potential of artificial intelligence (AI), big platforms and big data, which has substantially changed citizen science. An example is the so-called 'Galaxy Zoo', which pioneered new methods for the large-scale visual classification of galaxy images, crowdsourcing citizen science tasks to half a million members of the general public [36]. In fact, our ability to sense has gained a considerable boost in recent years—in particular from 2010—due to the evolution of sensing technologies such as mobile devices and data quality improvements [37,38]. However, what exactly is 'technology' in the context of citizen science? A definition of technology can be derived from the juxtaposition between things that 'occur naturally' and those that are 'human-made' [39,40]. A technology in this context would be the product of a reasoned act of human or even animal intelligence. At a semiotic level, the word 'technology' has an ancient meaning, deriving from the Greek roots *techne*, 'create', and *logos*, 'order', 'logic', which combined mean 'creation of order'. From the combination of the Greek roots, Carroll defines technology as 'something that is organized [thus implying the creation of order] whose aspects function with a purpose that can provide some benefit.' [39]. Technology is thus conceptualized as a manufacturing and ordering effort aimed at creating value.

An example that is illustrative here is man's use of maps. In fact, as will be outlined below, citizen science and mapping are inherently linked, and briefly outlining the evolution of cartography sheds light on citizen science in history. From the start of cartography in the form of mapping stars starting from what has been estimated at 14,500 BC, humans refined their capacity to create accurate maps. Such mapping of our environmental surroundings soon became crucial to a number of activities, such as route planning, legal demarcation of human settlements and other spaces, as well as the monitoring of natural resources [11]. Improvements to our mapping capacities can be regarded as a tireless human effort to enhance our sensing capacities. This occurred in large part through the development and use of new technologies such as, for instance, the invention of the telescope in the 17th century, which strengthened human ability to observe remote objects. In more recent times, maps have also become a central tool to track human health and wellbeing, for example through damage maps for disaster relief and maps aimed at coordinating humanitarian aid programmes [41]. The human drive to enhance their mapping potential can be therefore considered a constant throughout human history.

A turning point can however be identified around the year 2010, through the rapid development of geo-information technologies, and in particular the proliferation of location-aware devices and of the interactive, interoperable, user-generated 'Web 2.0' [11]. This drastically boosted man's mapping potential, making it possible for citizens to easily acquire, use and share geographical information [3]. The advances in geo-information and sensing technologies made all sorts of types of citizen science evolve, but they can be regarded as particularly useful for facilitating reactive forms of citizen science as they allow citizens to engage in scientific enquiries fully independently from governments and traditional scientists. Any person with a mobile device could act as a 'sensing citizen' and

report environmental information, demonstrating the revolutionary and democratizing potential of this technology.

In (relatively) recent times, the evolution of citizen science has been substantially influenced by AI progresses. Particularly in environmental monitoring projects, AI has offered enhanced functionalities to citizen scientists, which has affected the practice as a whole, as well as the individual contributions and experiences in engaging with citizen science. Among the many studies on the topic, McClure and others offer a picture of the development and uptake of AI techniques in citizen science, specifically for ecological monitoring [3]. The study suggests that AI can allow scientists and citizen scientists to gather and analyse larger volumes of data than what was possible with traditional methods, delivering cost-efficiency and accuracy. The study, however, also discusses the challenges of AI-based or enhanced citizen science. For example, among the challenges, the authors list financial resource constraints for developing this integration and the need to pay attention for participant engagement and training.

