Letter to the Editor

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Rethinking environmental noise assessment through a noise footprint framework

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1 A need to incorporate noise in environmental footprinting

A significant body of research across the world [1] assesses the impacts of noise on human health [2] and emphasizes the need for increased attention [3]. New technologies on noise prediction [4] and the establishment of methods to measure soundscapes [5] introduced fresh perspectives to link noise (or sound) to human well-being. A linear description of this phenomenon typically involves a source producing a quantifiable amount of sound power, resulting in pressure at the receiver point [6]. Unfortunately, the aforementioned interaction is not always linear and most importantly, it could be asynchronous. Noise impacts may not necessarily be direct, as research has identified long-term consequences for human and environmental health [7] in a variety of spatiotemporal scales and conditions [8].

It is meaningful to move beyond linear boundaries and geographical constraints in noise assessment by considering the total noise generated across all phases of systems such as products, processes, services, activities, and personal choices. The acoustic impacts of tangible goods throughout their entire life cycle should be evaluated from a cross-sectoral perspective, recognizing that individual consumer choices ultimately influence human health, environmental quality, and other key assessment endpoints. With this growing knowledge, we have the potential to do much more. A significant advancement in noise assessment would be the adoption of a holistic, responsibility-based framework that moves beyond direct source–receiver interactions and acknowledges the complex interdimensional and spatiotemporal dynamics of noise.

The concept of an environmental "footprint" is highly relevant in this context. While there is no universal definition of "footprint" [9], it is generally understood as a quantitative measure of the potential impacts caused by a product, service, or organization throughout its entire life cycle [10].

Several approaches regarding the calculation of carbon footprint [11], water footprint [12], and energy footprint [13] have been developed. Among these, the carbon footprint has played a particularly influential role in advancing environmental protection, guiding informed decision-making, and promoting social engagement, especially in the context of climate action and lifestyle changes [14].

Since sound environments and their perceptual construct, the soundscape, are recognized as resources that must be protected and managed sustainably [15], the development of a noise footprint framework is therefore both valuable and necessary.

The calculation of the total noise generated by all relevant sources within a process, under a noise footprint framework, could promote noise-aware citizens, positive soundscapes, and overall quieter environments, similarly to how carbon footprints aid in identifying and reducing environmental impacts. To achieve this, alongside a clear definition and scope, a noise footprint indicator reflecting the cumulative acoustic pressure exerted on human and environmental receptors will be developed.

Nevertheless, the above is not without potential misconceptions. In the context of noise, the notion of a noise footprint can be loosely linked to the spatial extent of noise propagation, often visualized through noise mapping.

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However, this spatial interpretation may oversimplify the multidimensional nature of noise impacts. Even though undeniably useful to urban planners, governments and regulatory bodies for identifying "noise hotspots" and highlighting limit breaches, affected populations, and exposed dwellings within a specific area, noise maps represent only a snapshot in time. They stand as a static picture that indicates where noise levels from a single or a combination of sources are high, whilst a noise footprint can be comparable across products, services, or lifestyle choices, supporting more targeted and effective mitigation strategies. To this end, noise footprinting could work alongside strategic noise mapping but serving a different purpose.

In order to make the future noise footprint process more effective and help create a robust and consistent methodology for its calculation, a set of key elements underlying methodological and policy aspects are suggested.

1.1 Methodological consistency and accuracy

A particular methodological challenge arises from the use of decibels which is a non-additive, logarithmic unit, complicating aggregation and comparison. For example, Cucurachi *et al.* [16] presented a consumption-based, land-based mobility noise footprint assessed at national, municipal and household levels. This study demonstrates how the impact of sound emissions from private and public transportation can be measured using inventory data converted into sound energy (joules).

1.2 Flexibility and modularity

Noise footprints should be flexible and modular, serving as indicators of the total noise associated with the life cycle of a product or service. Flexibility, particularly in environmental policies, refers to adaptability and can drive technological innovation and sustainable development. Nevertheless, it carries the risk of vagueness with a possible imminent "implementation gap" where intentions fail to translate into effective action. To address this, strong regulatory enforcement can serve as a moderator, minimizing the risk of implementation shortcomings [17]. In addition, modularity regards a system of which the basic components can be adjusted without affecting the entire system. Hence, modularity can provide the structural foundation that enables flexibility while avoiding vagueness.