To conclude this reflection on technology and citizen science, it is worth citing Volti's definition of technology as a 'system created by humans that uses knowledge and organization to produce objects and techniques for the attainment of specific goals' [42]. This knowledge and organization targeted towards the achievement of certain objectives is also at the origin of the citizen science phenomenon that, in this regard, can be classified as a technology on its own behalf. This links in with the work of Milan and van der Velden who [43], referring to Braman [44], further suggest that 'data' should also be considered a technology. They again start from the ancient Greek word *techne* in its meaning of 'crafting'. The word technology, in the authors' view, would not refer only to the tool per se, as commonly understood, but also to the process of human engagement, connecting art and engineering [43]. The engagement component of the word 'technology' seems particularly appropriate to the forms of reactive citizen science discussed in this article. Furthermore, this conceptualization suggests that not only the tools used by the sensing citizens but also the data produced through citizen sensing can be regarded as a technology. Besides being an enabler for developing citizen science, technology can also be regarded as a key driver for citizens to actively participate in monitoring their environment. In the literature, various examples can be found of how pollution resulting from modern technologies sparks such involvement in a reactive manner. Abe, for instance, points to the 'Radiation Disaster Alert Network' that emerged in the aftermath of the Chernobyl nuclear disaster in 1986 as a grassroots network of volunteers who use dosimeters to measure radioactivity for their health and safety [5]. The 2011 Fukushima disaster, Abe details, similarly triggered a great increase in civic radiation monitoring, organized in networks of citizens working together [5]. Even earlier in the history of Japan, two serious environmental disasters, the Minamata severe mercury poisoning from 1932 to 1968 and the Itai-Itai cadmium poisoning from 1912 to around 1970, sparked embryonic forms of civic monitoring which led to court cases, as our correspondence with an expert of Japan and citizen science held during fall 2021 in view of this study demonstrated.

In several cases around the world, such as those researched by the 'Sensing for Justice' project through virtual and physical ethnography [44], ordinary people respond to pollution resulting from factory farms and petrochemical companies [45], among the other examples, by actively engaging in civic monitoring activities in order to influence policy decisions or even start legal proceedings [46,47]. While deploying a reactive citizen science initiative, people often explicitly or implicitly engage with the law, as the framework against which monitoring findings can demonstrate potentially illegal behaviour by the enterprises responsible for pollution. They 'appropriate' technology as an instrument to have a voice in law enforcement actions. This link between (reactive forms of) citizen science and legal claims imbued with justice discourses can be traced back in history. At the time of the industrial revolution, not only did a strictly 'environmental' form of sensing flourish to denounce the impact of pollution on the environment. It also became important to monitor the health conditions of the workers that were daily exposed to the human

costs of industrialization. It was then that ordinary people started appropriating science and turning it into citizen science to denounce the poor conditions in the factories. They collected data and first-hand experiences to counter-balance the power of big corporations augmented by rampant economic and technological developments. For example, in Italy, factory workers actively gathered data to show the flaws in industrial systems, contest risk management and health protection practices and ultimately demand improvements.

Callon and Rabeharisoa offer other historical examples of these reactive forms of citizen science, such as popular epidemiology in low income neighbourhoods, women-led health studies of the menstrual cycle and HIV activism in the 1970s and 1980s [48]. This overall demonstrates that alternative modes of citizen science have a long history [8]. Over time, these forms of citizen science have been mostly associated with emerging social groups and were entangled with social justice protests, as the case of the Occupational Health Movement shows [49]. Such historical developments suggest that—even long before present days—citizen science was there to challenge the existing social and power relations and adopted a clearly 'reactive' discourse. This characteristic can be read in light of the more recent developments in the field called citizen *social* science, as Tauginienė et al.'s study demonstrates. The authors adopted a meta-synthesis approach to explore how citizen science is practised in the social sciences and humanities, in particular to address 'wicked' problems. They conclude that the integration of citizen science practices in these disciplines is growing and yielding rewarding results [50].

In light of what has been discussed here and in the preceding sections, in Figure 1, we offer a timeline-based taxonomy of the illustrated evolution of citizen science over time.

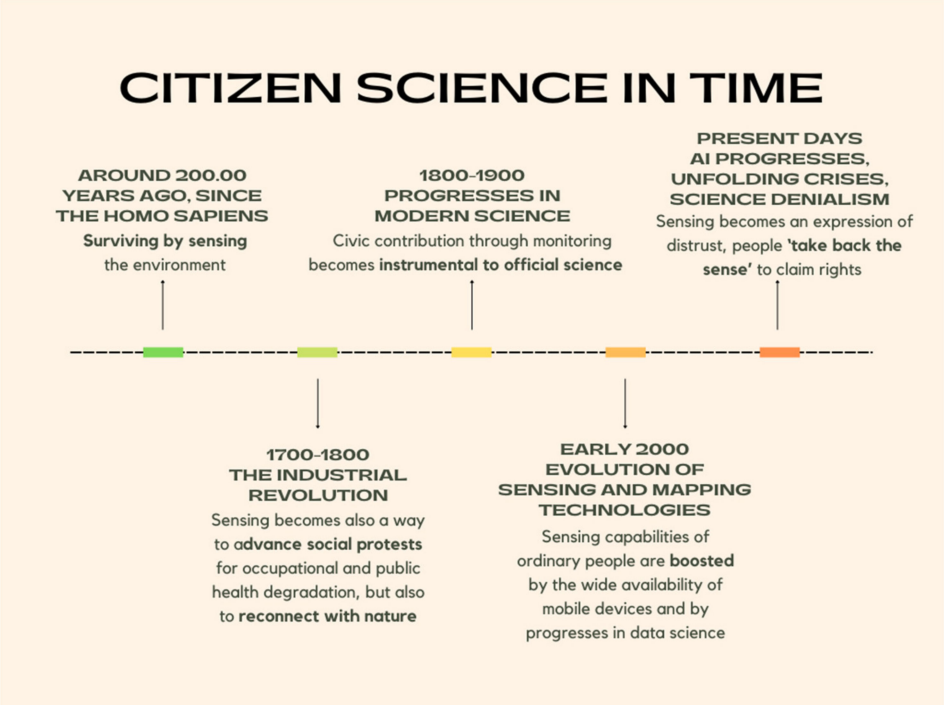

Figure 1. Timeline-based taxonomy of citizen science evolution.

5. A Legal Perspective on Citizen Science over Time

Throughout the article, we have discussed how people have always had to use their senses to explore and scrutinize their environments while at the same time preserving their own health and survival. Using our senses to assess whether drinking water was 'safe' or foul was posited here as an 'embryonic' form of citizen science, in which humans collect environmental information and form assumptions. When citizen sensing could no longer suffice in terms of ensuring the quality of our environment, humans increasingly resorted to the development and use of technology, of which the water supply networks found in

ancient civilizations are examples. Particularly since the industrial revolution, however, technology has also become a key driver of environmental pressures on its own behalf. This, in turn, led to a push for environmental laws and regulations to ensure that pollution would be kept within safe parameters.

What our analysis of citizen science in time highlights is a trend of people deciding to 'take back the sense' through civic monitoring, as people are no longer satisfied with delegating tasks to institutions that appear unable to protect their interests [35]. Using new technological resources that have become available in recent times (for example, lately, AI-enhanced environmental monitoring), citizen science can provide a key tool to enforce environmental laws and rights. Particularly when joining forces with other civic actors, non-governmental organizations and scientists, at times using the law by turning to courts or creating partnerships with (local) governments and enforcement agencies, citizen science can potentially be a crucial tool to reverse potentially harmful political decisions and face corporative powers. In this panorama, a new push within the legal domain is emerging to recognize the civic right to contribute to the production and analysis of environmental information [47], which could mirror this new trend of reactive environmental citizen science.

The phenomenon of lay people struggling with official environmental management and deciding to 'take back the sense' through reactive environmental citizen science is an expression of a protest against the status quo [35]. Often, distrust is a trigger for this type of citizen science; resisting mainstream environmental decision-making and the evidence underpinning such decisions shows civic scepticism towards governors [51–53]. This can also be understood as a manifestation of rights [47,52,53], both substantive rights, such as for instance the right to life, as well as procedural environmental rights, such as the right to scrutinize the evidence base on which the contested decisions are taken. In particular, this latter right is enshrined—in the European context—by the United Nations Economic Commission for Europe (UNECE) Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters adopted on 25 June 1998 in Aarhus, Denmark, also referred to shortly as 'the Aarhus Convention'. When governments fail to uphold such rights, the breach is essentially two-fold: not only are rights violated but this is also carried out precisely by the actors that have established such rights, namely governments [47]. Looking at this trend, we can pinpoint an emerging discourse that defends the idea that listening to civic data is a governmental obligation. Furthermore, a rights-based discourse emerges as a legitimization strategy to defend the role of citizen science in informing decisions. Law, and in particular environmental and human rights law, along with participation rights, can offer citizen science a strategic resource to defend the entitlement of ordinary people to monitor the environment and gather data for the sake of human and environmental health. In addition, legal provisions that give recognition to a certain natural body—for example a river—in the form of legal personhood could grant citizen scientists an entitlement to act as guardians on its behalf. At the same time, law must be *understood* by the people and properly navigated, as citizen scientists may also incur in legal risks when performing their monitoring activities, for example being charged with defamation claims and other strategic attacks through court proceedings from interested corporations [51,53]. All this requires further thought and (legal) articulation.