1.3 Noise awareness and education promotion

The noise footprint framework should offer the tools to allow the quantification of the impact of human activities and personal or collective choices on the environment in terms of noise pollution. Such a framework should serve as a scientific assessment tool but also as an educational resource effectively communicating these impacts to advance awareness. For example, the development of a personal noise footprint calculator, similar to widely used carbon footprint tools, could empower individuals to understand their contribution to noise pollution and encourage more sustainable behaviors at both individual and societal levels [18].

1.4 Alignment with environmental policies

It is undeniable that noise can sometimes be unavoidable. To address this, the concepts of compensation and offsetting could be applied. Through this approach, offsetting can be applied to balance unavoidable noise emissions. Such an approach contains multiple co-benefits toward the sustainable management of urban green areas. Similar benefits can be obtained through the promotion of soundscape interventions that can be defined as site-specific designs to preserve or improve a soundscape [19,20]. Actions aimed at minimizing the noise footprint through noise reduction techniques, the adoption of sustainable materials and the advocacy for soundscape interventions, collectively represent a significant step toward healthy sound environments. Furthermore, the noise footprint framework could support policy mechanisms that address environmental degradation while offering economic incentives to stakeholders. For example, "nature credits" [21] are tradable certificates that reward verified positive environmental actions. A similar scheme of "soundscape credits," certified under the noise footprint framework, could be developed to promote sustainable noise management.

2 A call to action

The introduction of a noise footprint framework, aligned with other environmental footprints such as the carbon footprint, offers an alternative approach to assessing environmental noise, shifting from isolated measurements to a holistic view that captures cumulative impacts across life cycles and sectors.

This framework will involve the development of original metrics to quantify the cause-effect chain linking noise emissions to their impacts. Given the complexity of this chain, the focus should be on the intermediate/midpoint stage, assessing decibel-based indicators that characterize the physical properties of noise pollution. However, physical measurements alone cannot capture the full spectrum of effects on human health.

As the regulatory landscape in noise action plans evolves, showcased by recent initiatives in Wales that embed the soundscape approach [22], there is a timely opportunity to advance noise assessment by incorporating more holistic and perceptual dimensions.

It will be beneficial to incorporate in the noise footprint the perceptual dimension by integrating psychoacoustic metrics [23] and Soundscape Perception Indices [24], which reflect how noise is experienced and interpreted by individuals compared to specific targets.

As noise pollution is linked to consumption-based emissions across personal, product, organizational and city-level activities, bottom-up footprinting approaches similar to carbon footprint calculators [25] can empower citizens, inform more effective policies and result to more livable environments [26].

This effort will be further strengthened by the introduction of a noise footprint calculator designed to measure and communicate the environmental impacts of noise. Increasing awareness of individual contributions to noise pollution can motivate people to take meaningful action, enabling them to develop their own solutions to mitigate noise-related problems.

Access to a tool informing on the individual's contribution to noise pollution could produce motivation and create a sense of moral obligation, hence reinforcing citizenship and social responsibility. For example, understanding the noise impacts of a product throughout its life cycle and not just during the use phase could encourage better choices, improving soundscapes beyond the user's immediate audible sphere. Nevertheless, individual actions and lifestyle alterations alone are not enough to cause a desirable change. Greater accountability and transparency regarding noise-related information from larger institutions and authorities are essential to support healthier sound environments and sustain positive behavior change.

To achieve this, a wide range of interventions and activities will be implemented to refine the noise footprint. These, amongst others, will include assessments in the building sector, such as evaluating the impacts of noise-producing equipment, as well as analyzing the total noise generated throughout the entire life cycle of a product, from material extraction and transportation to use and disposal.

We invite the noise research community, policymakers and stakeholders to collaborate in refining this concept, developing robust methodologies, and integrating noise footprinting into environmental policy.

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