6. Discussion of Key Findings

Our thematic review of the literature enabled us to identify a number of constants in the evolution of citizen science. Among these permanent features, we can list the fact that humans have always used their own senses for survival. In this context, it is worthwhile to notice how the word 'sensing' has two meanings. On the one hand, sensing stands for the act of 'detecting'. However, the word also means the act of 'feeling' or 'experiencing' something (corresponding to the German word *ahnen*: 'to suspect; to presage; to intuit') [5]. This entails an emotional act beyond solely detecting. As such, we have situated citizen science practices throughout history and more recently not only situate

themselves as a method of environmental data detection but also as an *emotional engagement* with environmental problems. Such an engagement mirrors people's values, struggles and imaginaries, such as feelings of distrust and of responsibility for addressing environmental issues. Another recurring trend is the fact that ordinary people have been engaged for a long time with science and its results, mostly in a 'subordinate' and 'instrumental' role in the past and increasingly appropriating scientific processes and results. The drive for mapping our living environment is another constant, where, however, technological progresses have enhanced people's capacity to act as sensing and mapping devices and to produce accurate and reliable data. The constant presence of human curiosity and a tendency to not believe without checking is a recurring theme in the evolution of citizen science, and especially characterizes the more reactive forms of the practice. The need to go into the wild and monitor in more recent times is instead a rather novel response to contrast people disconnecting from nature due to increasing urbanization and industrialization, responding at the same time to the urgency to watch over intensified environmental pressures. It is in this context that a 'rupture' emerges among the constants: more and more ordinary people distrust and contest environmental data from official sources and are deciding to 'take back the sense' through civic monitoring.

In the summary Table 1 below, we offer an overview of the recurring aspects that our analysis shows in relation to citizen science practices, and we pinpoint turning points. For both aspects, we reflect on the socio-political and legal implications of these constant or breaking features.

Table 1. Organic overview of constants (C) and turning points (TP).

Occurrence	C	TP	Socio-Political Effects	Legal Effects
Humans using their own senses for survival (Schudson 1998 [21])	X		People learn how to strengthen their senses and pass down this knowledge	n/a
Lay citizens engaging with science and its results (Silvertown 2009 [29], Vetter 2019 [6], Vasiliades et al. 2021 [13], Adamou et al. 2021 [14])	X		Involvement in participatory citizen science projects helped contribute to scientific knowledge production	The Right to Science is recognised as a fundamental right by the Universal Declaration of Human Rights and by the International Covenant on Economic, Social and Cultural Rights
Civic monitoring being instrumental to official monitoring (Eitzel 2017 [27], Vasiliades et al. 2021 [13])	X		Stable cooperation between citizen scientists and traditional scientists and with governors were set up to facilitate this mutual support	A few laws over the world recognize the role of citizen science for environmental monitoring, e.g., the Crowdsourcing and Citizen Science Act (US)
Mapping our living environment (Harley 1987 [20])	X		People have a long history of studying, creating and designing maps through cartography	Maps have a crucial role in establishing borders and other geographical features that have legal implications
Humans' curiosity and tendency to not believe without checking with their own eyes (Berti Suman 2021 [47])	X		People refine their sensing skills and develop instruments to better scrutinize their surroundings, e.g., the telescope	This fact-checking desire has led to the legal recognition of access to information rights and to transparency obligations by the governments and has stimulated public participation in policy decisions
Humans disconnecting from nature due to inter alia urbanization and industrialization (Pyle 1978 [25])		X	People are pushing for 're-appropriating' their connection with nature by spending free time in the wild, including monitoring it through citizen science	National and international laws recognize the right to enjoy a healthy environment and have intervened at a legal level to preserve nature
Intensified environmental pressures from industrialization (Gleick 2001 [23])		X	Increased need for (governmental) intervention addressing pollution	Emergence of environmental laws and regulations and the setting up of public monitoring agencies

Table 1. *Cont.*

Occurrence	C	TP	Socio-Political Effects	Legal Effects
Citizens' ability to sense associated with the evolution of sensing and geo-information technologies, mobile devices and data quality improvements (Foody and others 2017 [11]) and more recently a trend of the reliance of citizen science on crowd-sourcing (Sauermann and Franzoni 2015 [34]), and to AI-enhanced capabilities (McClure and others 2020 [3])		X	Any person with a smartphone became able to act as 'sensing citizen' and report environmental information, amplified by the use of social networks and enhanced by AI-powered capabilities for citizen scientists	This stimulated regulatory efforts by governments and an increasing interest from governments on how to use and regulate these data flows and human interactions with AI as potentially critical for human rights and for national security
Lay people distrusting or contesting official environmental monitoring data and deciding to 'take back the sense' through civic monitoring to advance social and environmental justice claims (own conceptualization based on Berti Suman, Schade and Abe 2020 [35], Berti Suman 2020 and 2021 [35,47], Mahr and Dickel 2019 [8], Callon and Rabeharisoa 2008 [48])		X	Often, these initiatives take the form of a protest against the status quo and have triggered or alimented social movements	A new push within the legal domain is emerging to recognize the civic right to contribute to the production and analysis of environmental information

7. Conclusions, Limitations and Future Directions

In this review article, we explored the historical evolution of citizen science to make a case for a relatively 'new' trend: that of lay people deciding to 'take back the sense' through performing environmental monitoring as a response to failures or to the inertia of appointed institutions. We focused on the emergence of uninvited, reactive environmental citizen science that is born of a distrust in official environmental monitoring. Compared to the perhaps more 'traditional' forms of citizen science, in which citizens assist scientists in the collection of environmental information, we highlighted the experiences of post-disaster (as a 'distrust shock') citizen science such as the post-Chernobyl and post-Fukushima contexts, where citizens 'take up arms' and engage in the active monitoring of their local environments themselves [54].

By doing so, we wish to convey two key messages. First, that part of the 'driver' that motivates people to engage in citizen science is an inner, as rooted in our humanity, tendency to use our own senses for ensuring our survival. Later, the human ability to monitor the environment became subordinate to professional scientists' needs, who were engaging with crowds of volunteers to gather data, for example, on biodiversity. In more recent times, from being 'instrumental' to official science, the engagement of ordinary people with science became and is becoming more and more imbued with a 'reactive' discourse: that is, of 'taking back the sense'. This appears particularly driven by situations where appointed authorities and scientific institutions are seen as struggling to cope with ever more complex and entangled crises and related scientific issues that must be addressed. Our second key message is that this citizen science 'rupture' from constant trends should be studied not only as a present phenomenon but rather as a feature that is manifested differently but in several instances back in history (for example, in the workers' movement for better occupational health conditions). The discourses used back then should be studied and put in relation with those used today.

Furthermore, we pinpoint three aspects that deserve greater attention in observing and analysing the evolution of citizen science over time. First, that of the role of the law and

rights-based discourses in framing citizen science practices, as scholarly debates on citizen science interfacing with the law are still scant with few recent exceptions [53]. Second, we believe that the impact of AI and other recent technological developments on nature and citizen science as well as on people's engagement should be studied closely. Third, we defend that it is crucial to explore reactive citizen science as a space to bring to the fore unheard voices from marginalized and underrepresented groups. Nonetheless, we suggest that there are risks to consider, e.g., especially in the areas of public health and climate science, where for instance denialism can spread easily, as well as through grassroots-driven forms of science. Official science should be able to enter into dialogue with these realities and offer credible and authoritative answers for handling pressing matters and (re)gaining legitimacy and trust in the eye of broader society.

Finally, we highlight some limitations of our study. First, we considered that the current systematic studies of the evolution of citizen science throughout history are scant and that the type of citizen science we focused on, namely uninvited, reactive citizen science, is often overlooked in theoretical and empirical studies on the practice. Being ourselves legal scholars, we hope that, in the near future, historians will more deeply engage with some of the topics highlighted in this article as avenues for future research—such as the interplay between citizen science and the law over time—to develop new, broader and deeper research insights. In addition, there is a context-bias limitation due the fact that this article mostly takes the perspective of Europe and more in particular of the EU *acquis*. We also hope that similar studies will be carried out in other contexts, such as in the Asian or African regions, in order to gain a more comprehensive and context-informed understanding of citizen science over time. Lastly, we consider it relevant to empirically investigate what drives personal decisions to turn to sensing (in other words, the decision to 'take back the sense'). Further study of such personal drivers could also shed light on distrust dynamics and ways to overcome them. This may, in turn, provide advice on how to mutually reinforce environmental citizen science and government-led environmental monitoring in order to foster improved environmental outcomes.

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